Dynamic ventilation

Making it more attractive to retrofit gas-boilers with ventilation heat-pumps

Master graduation thesis
Writen by Marijn van Limborgh
MSc. Integrated Product Design
Faculty of Industrial Design Engineering
Delft University of Technology

Dynamic Ventilation

Making it more attractive to retrofit gas-boilers with ventilation heat-pumps

Master graduation thesis by

Marijn van Limborgh

TU Delft supervisory team

Dr. Ir. Arjen Jansen

Ir. Peter Kraaijeveld

Joule Technologies supervisor

Crispijn Verkade

April 2025

MSc. Integrated Product Design

Faculty of Industrial Design Engineering

Delft University of Technology

Landbergstraat 15, 2628CE Delft, Netherlands

Preface

With the end of this thesis, this project marks the conclusion of my time at TU Delft. Although the project was carried out individually, I received a lot of help and encouragement, for which I would like to express my appreciation.

I wish to thank my supervisory team for their support and guidance throughout the project and for thinking along with me through the many curveballs I threw your way. I would like to thank Arjen for his sharp eye, often noticing early on where I was struggling and making sure I stayed on track. Both personally and professionally. Peter and I shared many interesting brainstorming sessions, often exploring topics a bit outside the scope of the core project, which gave me a lot of energy. I still believe that the two of you make a great supervisory team, because you usually have different views and interests both on the project and desired results. This allowed me to get a more balanced view of what should be done and discuss items with you accordingly. Furthermore, together with Crispijn you often spotted mistakes in my project /process and allowed me to find a way to solve it, instead of telling me how to.

From Joule Technologies B.V., I would like to give special thanks to Crispijn, who offered me a lot of freedom during the project, patiently introduced me to the HVAC industry, and helped me navigate the team and company. I would also like to thank the rest of the team at Joule. The experts there helped me both gain technical knowledge and work through specific challenges. In particular, I would like to thank Frank, Klaas Jan, Manon, Piotr, and Tom, who each made significant contributions to different parts of the project.

Of course, there were also people from outside Joule who supported me. I'm especially grateful to Jean Paul, Mark, Rogier, and Stan. Each of whom shared insights that helped me gain better understanding of field.

During this project travel time was a challenge, which was made much easier by Arthur and Pieter, who often gave me a ride home.

I was fortunate to be surrounded by my girlfriend and friends, who helped me recharge and take my mind off the project when needed. There were definitely moments where this was essential for getting back on track.

Last but not least, I want to thank my parents and brother for all their love and support. Thank you for taking in a very tired Marijn several times a week, providing me with a comfortable environment to relax when I needed it most. And not to forget, thank you for helping me spot and correct some of my super dyslexic sentence constructions.

Executive summary

English

Sustainable solutions for climate systems are often aimed to be integrated into newly build residences. For existing systems, retrofitting poses challenges. However, it's important to adapt solutions so they can more easily be integrated into existing households too.

Climate systems in Dutch residences are primarily powered by gas-boilers, although all electric heat-pump systems are steadily on the rise. Just like other solutions, they pose their own set of challenges for retrofitting. This thesis aims to make retrofitting more attractive by finding areas in climate systems that can be improved, making the system more efficient, comfortable and/or healthy.

"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."

This thesis is done in cooperation with Joule Technologies and will focus on making it easier/more attractive to retrofit residences with Joule technology's new ventilation heat-pump BEN.

In insulated residences ventilation is responsible for ≈43% of the climate system's energy loss. During the project the importance and possible impact of increased ventilation control was found to be important. For modern systems this exists, but the required infrastructure and cost to apply such a system to existing residences does not make it attractive.

This project begins by analysing where climate systems are installed, how users interact with climate systems, what problems are encountered during retrofitting and analyses current solutions available on the market. It then explores the problem space to find areas improvement areas, of which one is chosen, analysed and improved by a system addition. This is then further developed into a product and analysed to see if the solution is viable and interesting enough for Joule technologies to add to their BEN line-up.

This process provided a prototype for the dynamic valve (Figure 0.1).Valves are placed on the ends of the ventilation system to distribute flow to the right areas. Dynamic valves do the same, but can measure the status of air, adapt the air distribution and communicate with the ventilation heat-pump how much ventilation is required. Providing more precise control over area-specific climates in the residence.

Simple communication is lacking in the HVAC market as users often are only provided with the current temperature and a target temperature. The influence of changes on their system is not shown, sometimes causing confusion or misunderstanding. As dynamic valves take over the user's ventilation control it's important to inform the user. The visual movement in dynamic valves communicates to users what the ventilation system does.

Figure 0.1: Dynamic valves

Venting only when required reduces the total flow of vented air, saving energy by reducing required heating/cooling of incoming air. For insulated residences, this allows BEN to save ≈11-14% on the occupant's energy bill for climate control, whilst making their climate healthier and more comfortable.

Each dynamic valve costs ≈€33-53 to produce, depending on the CO_2 sensor type and power source.

The concept is promising, but the solution needs further development before implementation. The following steps are required to reach TRL 7:

1. Eliminate whistling noise
2. Replace the seal with legs and foam
3. Test a VOC CO_2 sensor for accuracy
4. Build an automated prototype with sensors
5. Conduct a full-scale system test
6. Adapt and test product look and feel

After these steps a better evaluation can be made on the value of dynamic valves (Figure 0.2) as addition to the BEN environment.

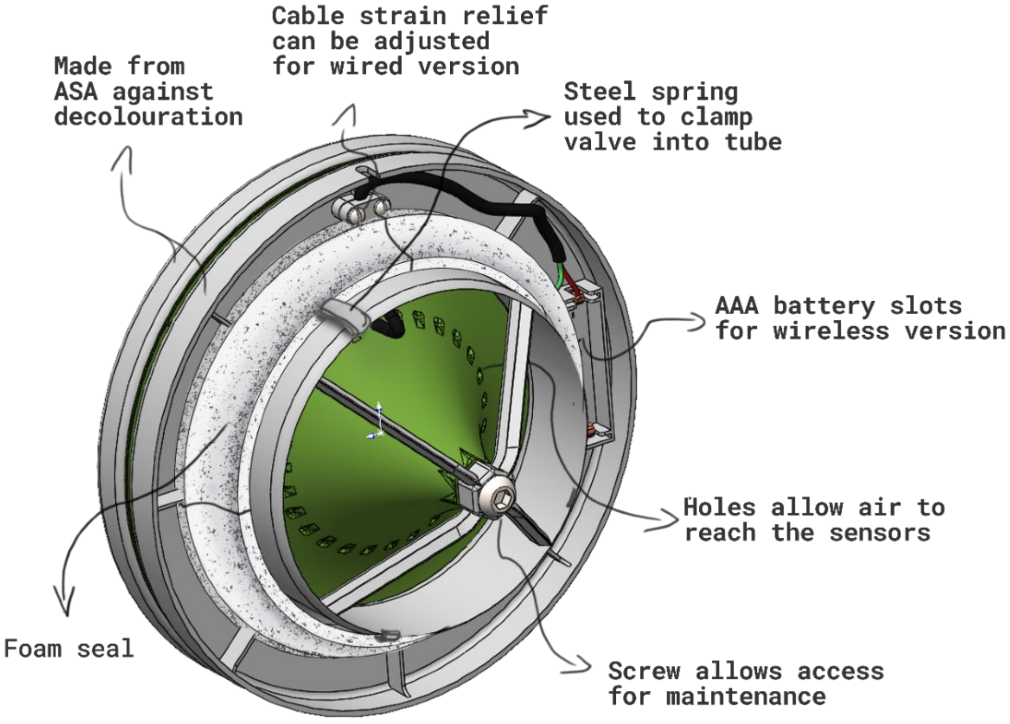


Figure 0.2: Dynamic valve

Dutch

Duurzame oplossingen voor binnenshuis klimaatsystemen zijn vaak gericht op installatie in nieuwe woningen. Voor bestaande systemen brengt het achteraf inbouwen uitdagingen met zich mee. Echter is het belangrijk om oplossingen ook toepasbaar te maken voor bestaande woningen, zodat ook deze systemen verbeterd kunnen worden.

Klimaatsystemen in Nederlandse woningen draaien voornamelijk op gasgestookte ketels, hoewel volledig elektrische warmtepompsystemen steeds vaker voorkomen. Net als andere oplossingen brengen ook deze uitdagingen met zich mee bij installatie in bestaande woningen. Deze scriptie heeft als doel om het aantrekkelijker te maken om bestaande woningen aan te passen, door verbeterpunten in klimaatsystemen te vinden die het systeem efficiënter, comfortabeler en/of gezonder maken.

"Ontwikkel een gecontroleerde, decentrale toevoeging voor het nieuwe systeem van Joule Technologies, die geïntegreerd kan worden in bestaande Nederlandse huishoudens en het klimaatsysteem toekomstbestendig maakt door middel van slimme functies."

Deze scriptie is uitgevoerd in samenwerking met Joule Technologies en richt zich op het makkelijker en aantrekkelijker maken systemen om te bouwen met Joule Technologies' ventilatiewarmtepomp BEN.

In bestaande geïsoleerde woningen gaat ≈43% van de energie in het klimaatsysteem verloren via ventilatie. Tijdens het project werd duidelijk dat gericht afzuigen een groot verschil kan maken. In moderne systemen bestaat deze mogelijkheid al, maar de vereiste infrastructuur en kosten maken het momenteel onaantrekkelijk voor bestaande woningen.

Het project start met een analyse van waar klimaatsystemen worden geplaatst, hoe gebruikers ermee omgaan, welke problemen optreden bij ombouwen, en welke oplossingen momenteel op de markt zijn. Vervolgens wordt het probleemgebied verkend om verbeterpunten te identificeren. Eén van deze punten wordt geselecteerd, geanalyseerd en aangepast. De oplossing wordt verder ontwikkeld tot een product en geëvalueerd op haalbaarheid en potentie voor toevoeging aan de BEN product line-up van Joule Technologies.

Dit proces leidde tot het prototype van een dynamisch ventiel (Figuur 0.1). Ventielen worden aan het uiteinde van ventilatiesystemen geplaatst om luchtstromen te verdelen naar de juiste ruimtes. Dynamische ventielen doen hetzelfde, maar kunnen de luchtkwaliteit meten, de luchtverdeling aanpassen, en communiceren met de ventilatiewarmtepomp over hoeveel ventilatiedebiet nodig is. Dit zorgt voor nauwkeurigere controle over het binnenhuisklimaat.

Eenvoudige communicatie ontbreekt vaak in de HVAC markt. Gebruikers krijgen meestal enkel de huidige en gewenste temperatuur te zien. De impact van systeemaanpassingen worden niet getoond, wat tot verwarring kan leiden. Omdat dynamische ventielen de ventilatieregeling van gebruikers overnemen, is duidelijke communicatie belangrijk. De zichtbare beweging van de ventielen laat gebruikers zien wat het systeem doet.

Figuur 0.1: Dynamische ventielen

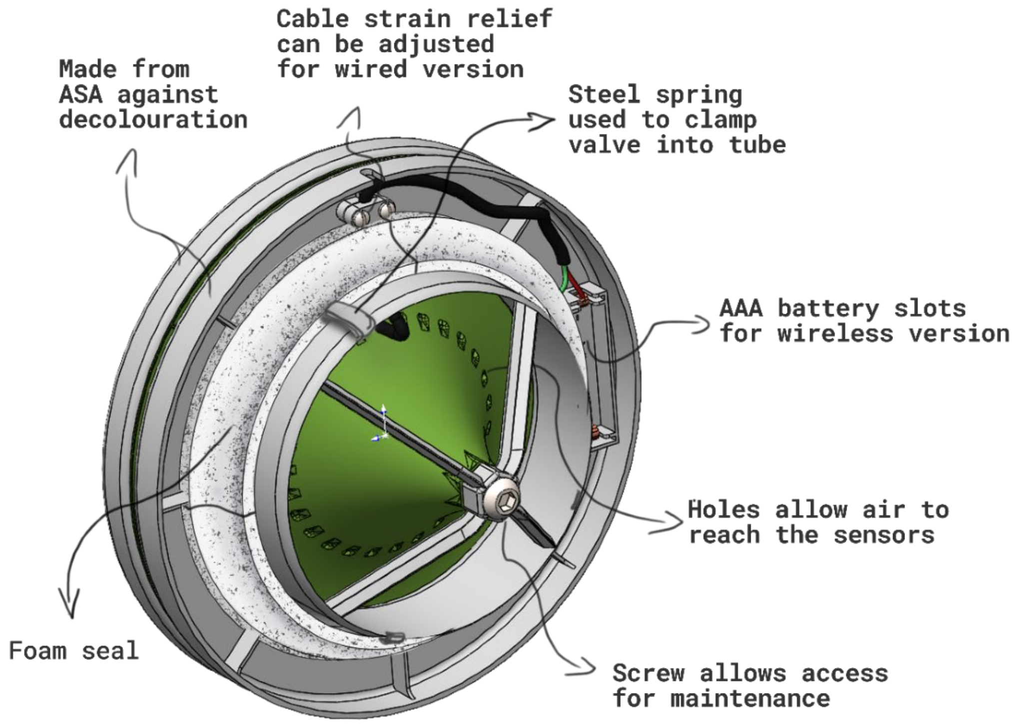
Door alleen te ventileren wanneer nodig, wordt het totale debiet dat verplaatst moet worden verlaagd. Hierdoor hoeft minder binnenkomende lucht verwarmd of gekoeld te worden. BEN kan op deze manier circa 11–14% besparen op de energierekening voor het klimaatsysteem, terwijl het binnenklimaat gezonder en comfortabeler wordt.

De productiekosten liggen rond de €33–53 per dynamisch ventiel, afhankelijk van het type CO_2 sensor en de benodigde stroomvoorziening.

Het concept is veelbelovend, maar heeft verdere ontwikkeling nodig voordat het kan worden geïmplementeerd. De volgende stappen zijn vereist om TRL 7 te bereiken:

1. Hoge piep bij hoog luchtdebiet moet weg
2. Vervang de rubber seal door metalen veren en schuim
3. Test de VOC CO_2 sensor op nauwkeurigheid
4. Bouw een geautomatiseerd prototype met sensoren
5. Voor een volledige systeemtest uit (TRL7)
6. Het uiterlijk en gevoel van het product aanpassen en testen

Na deze stappen kan er beter geëvalueerd worden of dynamische ventielen (Figuur 0.2) een waardevolle aanvulling zijn op het BEN-systeem van Joule Technologies.



Figuur 0.2: Dynamisch ventiel

Glossary

BEN	Become Energy Neutral is the name for Joule Technologies' new heat-pump.
BEN environment	The product line-up that will be built around BEN.
Climate control	The heating, ventilation and cooling of indoor spaces.
Centralized system	A climate system that has one control point, and does not differentiate between areas.
Decentralized system	A climate control system that differentiates between areas.
Controlled decentralized system	A climate control system that has multiple control points and can adjust its differentiation between areas.
Flow	The steady and continuous movement of air/water, measured in m3/h.
Ventilation heat-pump	A heat-pump consumes electricity to move energy from one medium into another. A ventilation heat-pump utilizes vented air to do so. Joule Technologies heat-pump called BEN can use both vented and outdoor air, but will still be referred to as a ventilation heat-pump.
Valve	Duct cover that partially blocks air to allow for flow distribution across different ends of the ventilation ducts.
0-position	The position at which the valve meets the legal ventilation requirements.

Table of contents

01 - Introduction

This chapter introduces the problem, company, explain what the assignment entails and how it was approached. At the end a description is given about what information can be found in which chapters.

(1.1) Situation

Climate systems in Dutch residences are usually powered by gas-boiler or district heating, only capable of heating the residence. The use of all-E (All electric) climate systems is steadily rising, of which most are heat-pumps (CBS Statline, 2024).

Gas-boilers and most district heating have high working temperatures, which is what most Dutch climate control infrastructure (Pipes ② and emitters ③) is engineered for (Figure 1.1). Energy emitted from the climate system is mainly removed/lost by transmission loss and ventilation ⑤.

Retrofitting a climate system with high working temperature (75-85°C) to one with a low working temperature (35-45 °C) provides problems and makes retrofitting more difficult and expensive. To reach the same room temperatures, other attributes need to be changed to even out the total provided energy. A higher flow from the heat-pump ① to the emitter③, a larger emitter and a lower total energy loss are usually required.

Newer buildings are designed with higher buildings standards (Rijksoverheid, 2024) (NEN, 2020). They usually have better insulation ⑥, climate systems for low working temperatures and smart solutions that further decrease total required energy. For example smart thermostats ④ and area-specific control.

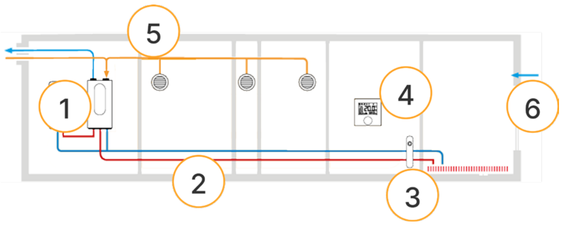


Figure 1.1: Different parts of a domestic climate system

Currently, retrofitting existing residences with these newer solutions can be a hassle as most solutions require existing climate control infrastructure to be partially or completely replaced. Adapting these solutions for existing buildings would make it more attractive to retrofit them, instead of mainly using solutions for newly build structures.

Although not all solutions can be adapted for existing homes and/or ventilation heat-pumps, some solutions could increase perceived climate comfort whilst decreasing total energy use.

(1.2) Company introduction

This project is done in cooperation with Joule Technologies, the development party of the Joule group. A group of companies that jointly develop, sell and commercialise HVAC products in several European countries.

Currently Joule Technologies is introducing the BEN ventilation heat-pump (Figure 1.2) in Europe. BEN is a special ventilation heat-pump as it is capable of running on both indoor and outdoor air independently and combined. For this project it's important to know that BEN is designed to be used both in new climate systems and existing climate systems that are retrofitted. As BEN can use vented air, it also takes control of the domestic ventilation system, giving BEN control over most of the climate system's energy streams.

The product proposal resulting from this master thesis should fit within the future BEN system product line-up. A system of support products that will be created around BEN to help strengthen its focus on health, comfort and efficiency.

Figure 1.2: BEN ventilation heat-pump

(1.3) Assignment

This project aims to explore the problem space, find design directions for improvement and propose a product that can be placed into the BEN line-up. The product should be a decentralized addition, that improves climate comfort, health and/or total system efficiency. It should work in climate systems of existing Dutch residences, with the aim of making retrofitting easier and/or more attractive.

The addition of new components to an existing climate system can make it more complex. Reusing part of the system is beneficial, as it might make transitioning easier/more attractive. Extra attention should be given to make sure the addition in combination with the pre-existing system does not negatively affect the outcome.

Retrofitting increases cost and a system's footprint, while a reduction in required climate control energy might decrease both. During this project a middle ground should be found between these two aspects or the system should have other properties that would justify it not being ideal.

Adding complexity to a system directly impacts the difficulty to understand that system. Heating systems are already hard to understand and/or steer for most 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 usually understand their own systems, 3th party repair companies/installers don't always. Making the system easier to understand and control would be advantageous.

These factors are combined into this project's assignment:

"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."

The project scope contains all parts of the system that originate from the BEN ventilation heat-pump, or return to the ventilation heat-pump ②④⑤, except the insulation ⑥ and heating elements ③ (Figure 1.3). Insulation is not taken into account as good insulation is a requirement for heat-pump powered systems. Heating elements like radiators or floor heating are not produced by Joule Technologies and will therefore not be part of this project's scope. The project assignment can be found in the original project brief (Appendix A).

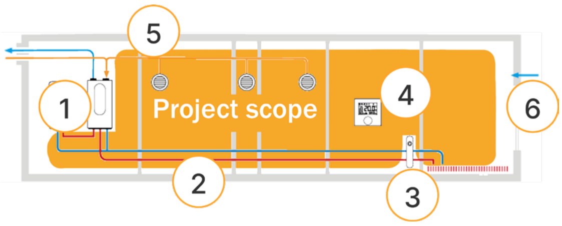


Figure 1.3: Project scope

(1.4) Project approach

The start of the project is structured using a design by research approach, after which the project switches to a research by design approach. Using insights found during process to generate new improvements and expand the different solution directions towards a final product.

To accomplish the project it was divided into 4 steps. Explore the field, explore the solution space, develop solution for one design direction and evaluate the value of the concept (Figure 1.4). Information about each can be found in the corresponding chapters.

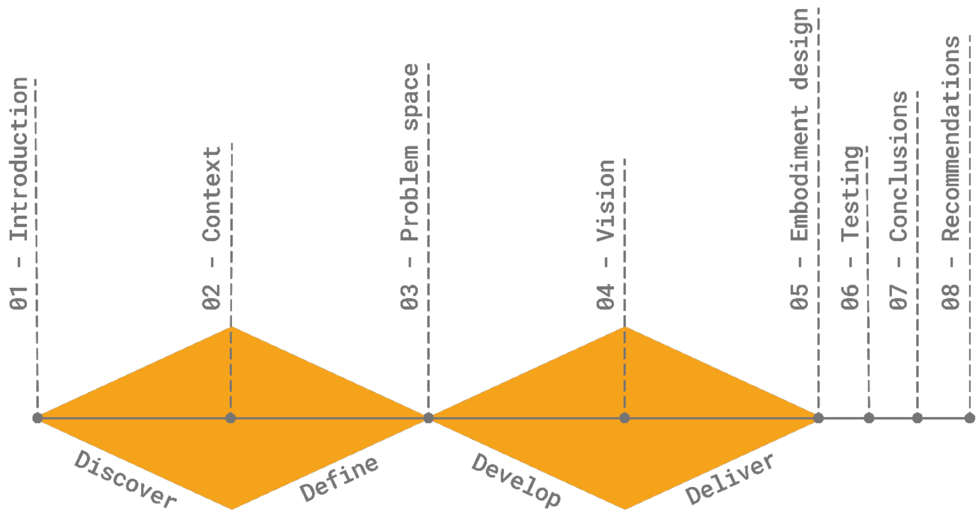


Figure 1.4: Design process and chapters

02 - Context

Gives an overview housing types and occupant behaviour (2.1). Issues surrounding installation, maintenance and retrofitting (2.2) and other products on the market (2.3).

(2.1) Housing types and occupant behaviour

2.1.1 Types of housing and climate systems

Differences for ventilation and heating requirements are dependent on the type of residence and the building year. The ≈7.5 million Dutch residences are categorized in 8 different categories (E.g. Duplex, terraced, apartment building, etc.), each subdivided based on building date. Each of these residences have different characteristics (E.g. size, type of insulation, room size, number of floors, etc.). All of these factors influence how climate systems react and thus how they should be installed. Most climate systems in Dutch residences only have the ability to heat the residence (RVO, 2022).

Generally a larger residence, has more pipe conjunctions, height difference and a higher total flow, making mistakes in calibrating the system more likely (Appendix B2&3). Newer residences require higher flow through heating pipes, due to lower working temperatures. Making pipe diameters larger and/or requiring more powerful pumps to transport water around the system.

The amount of heat-pumps used in the Netherlands is rising, with a yearly increase of roughly 50% since 2018 (Centraal Bureau voor de Statistiek, 2022). In 2022 however, ≈87% of climate systems in Dutch residences still were gas powered gas-boilers. ≈6.7% was powered by district heating, meaning they do not have a power source for climate control in the residence. 1.1% has a hybrid solution, often with a heat-pump for the initial temperature rise to 20-50°C and a gas-boilers to bring the last bit up to the 50-80°C temperature working temperature. Only ≈2.3% ran on heat-pumps (CBS Statline, 2024) (Table 2.1). Although this data gives us a rough estimation, the accuracy of this data is questionable. CBS has a 2nd data pool with the amount of heat-pumps placed in Dutch homes. This one states that in 2021 ≈12.5% of Dutch homes had heat-pumps installed (Centraal Bureau voor de Statistiek, 2022), meaning that the total number of hybrid and all electric systems is most likely higher.

Energy sources in Dutch climate systems	
Gas-boiler	87.0%
District heating	6.7%
Hybrid	1.1%
Heat-pump	2.3%
Unknown	2.9%

Table 2.1: Division energy sources in Dutch residential heating systems in 2022 (CBS Statline, 2024)

2.1.2 Influence and the understanding of occupants on heat-pump systems

Most Dutch occupants control heat-pumps as if they are gas-boiler powered systems (Appendix B1,2,3,5). Gas-boilers and heat-pumps are powered by the same types of thermostat and applications, which don't explain the difference on how different systems should be controlled. Differences are primarily caused by lower total heat capacity of the heat-pump and the heat-pump working more efficient at lower power consumption (Column-het-belang-van-goede-inregeling, 2019).

Users notice the difference in heat capacity because of the type of heat emitted (e.g. lack of radiation heat) and how fast temperature changes when requested (Appendix B2). Users expect that lowering temperature when the residence is not in use, decreases total energy consumption. Using heat-pumps to quickly heat a residence when higher temperature is desired often consumes more energy than keeping the residence at a near-constant higher temperature.

Some occupants have other comfort preferences and/or differ in motivation to learn how to use a system. Interviews suggest, in most households there is only a limited amount of people that keep tabs on what's happening to the heating system. Usually, the homeowner or main renter. This party has insight in the energy bill and are usually a little more interested in understanding how to most efficiently operate the system. Other parties like guests, family, roommates or children operate the same system on a more emotional, less predictable basis. (Appendix A1&2).

For homeowners retrofitting the climate system is more valuable (Clahsen, 2019). For them upgrades to their heating system are worth more as they save on future heating costs, increase comfort and/or increase property value.

Homeowners are more interested in details about energy consumption and air quality (Appendix A1&2). Alternatively, most housing associations do not want to share detailed information about air-quality with occupants, to avoid extra work answering questions/complaints (Appendix B2). Renters are often less interested in what is heating their residence. Most likely because they have less insight and do not gain any say in what it is and if they wish to change it. They mostly care that the system does what they ask from it (Veltman, 2022).

Older people and people originating from warmer countries might want their homes to be on a higher constant temperature, which most climate installations are not engineered for (Appendix B2). For systems with a higher working temperature, inefficient use can be partially compensated by the higher heat-capacity. For heat-pumps inefficiency is more noticeable. Both in comfort and the energy bill.

2.1.3 Ventilation

The Netherlands is a "ventilatieland" (Personal communication, K.J. Veltman). Having a high amount of active ventilation in existing buildings compared to other European countries (Carrer et al., 2020). The most common ventilation method in Dutch residences is 'natural ventilation', where cracks in material, door-posts and windows provide enough ventilation (Table 2.2). This method is more common in older residences and often used in tandem with mechanical methods. As legislation became more strict, newer residences have better insulation, and thus less natural ventilation. This causes differences in ventilation systems to be mostly dependent on the building year, although apartment buildings tend to use balance ventilation more than other building types (RVO, 2022).

Types of ventilation in Dutch residences	
(A) Natural ventilation	51%
(C) Mechanical ventilation	44%
(D) Balance ventilation	4%
Total nr. of residences	≈7.5 million

Table 2.2: Division of ventilation types in Dutch residences in 2022 (RVO, 2022)

Ventilation systems consist of a ventilation fan ① for creating flow, tubing to guide flow, valves to limit flow ②-⑥ and an inlet to let outside air enter the residence (Figure 2.3). Inlets can be openings that allow natural flow, built in vents or a balance ventilation system.

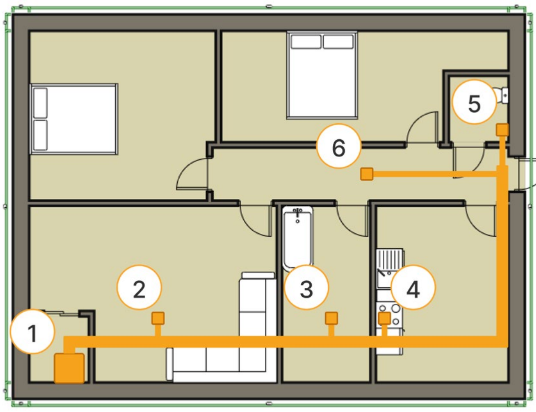
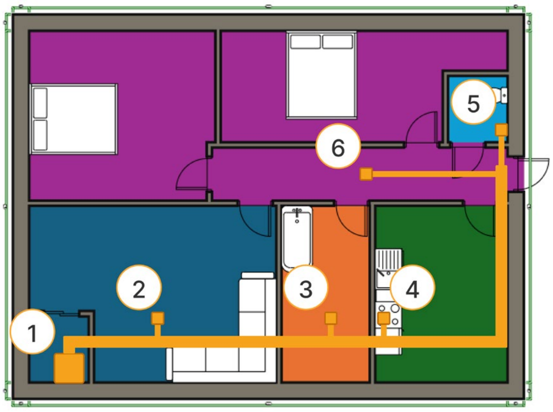


Figure 2.3: Example of a ventilation system

Dutch ventilation systems often are controlled by a high, medium and low setting, which should be adapted by users. However, personal experience and conversations indicate that most users barely adapt these. People mostly use low, with some using high only while cooking or showering.

The value of high, medium and low are determined by Dutch building legislation (Rijksoverheid, 2024) and the NEN 1087 norm (NEN, 2020). The flow at high must be greater than the sum of the required flow of all rooms. Flow at low must be higher than the required flow of the residence's largest room. Medium II is set in between (Figure 2.4).

Valves and maximum total flow are calibrated to divide flow so that each room receives it's legal minimum when the system is set to high.



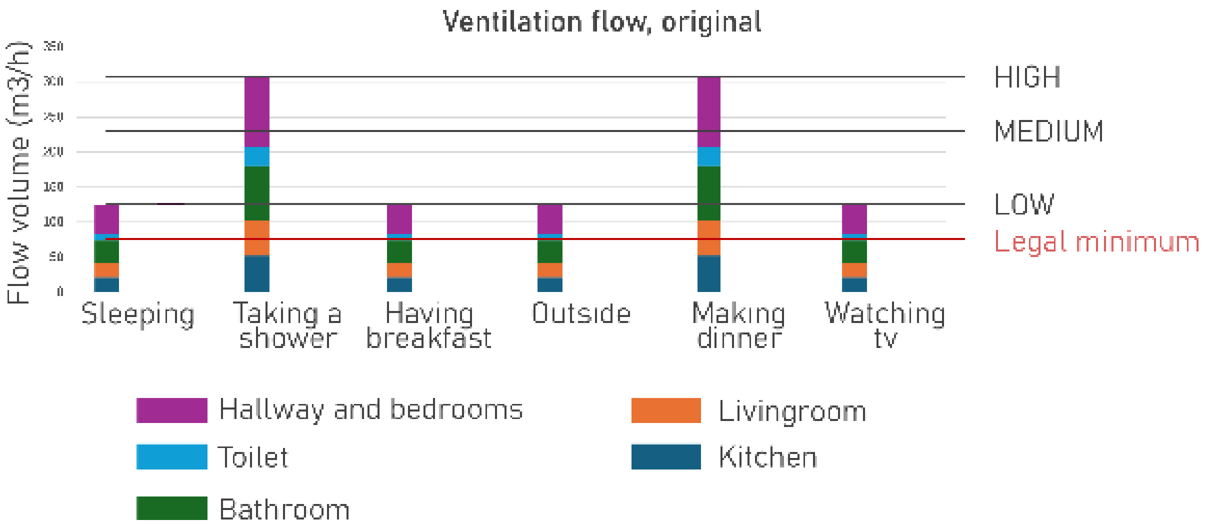


Figure 2.4: Example of current situation

(2.2) Issues during heat-pump installation

2.2.1 Introduction

Installation issues often arise due to the wide variety of systems (Steenbekkers & Scholte, 2019). For retrofitting most issues arrive due to differences in what temperature the old infrastructure was designed for and the difference in heat-capacity between heat-pumps and gas-boilers (Doornbos et al., 2019).

Before heat-pump installation, a residence is first inspected to calculate required energy capacity. If the required energy-capacity is too high, this must be solved before installation. To achieve this, residences are often insulated or provided with other solutions like a separate electric heater for the bathroom (Appendix B1&2).

2.2.2 Calibration

All junctions in the network of pipes and emitters require to be set differently to allow for equal energy division throughout the residence (Kamerpoort 2023). It is usually set to be accurate when all emitters are active. However, users often try to keep the system partially turned off, bringing the system out of balance.

Although the process is similar to that of gas-boilers, lower operating temperature systems require calibration to be done more precisely as it's easier to disturb the calibration balance (Column-het-belang-van-goede-inregeling, 2019).

Most installation technicians in the Netherlands are used to gas powered systems (Appendix B2). When retrofitting an existing system the reuse of existing infrastructure further complicates installation, as existing infrastructure might not be ideal for this application. The wide variety of heat-pump systems and partial reuse of old systems makes correct calibration of heat-pump systems more difficult than its gas powered counterpart (Steenbekkers & Scholte, 2019).

2.2.3 Retrofitting ventilation

Ventilation infrastructure only needs to be replaced if added insulation would cause ventilation to be lower than the legal ventilation minimum. Although often not required, in that case, the addition of new and/or wider ventilation channels might be needed. In most cases, recalibrating the ventilation system should be enough to keep the system above legal limits. BEN uses both outside and inside air to operate, so it replaces the ventilation fan at the end of this system.

(2.3) Air quality

2.3.1 What to measure

Air quality in buildings is dependent on different factors. However, not all of these can be influenced by venting the residence. Factors that can be influenced by venting are ones that originate from inside the residence. Relevant ones are CO_2 (Carbon Dioxide), PM (Particulate Matter), CO (Carbon monoxide), °C (Temperature) and rh% (relative humidity) (Table 2.5).

Factor	Sensor cost (€)	Sensor lifespan (Years)
CO_2	≈2-24	>10
PM	-	>10
CO	≈8	2-5
°C	≈2	>10
Rh%		

Table 2.5: Overview of sensor types

CO_2 can be used to detect the precense of people and detect ventilation need. Steering ventilation with CO_2 legally requires a certain precision for newly build residences (Rijksoverheid, 2024). Sensing CO_2 can be done with a VOC or a NDIR sensor. A VOC sensor costs less and consumes less power. However, it might not be accurate enough, which is currently being tested by Joule.

PM is no issue when a residence contains a mechanical ventilation system and is therefore not relevant for this project (Asim et al., 2022) (Branco et al., 2019).

CO mostly emerges in case of fire or gas a leak, causing CO sensors to be used in fire alarms. CO sensors are not used for determining adaptations in airflow.

Measuring °C and rh% is inexpensive and often done with the same sensor. Temperature sensors are accurate and often implemented in thermostats.

Measuring humidity precisely is expensive, thus rh% is usually measured. Rh% can be used to get an indication of humidity, but it is not precise. It's difficult to distinguish between it getting more humid outside or inside. When outside humidity rises, venting more does not decrease humidity. To detect events with a rh% sensor it either needs to compare its own values with others in other rooms or react to humidity spikes (P. van Oostrom, personal communication). As steering items this way is not new, for the purpose of simplicity, during this report rh% will be represented by a percentage range, even though this is not entirely accurate. In the final product this range would need to be modified to either react in comparison to other sensors or spikes.

(2.3) Analysis of existing products

2.3.1 Introduction

All Dutch residents come into contact with the HVAC market it, as indoor climate control systems are used in most structures. As such, there are already inventions and products on the market that are relevant in the problem space of this project. In appendix D different product categories that were analysed.

This section will highlight the relevant learnings, trends and potential areas for improvement.

2.3.2 Key learnings

Climate systems with digital gateways often provide information through applications. However, the current format of applications has limits in how it informs users.

Many climate control products suffer from a gap in user understanding. Users are rarely informed in a simplistic way how to operate systems efficiently, which can lead to inefficient behaviour, misconfiguration, or missed energy-saving opportunities.

Some solution require extensive infrastructure changes for retrofitting, making them less attractive for existing residences due to high costs and the disruption they cause.

Products that allow for area specific climate control, such as smart valves or energy dividers, can reduce energy use and comfort. However, improper use or poor system calibration can reduce their effectiveness.

There are different products categories aimed at enhancing indoor air quality, now often controlled by the user's feeling, instead of data. When combined with accurate, area-specific data, these products might be used more effectively.

03 - Problem space

Explores possible solution spaces and clarifies the choices that led towards the project's focus on dynamic ventilation.

(3.1) Problem definition

3.1.1 Context analysis

Climate systems and their requirements vary significantly based on a residence's attributes, building year, type of installation, ventilation type and the behaviour and preferences of its occupants. Most occupants do not understand how to efficiently operate a heat-pump powered climate system.

Most products that inform users and allow for more precise control are focussed on interested users. The average user does not spend as much attention to this. Products that inform users in a simplistic way and/or about their behaviour seem to be scarce.

The HVAC market could benefit from standardisation of the information presented to users and the information shared with other parties. A more uniform approach would help 'smart' solutions (e.g. thermostats) align better to optimal heating paths and give more insight to users.

Installation and retrofitting of heat-pumps presents challenges due to differences in system requirements, building structures, and installer expertise. Furthermore, reusing existing infrastructure can introduce inefficiencies. Integrating solutions of multiple products into one and designing addons without major remodelling requirements could simplify the process of installation and avoid system communication issues.

Owners need to be incentivised to invest in additions to the system, comfort and health are often not primary factors for people to invest. Dynamic heating and ventilation systems offer energy-saving potential, whilst also useful for increasing climate comfort. Currently they are too costly and complex to retrofit.

Joule Technologies aims to market BEN as a system that distinguishes itself through health and comfort. Currently, although BEN is tested as a high quality ventilation heat-pump, it does not clearly distinguish itself on health and comfort from other ventilation heat-pumps.

3.1.2 Relevant problems

This provides us with several problems in the HVAC industry and during retrofitting:

❶ Users often lack understanding to control residential climate systems efficiently.

❷ The industry generally lacks simple use-cues that inform users about what their system is doing or what the influence of their action on the system is.

❸ Most products are made to fit a more universal system, simplifying communication and estimation options that can be used in other products.

❹ Remodelling can make retrofitting cumbersome and increase cost.

❺ Home-owners are mostly incentivised to retrofit existing systems when the cost can be seen as an investment.

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

3.1.3 Problem spaces/solution areas

These problems were split in the following 4 problem spaces, which were further explored:

1. Total system efficiency ❶❺
2. Air quality ❶❻
3. Ease of installation ❸❹
4. Usability ❶❷❸

Out of these, three primary solution directions have been picked. These have been thought out further, after which one was picked to continue the project with, based on potential improvement for each of the 4 problem areas.

(3.2) Design directions

3.2.1 Direction 1 - More innovative control points

Simplistic additions to control points can be used to increase the user's understanding of what is happening to the system. Currently, information on control points in the market is primarily split into two sections. The first are thermostats, used by every user, containing current temperature and buttons to change it. The second being applications, used only by interested users, containing more detailed information, allowing for changes to be applied through schedules. Control points for heat-pumps look similar to that of gas powered systems, strengthening the impression that the system works the same.

Providing occupants with relevant information in a more natural/simplistic way is missing in the industry. Consciously adding relevant use-cues to future products could majorly increase the market position of BEN on user-friendliness.

Planning what should be added to their future thermostat, would allow them to align the app now. Making BEN ready to implement a more user-focussed thermostat the next time Joule redesigns theirs.

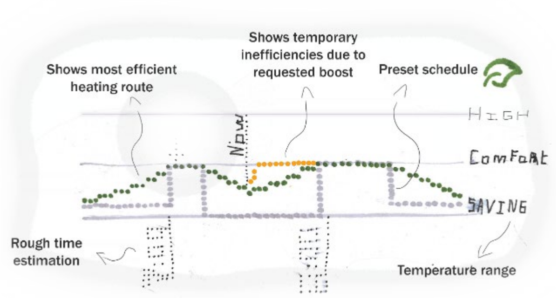


Figure 3.1: Example of proposed control point improvements

3.2.2 Direction 2 - Area specific measuring and addition

Making air more healthy and comfortable can be reached by adapting air quality. The range in which air-quality is healthy for humans is more exact, whilst the feeling of comfort differs. Allowing users to adapt factors influencing air-quality within a healthy range might increase the feeling of comfort.

This could be done by filtering or adding something to the air coming in. However, this can only be done with residences that have balance ventilation or are well insulated, having dedicated air-inlet vents. What is possible for all residences, would be adding a loose standing control unit that measures CO_2 and humidity. Can humidify the air and notify the BEN to vent more air when too much CO_2 or humidity is detected.

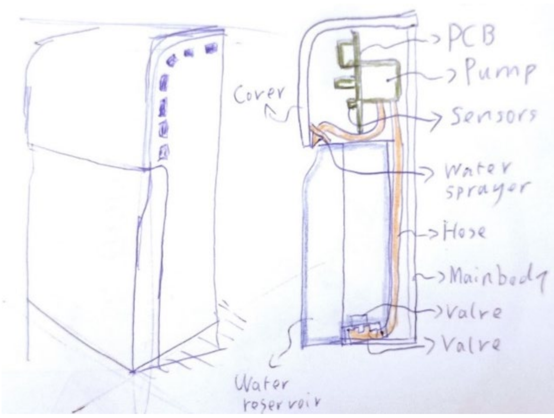


Figure 3.2: Example of separate air-quality sensor + humidifier

3.2.3 Direction 3 – Dynamic ventilation

Creating a more healthy environment can be done by minimizing CO_2 and optimizing humidity levels. Measuring/adjusting from a central point does not work as averages of areas quickly even out. Venting till all areas are at a lower value could create overventilation and unnecessary energy loss.

Creating a system that can sense air-status, steer where air is vented and adapt the total ventilation flow could increase air-quality, whilst saving on heating cost.

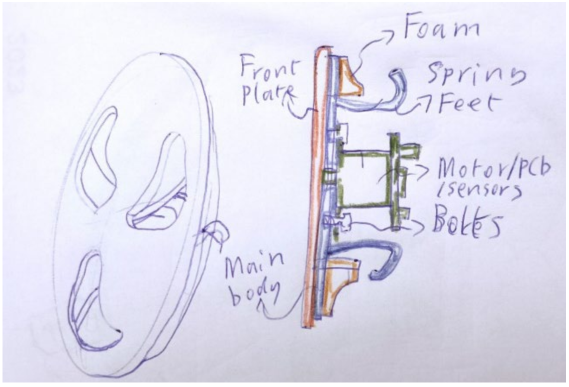


Figure 3.3: Example of dynamic valve

(3.3) Comparison of design directions

3.3.1 What to compare on?

In section 3.1.3 four different solution areas were defined. Each idea is evaluated on these 4 topics in order to create a final decision (Table 3.4).

Total system efficiency is aimed at both energy use and potential for reducing climate system expenses, thus if an idea can be seen as an investment for the buyer.

Air quality encompasses both the literal quality of air, translating in health benefits, and potential increase in comfort.

Ease of installation targets minimizing hassle during installation (E.g. nr. of installation steps, type of remodelling required, etc.) and additional installation costs.

Usability is used to evaluates knowledge required for the user effectively operate the idea and if the idea manages to inform the user with simple use-cues.

3.3.2 Motivation for direction choice

In table 3.4 scores given to the 3 different directions can be seen in a Harris profile. This section clarifies the motivation behind these scores.

1. More informative control points would be a system addition integrated into the BEN environment, thus a user could not determine to separately investment non-optional, however this minimises hassle and additional costs. It does not change air-quality, although it might change someone's perception on air-quality and thus comfort.

2. Area specific measuring places an extra object in the room, which might be able to help the climate system steer, but to do so effectively requires additional products. This limits scores on the individual product.

3. Dynamic ventilation scores well on most fronts. It enables change in air-quality , and is able to inform users about what it does. Dynamic ventilation requires more effort, possibly cost and knowledge to install and use than the other design directions. However, its potential for saving energy, makes this design direction the only one that can truly be seen as an investment and thus is the most likely direction to be implemented by home-owners.

3.3.3 Confirmation of investment potential

To confirm if the investment potential the required heating energy of average Dutch residences in different categories (RVO, 2022) was calculated for both convection and ventilation losses (Appendix C). This model concluded that roughly 43% of heating energy in Dutch residences is needed due to ventilation losses.

The model in appendix J takes this one step further and compares ventilation flow and required ventilation electricity for systems with and without dynamic ventilation. Energy requirements in different situations in the house are first defined (Section 4.1) and allocated per hour. Then weather data from 2024 was imported and energy loss through ventilation per hour was calculated for a ventilation in a system with and without dynamic ventilation with the following formula:

$$\sum_{h=1}^{8784} Q = \frac{V * \rho * c_p(Tin - Tout)}{3.6 * 10^6} + E$$

$Q = Ventilation\ energy\ loss\ (kWh)$
$V = Flow\ (m^3/h)$
$\rho = Air\ density\ (kg/m^3)$
c_p = Specific heat capacity $air\ (J/kg * K)$
$Tin = Inside\ temperature$ (°C)
$Tout = Outside\ temperature$ (°C)
$E = Fan\ energy\ consumption\ (kWh)$
$h = Time\ (h)$
$*If\ Tin - Tout < 0\ then\ (Tin - Tout) = 0$

This model shows dynamic ventilation can reduce energy loss through ventilation by 26%-33%. Resulting in a 11%-14% reduction in the total energy bill, confirming the potential of dynamic ventilation as an investment.

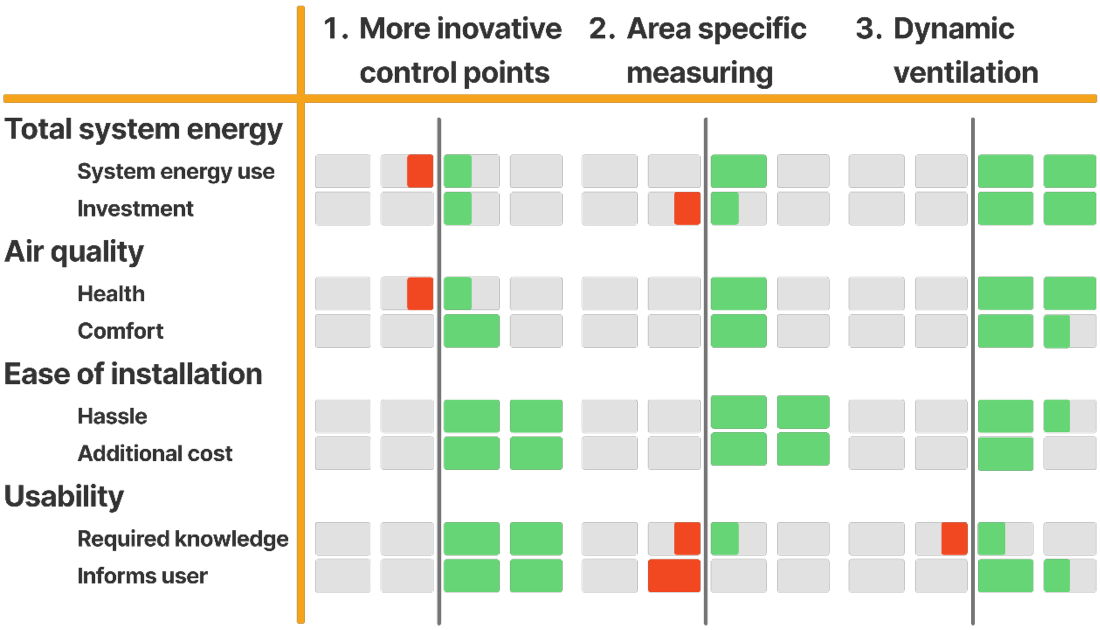


Table 3.4: Harris profile of design directions

04 - Vision

Explains what the final product should do and its goals. 4.2-4.4 divides these goals in 3 categories and explains how this can be achieved in more detail.

(4.1) What should the product do?

4.1.1 Design goal

The focus of this design is on creating a healthier and more comfortable climate, whilst saving on heating costs by enabling the BEN to adapt the amount of air removed from each area.

Additionally, ease of retrofitting existing systems is an important factor in the original assignment. To minimise impact and effort during refitting, replacing the valve was deemed the easiest and cleanest option. Valves are placed on the ends of the system with the function to partially block airways in order to divide flow. In this design their use is kept identical, but the amount of flow they block will become dynamic. Replacing a valve can be done without disconnecting other components of the system.

Lastly, informing the user in a more simplistic/natural way was deemed a factor where most of the market is lacking. Although ventilation fans are often quite loud the BEN is more quiet. BEN's fan is always moving similar amounts of air, mainly varying between outside and vented air. Thus, you lose the auditive feedback present in the current system (P. van Oostrom, personal communication). Adding a component to this product that shows what the system is doing could be beneficial for usability and the user's trust in the system.

The different focus points for this design can largely be categorized into the following 4 goals:

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

4.1.2 Desired change to situation

The addition of dynamic valves should maximise flow when desired and minimise flow when not. This would look similar to figure 4.3. Where flow in all rooms that are not in use is minimised, whilst providing optimal flow in rooms used. Note that total required flow for healthy air is likely to be lower than depicted. For rooms in use, this comparison aims to reach the amount of flow reached with high ventilation, which is usually not required. Thus, during normal use, total flow is likely to be lower, making energy savings higher.

With this model two different residences were compared. Energy savings are modelled to be ≈11-14% and will most likely be higher due to the model requesting higher ventilation than is likely to be required. This varies based on type of residence, user behaviour, preference, the amount of people in the residence etc..

Room types could be bound to certain valves, enabling them to change their behaviour depending on room requirements. For example, allowing higher flow longer in rooms that are humid more often, like the bath or laundry room. This report does not explore what attributes should be assigned to certain rooms.

4.1.3 How to achieve this?

To achieve the goals and desired changes a lot of problems had to be tackled. Most of which can be summarized in the following 3 questions:

1.1 How to measure air quality?
1.2 How to steer flow?
1.3 How should the product be used?

These are further discussed in their respective sections. More detailed information about the goals, desired situation, how to achieve this and legislation can be found in appendix E.

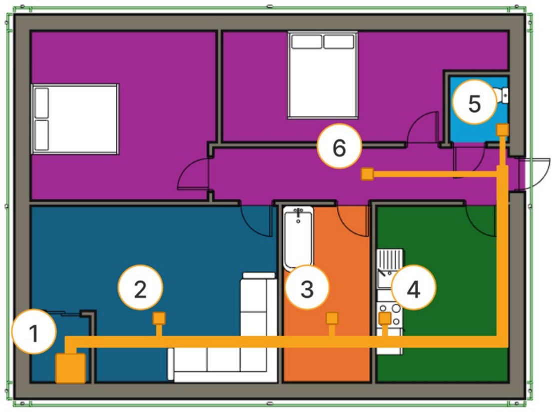


Figure 4.2: Example of flow division

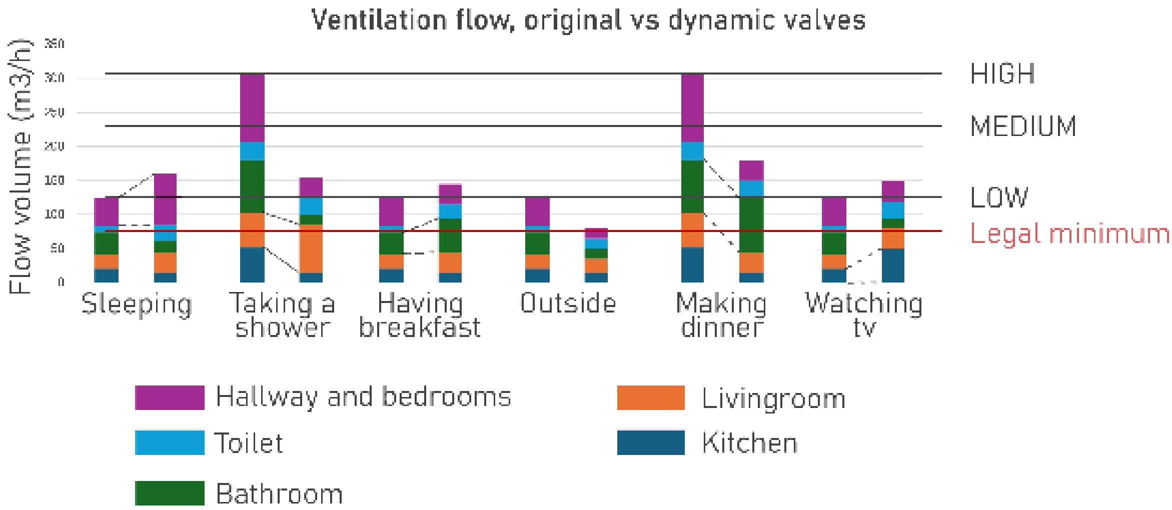


Figure 4.3: Example of desired change in multiple situations original valves (Left) and desired influence of dynamic valves (Right)

(4.2) How to measure air quality?

4.2.1 Section introduction

In order to react to events the status of air must first be determined. This section discusses what should be measured, when action should be taken and what is required to do so.

4.2.2 What to measure

In section 2.3.1 4 relevant factors were found to be important for determining air quality (Table 4.4).

Factor	Sensor cost (€)	Sensor lifespan (Years)	Added value for project if implemented
CO_2	≈2-24	>10	High
CO	≈8	2-5	Medium
°C	≈2	>10	Medium
Rh%			High

Table 4.4: Overview of sensor types

Two CO_2 sensors are available. The NDIR sensor requires too much power for a battery powered system, but might be required due to government regulations for new residences (Rijksoverheid, 2024). Until Joule knows if a VOC sensor would be accurate enough, two versions of the product should be designed to keep the product suitable for both existing and new residences. Using a VOC sensor would be cost effective and allow it to be powered by 2 AAA batteries.

CO is not used for steering air (Figure 4.4). Although it might be interesting to keep a slot available on the PCB to make it possible to integrate a fire-alarm in to a future version, adding this now would increase licensing cost, production cost, increase power consumption, maintenance requirements and decrease lifespan. Thus it will not be added.

Temperature is useful as an extra control point for the BEN system and to compare inside to weather broadcasted outside temperatures. If outside temperature is more desirable, ventilation can be used to make the residence more comfortable.

To detect humidity with a rh% sensor it either needs to compare its own values with others in other rooms or react to humidity spikes (P. van Oostrom, personal communication). Thus, it'd be beneficial if the dynamic valves can be steered based on compared input.

4.2.3 When to react

To determine when the system should react a low, acceptable and high range have been set up (Table 4.5). The acceptable range, is the range in which air is healthy. Interested users should be able to adapt this range to their preferences. This could make the user feel more like they're in control. Probably increasing perceived comfort.

4.2.4 Sensor location

Tests showed that sensor readings are impacted by flow (Appendix F). However, sensing near the valve is beneficial as changes in air are pulled towards this point. It also allows the product to be sold as one package, instead of requiring sensors/switches in the room. To avoid faulty sensor readings, the sensor should be sheltered from direct flow, only allowing particles to reach the sensor through passive dispersion.

4.2.5 Conclusion of section

To effectively control the product, CO_2, rh% and temperature should be sensed. Action are dependent on the in this chapter defined ranges (Figure 4.5).

What type of CO_2 sensor should be used is still being tested, thus this project needs to design different versions for different sensors.

Placing the sensor in the valves would be beneficial, although they need to be shielded against flow. Details can be found in appendix F-sensors.

Sensor type	Low range	Acceptable range	High Range	Unhealthy / uncomfortable
CO_2 (ppm)	None	0-1000	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 dependent on outside humidity				

Table 4.5: CO_2 and rh% range categories (P. van Oostrom, personal communication)

(4.3) How to steer flow?

4.3.1 Section introduction

Valves steer flow by partially blocking the cross sectional area available for air to flow through. Dynamic valves do the same, but have the ability to adapt the amount of cross sectional area available. This section describes how to do this and how to react on measured sensor data.

4.3.2 Blocking air

Blocking air can be done by rotating or translating a blocking surface in front of the inlet opening. The exact method is not as important. More important are factors that influence the system like maximum flow area, minimum flow area, areas that can catch dust and shapes that make sound.

Reduction in flow area increases pressure, thus decreasing the maximum flow through that area. If all valves block more flow area, the fan needs more power to provide the same flow, making the system less efficient. Thus it'd be beneficial if the valves can block less of the original flow area, which is the cross sectional surface of the duct. For most residences, ducts containing valves have a 125mm inner diameter. 100mm diameter ducts are also used in older residences.

Minimum flow area is determined by tests performed during the project (Appendix E). In these tests an existing ventilation fan was directly attached to an opening that could be slid shut, whilst the fan ran at maximum rpm. With the pressure created by the fan, the lowest required flow area to steer flow in all situations was determined to be $\approx 5cm^2$.

Areas that can catch dust usually have sharp edges, small corners, rough surface finishes or are areas with large surfaces perpendicular to the flow area (Figure 4.6). These should be avoided in the design.

Figure 4.6: Example of dust accumulation

Sound can be produced by shapes that are not aerodynamic or by forcing a lot of air through small entrances. Heat-pumps have a reputation for being noisy, which is a reason for some not to adopt it (Reinders, 2020). Thus, the system should not create more noise than the original. The goal of the product is to minimise airflow through certain valves. Doing this at the initial valve might cause a relatively large pressure difference with a small entrance. The final prototype has to be tested for sound, which should not be louder than normal valves in similar circumstances.

4.3.3 Valve types

To keep cost down, it'd be beneficial if not all valves need to be replaced with dynamic valves. This has been tested, of which the details can be read in appendix E. The conclusion was that adding more special valve types would not be worth it due to low production numbers and a decrease in system efficiency. However, the system can work together with normal valves at the end of the system. For example making valves ②③④ dynamic and valves ⑤⑥ normal valves (Figure 4.7). Although not necessary, if that area has a loose sensor or one in another BEN product, it can be controlled in a similar manner without extra dynamic valves. Thus to finish the BEN ecosystem it'd be interesting to create normal valves with the same look for a uniform product line-up.

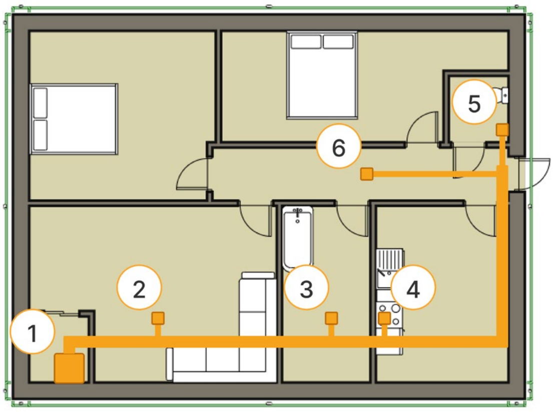


Figure 4.7: Example of a ventilation system

4.3.4 Controlling valves

Measurements of one valve do not directly influence the action of other valves. Although doing this could provide an efficient system, it would also create more opportunities for things to go wrong in the software and create a lot of extra data traffic (F. Helling, personal communication) (Appendix F). Instead, two loops are created that steer the system.

Steering flow can be adapted by changing the opening distance of each dynamic valve and by changing the total system flow of the fan. This should be done based on the ranges defined in 4.2.3. The position in the acceptable range determines the individual valve opening distance and the position in any valve's high range determines the total system flow (Figure 4.8).

This simplifies the control loops, but creates a delay before the rest of the system reacts and closes the valves. The delay is caused by the need for CO_2 and rh% to drop in other spaces before the other valves close.

4.3.5 Extraordinary circumstances

Exceptions to the control loop of this system might need to be implemented. Two examples scenarios where this is the case are weather and fire related.

Outside conditions might influence how the system should react. When outside temperature is more desirable the ventilation system should temporarily increase it's target ventilation to cool/heat the house. If outside conditions are humid or dangerous, the system should limit ventilation depending on the situation.

In case of fire CO_2 readings will rise. The range of the CO_2 sensors used can differentiate between possible fire and everyday use. Too make sure increased CO_2 readings do not make the system turn on ventilation to maximum and provide oxygen to a possible fire, a shut-off point should be implemented for the CO_2 sensor readings.

4.3.6 Conclusion of section

Dynamic valves can regulate airflow by adjusting the cross-sectional area available for flow. Maximum flow area should be maximized. Minimum flow area might be sound sensitive, which needs to be tested. Sharp edges, small corners and rough surface finishes should be avoided and along the flow path, aerodynamic shapes would be beneficial.

Cost of the system can be reduced by working with normal valves on the end of the system. For a uniform BEN product line-up the addition of passive valves in the same shape would be beneficial.

A medium and high sensor value range has been defined, the medium sensor controls each individual valve's setting, whilst any sensor in the high flow influences total system flow. Details can be found in appendix F.

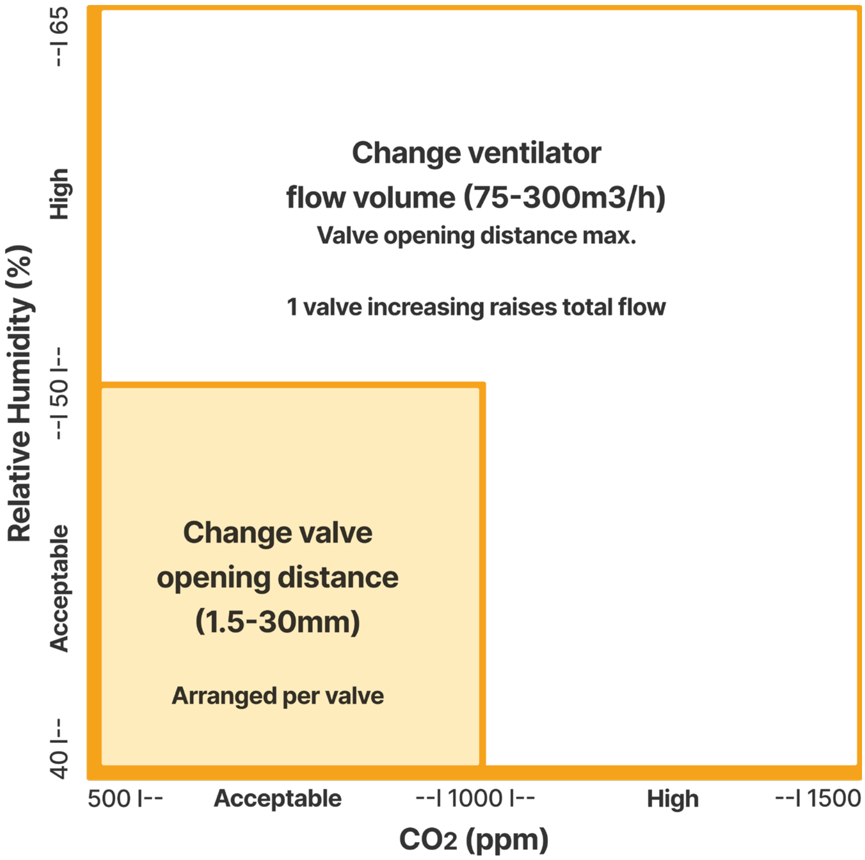


Figure 4.8: Proposition for desired reaction to sensor data

(4.4) How should dynamic valves be used?

4.4.1 Section introduction

Minimising hassle is a word combination used more often in this report. In this context its meant to signify making it easier to switch to a dynamic ventilation system. This section discusses the desired product interaction, where minimising hassle is an important subject as discussed in the previous chapters. The section discusses the following:

4.4.2 Pre-purchase product perception
4.4.3 Installation
4.4.4 Operation
4.4.5 Maintenance

4.4.2 Pre-purchase product perception

Although comfort is important, cost and legality are the most influential factors for homeowners to invest in better and cleaner climate systems (Rijksdienst voor Ondernemend Nederland, 2022) (Tunderman et al., 2024) (Appendix B1-4). For retrofitting existing residences, this makes reduction in heating costs an important factor, which must be tested if this idea is further explored after this thesis.

Sensors should be added to the valve to decrease cost and create a more complete all-in-one package. Other companies often hang sensors in extra control points spread through rooms, which is increases cost. Extra control points are not needed as the system steers itself for the user. Adding the sensors to the valves also reduces the amount of things that need to be installed. Details about installation will be discussed in the next section. However, removing extra installation steps and locations simplifies installation, reduces the amount of work required and reduces the amount of work that requires hiring craftsmen to perform.

Visually the product should embody comfort and health in combination with the BEN style (Figure 4.9). This style is not yet fully defined and a first version of a valve has the freedom to create part of this style (Personal communication, K.J. Veltman). Style elements to be kept in mind are the ‘BEN line’, a matte texture, a simple shape, avoid sharp corners and be mostly round. Details can be found in appendix G.

Figure 4.9: BEN style example

4.4.3 Installation

Combining multiple device functions is beneficial for price and system simplicity. Dynamic ventilation is meant to help users control their system, thus adding more sensors in control points throughout rooms is not beneficial. Instead adding the sensors to the valve would make it a plug-and-play system. Where replacing the valves and connecting them to the BEN/ventilation unit completes installation.

An exception to this could be the need to run a power wire. This is only needed if a VOC sensor cannot be used or a wired version is desirable. For example, housing associations often rather not leave the responsibility of maintenance and replacing batteries with the occupants. Thus, versions that require wiring might be advantageous.

Valves are usually attached to the inside of pipes, as these have universal standards. Three types of attachments are used often in valves and ducts (Figure 4.10).

Figure 4.10: Connection types for valves and pipes

Older valves usually use 3 spring feet, that pull the valves in place. They then close air leakage with a foam cushion that's pulled in place against the pipe. These valves can account for larger error margins and withstand a lot of force, but require some knowledge during installation. Improper insertion or removal can damage the wall/ceiling.

Newer valves often use versions that are installed in the ceiling. The edges of these valves are not visible, but due to added installation effort they are not suitable for all applications.

Pipe connectors use TPU seals that both seal the pipe-valve connection and pull the valve in place. They have a more professional/clean look when not installed and a tighter tolerance. This reduces less of the cross sectional flow area, enabling higher maximum flow. A disadvantage is that this tolerance can sometimes make installation more difficult as not all ventilation holes in existing residences are perfectly round.

During installation in some older residences putty is placed into pipes, most likely to create a smooth transition or to attach them (Figure 4.11). This means inner duct diameters are less constant then estimated. This disadvantage was discovered during the installation tests at the end of the project. During the project the choice was made to continue with the TPU rings. This might need to be reconsidered if this project is continued.

Figure 4.11 Tubing with putty on the inside

After installation the valves need to be paired to the BEN/ventilation unit. Pairing to the BEN can be done through ZigBee. The device should contain a button that can be used to initiate pairing, or pairing should start automatically when the device is powered.

The potential market would be larger if a separate station is made that can work with existing ventilation fans. The protocol for doing so is standard and requires a voltage change through a physical cable. Attaching a station that takes over the communication function of the BEN and steers the fan would be an interesting business case for the Joule group. Although personally, I do not think the production and sales departments will do so, as they seem to be more focussed on their own products. Thus during the project this extra option has not been further explored.

4.4.4 Calibration

Before system calibration, each valve needs to be connected to the system, assigned a name and set to a room/area type. Assigning names will make it easier to identify valves in the future. Assigning room types could be beneficial for adding different protocols to the valves, making sure they operate most efficient, based on their environment. For example, a bathroom might need to scan for humidity more often and a sleeping room should avoid quick changes to avoid noise.

Valves that are added to an existing BEN ventilation heat-pump/ventilation fan, can be calibrated by users or by installers. Most modern normal valves have different opening distances labelled. This labelling is universal, thus Joule could implement these same numbers to let users choose the calibration position. Otherwise calibration needs to be done by an installer.

For installers, the calibration process of dynamic valves is the same as that of normal valves, except opening and closing the valve during calibration is done through the installer application (Figure 4.12). Information about the status of each area can also be visualized in the application.

Figure 4.12: Ventilation calibration technician measuring flow

The position at which a valve is correctly calibrated is saved as the 0-position. If all valves require high or low flow, valves will return to this position so the legally required flow division per room at high flow can be achieved.

4.4.5 Operation

As most users do not understand how to correctly control in-house climate systems, the system should help take control for the user. However, most users do not like the feeling of losing control. From interviews and personal conversations it seems the feeling of losing control is mostly caused by a lack of information and understanding. Therefore, the system should show what it's doing in a simplistic way. Whilst keeping more detailed control available for users who are interested.

To keep the user from feeling they're lose control, each part of the system should have use-cues that inform them. For the ventilation system this is envisioned to be done by the moving blocking mechanism, making it noticeable for the user (Figure 4.13). In the app, within margins, the users can adapt the range at which the system reacts. For interested users this could enhance the feeling of having control, as the system follows what the user told it to.

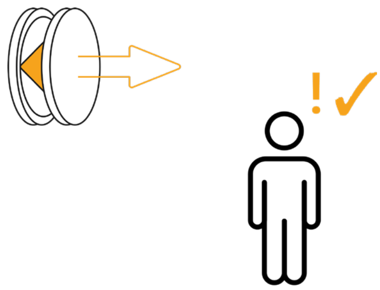


Figure 4.13: Visually informing users

As blocking movement in the final design a translating motion was chosen perpendicular to the wall/ceiling (Figure 4.13). This movement can be controlled precise with the chosen mechanism and the movement can visually be noticed. Additionally, visually enhancing this movement can be done by adding a colour to the back of the moving part. In this case, the Joule house-style colour was chosen, as this is envisioned to be used on more products in the future BEN line-up (Personal communication, K.J. Veltman).

4.4.6 Maintenance

Normal valves should be cleaned once a year in order to avoid dust buildup. For dynamic valves this will most likely be similar, although this should be tested if the project is continued.

For the battery powered version the AAA batteries should be replaced roughly every 1,5 years. To properly clean the valve it should be removed from the pipe, providing an opportunity to replace the batteries as well. If the user does not replace the batteries in time, the valve should sense it is low on power, and return to the 0-position. It then continues operating as a normal valve.

4.4.7 Repair

The BEN communicates with Joule's servers to log the state of different sensors. This can be used to improve systems in the field with updates and allows for preventive maintenance warnings (Figure 4.14). 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.

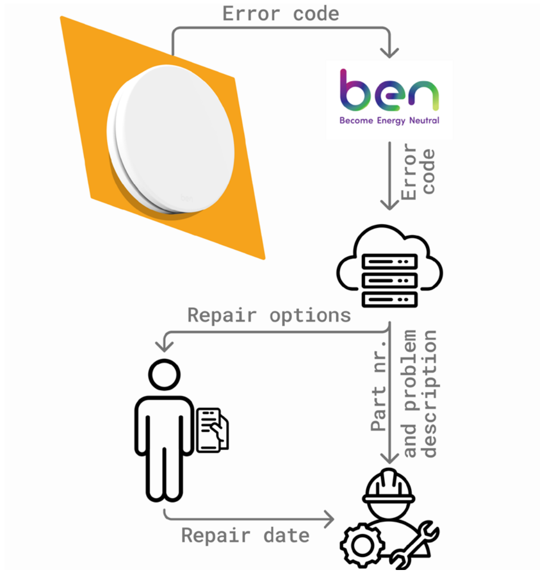


Figure 4.14: From error to repair request

As heating installations often come with maintenance contracts, adding the BEN and/or 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.

4.4.8 Conclusion of section

ROI and price are the most important factors for potential users to adopt these system. To achieve this sensors should be added to the valves, installation steps reduced, simplified and a clear and clean visual form language should be established.

Valves will be attached to the duct with a TPU seal, although this system requires reworking if the product is continued.

The calibration process is similar to that of regular valves.

System feedback should be provided through simple use-cues from different elements in the system. In this case it will be done by a translating body, that is also used to block airflow.

Cleaning and a battery replacement is required every 1,5 years. For repair, preventive maintenance requests can be send to owners, possibly bound to servicing contracts.

05 – Embodiment design

Gives a global description on the product's use. Shows required parts, their costs, explains some design features and notes important considerations.

5.0.1 Chapter introduction

Properties discussed in the previous chapter, vision, are combined to create the final product direction (Figure 5.1). This chapter discusses the following:

- 5.1 Iteration steps – Different steps in the process and reasoning behind them
- 5.2 General information – Discusses USPs (Unique Selling Point) and use
- 5.3 Product – Shows the product and parts required

Figure 5.1: Dynamic valves final prototype

(5.1) Iteration steps

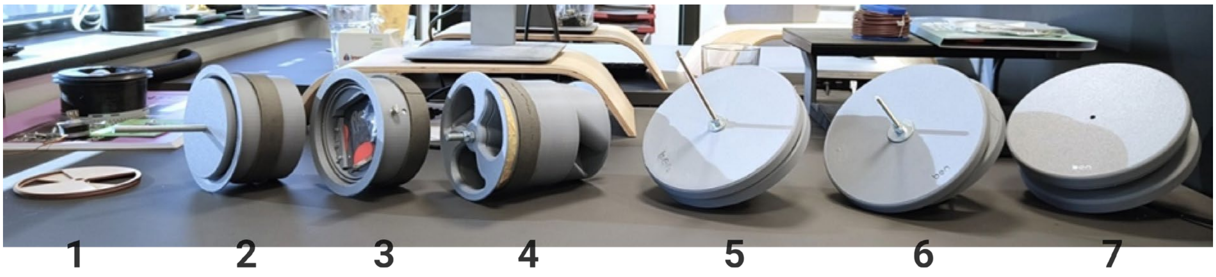


Figure 5.2: Different prototypes, created during development stage

5.1.1 Section introduction

During this phase of the design several concepts were made, tested and evaluated (Figure 5.2). Although this process was linear, prototypes 1-5 differ in working principle, ideas and vision.

5.1.2 Idea generation

As working principles were mostly worked out in the original vision, the most important question for prototype 1-5 was what kind of blocking mechanism could be used for airflow. The blocking mechanism needs to clearly communicate what the system is doing to users without being annoying.

5.1.3 Prototypes 1-4

Prototype 1 was made to get a look and feel for what would happen to air-pressure when restricted. It closely resembled the initial design direction of dynamic valves shown in section 3.4.

Prototype 2 was made to get a better idea of the duct size, size of required parts and airflow requirements. In essence it's a normal valve with sensors on the side and a motor on the back to rotate the blocking body up and down.

Whilst working on prototype 2 a new type of flow control was found (Figure 5.3). This device has a ring ① on the outside which adjusts the position of two sliders ②. Moving the sliders changes the opening available for airflow. In this opening, a baloon ③ was placed. This baloon is open to flow pressure in front of the device. Changes in pressure change the available airflow area by inflating/deflating the baloon, causing flow after the device to be similar at different flow pressures. Prototype 3 and 4 tried to integrate the option for constant flow.

Figure 5.3: Constant flow control

Prototype 3 should work both as a constant flow and a dynamic valve (Figure 5.4). The blocking mechanism is a film ① that is pulled towards an indent in the back when airflow is increased, decreasing the airflow area. At the bottom ②, the film is twisted back in place by a spring. At the top ③ a stepper motor is installed that can twist the film open, making it dynamic. For the constant flow version, this motor would be replaced by a knob that can adjusted by the installer.

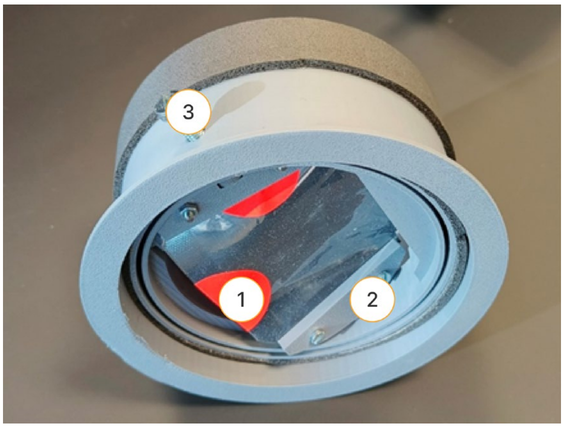


Figure 5.4: Prototype 3

Prototype 4 aimed to create an airflow steering mechanism that looks interesting and does not protrude outside of the wall. Furthermore, the status of the valve must be easily visible (Figure 5.5). It exists of one body ① with bodies ② on the inside that move up in a rotating motion, changing the amount of blocked air. These bodies were made so that an insert ③ could be added containing balloons. Allowing for a version with constant airflow.

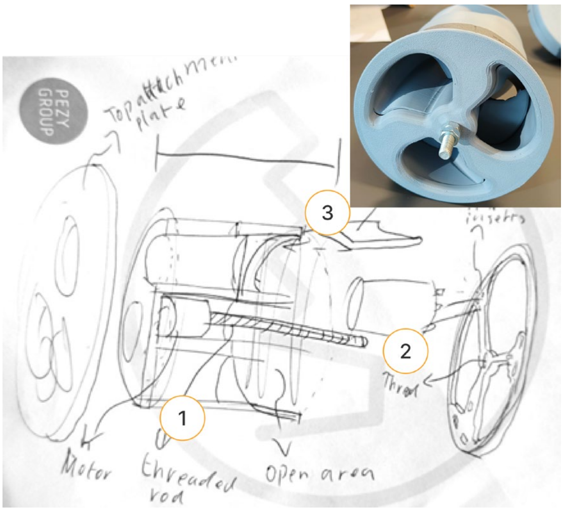


Figure 5.5: Sketch and image, prototype 4

Take-aways:

- ➢ The moving mechanism must be capable of making precise adjustments when cross sectional area available for airflow is small.
- ➢ Certain features in the design can cause noise, these should be avoided.
- ➢ Area required for the stepper motor and sensors is larger than expected.
- ➢ Space inside wall/ceiling is limited.
- ➢ Although constant flow principles work, they complicate the design.

5.1.4 Prototypes 5-7

After prototype 4 two focus points became more important.

1. The design needed to be simple. Making things spin, rotate and being pretty made things too complicated.
2. The design needed to be cost effective. The interview with Tom showed prices for electronics and sensors were higher than expected (Appendix B5).

A couple of new ideas were created, of which one was chosen (Figure 5.6). Important changes were moving the electronics ① into the blocking body ② and extending the blocking body up to the edge of the valve ③. By moving the electronics ① into the blocking body ② more space is available for airflow, and the valve no longer extends far into the duct. Having the blocking body ② come out over the outer body up to the edge ③ makes the gap in between the blocking ② body and the outer body ③ the smallest area available for airflow. Because this is a gap, the change caused by moving the blocking body is easier to notice.

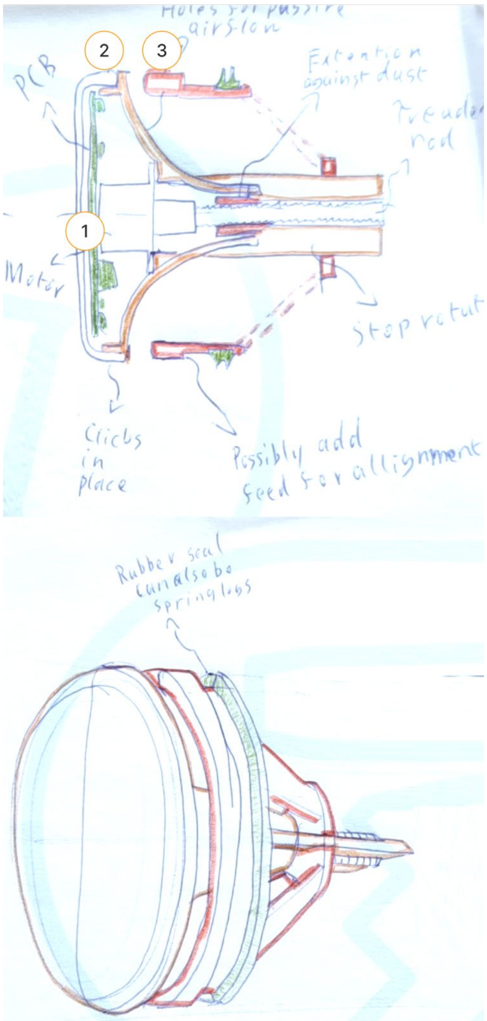


Figure 5.6: Sketch of prototype 5

Prototypes 6 and 7 (Figure 5.7) were improvements of prototype 5. Most notable changes are listed underneath.

1. Customized hex bar takes over the following functions (Outer body):
    a. Alignment of outer and inner body
    b. Provides a thread for the threaded rod, which is placed further towards the front
    c. Protects lubricant on threaded rod against dust
2. Batteries are relocated to outer ring (Outer body)
3. Size and available height determined (PCB)
4. Orientation and shape of passive diffusion holes altered (Inner body)
5. Assembly was made fool-proof (Everywhere)
6. Removal of unnecessary undercuts (Everywhere)
7. Addition of spacers (Blocking body)
8. Addition of cable strain relief (Outer body)

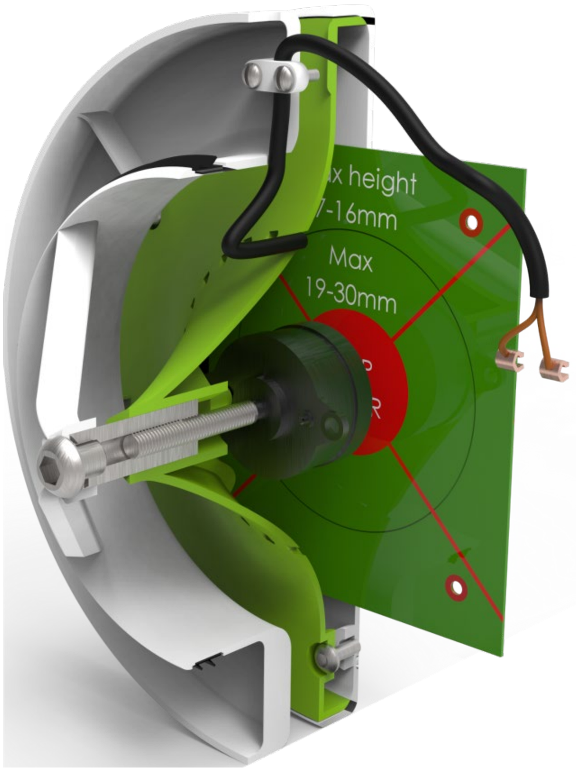


Figure 5.7: Render of prototype 7

(5.2) General information

5.2.1 Section introduction

Dynamic ventilation valves allow BEN to increase its control on the airflow out of the residence, get area specific air-quality data and show its user what the system is doing. It does this without the need for separate ducts for each valve and with minimal disturbance during installation. Energy savings through increased flow control make dynamic valves to be an investment people earn back over the years. These USPs are further discussed in their respective sections, after which operating procedure is explained.

5.2.2 Health and comfort

Location specific control over airflow and data allows the BEN to steer the in-house climate, as to provide a more healthy environment. Instead of determining airflow requirements on averages of all residences, the system can target more ideal airflow ranges. The assumption is made that a healthier environment also increases comfort, but comfort is a feeling. To further improve comfort the feeling of knowing that the system is doing something that makes your environment healthier is an important factor. How this is promoted in the product is further explained in use-cues.

5.2.3 Use-clues in a clue-less market

Not understanding what the climate system is doing can create the fear of losing control. It's interesting that whilst most users do not understand the system. Instead of adding use-cues, the market does their best to hide the system from view. This doesn't make systems more user friendly.

Existing use-cues lessen with the installation of BEN, as BEN seems to be much more quite then fan fans used before. Meaning the original auditive feedback disappears (P. van Oostrom, personal communication). Using the mechanism for blocking air to show what the mechanism is doing, provides a new visual feedback. This strengthens usability and trust in the system (Figure 5.8).

Figure 5.8: Using mechanism to communicate flow

5.2.4 Installation without hassle

By installing the product at the ends of the system no new ducts need to be ran meaning installation can be done swiftly and without making the entire home into a construction site. The only thing that may need to be connected is the power-outlet. To avoid this a wireless version is also made (Figure 5.9). Calibration can be done in a similar manner as original valves, making the effort of the entire installation process similar to those.

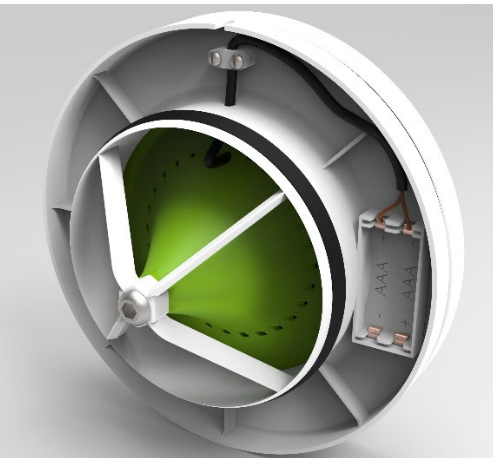


Figure 5.9: Battery powered dynamic valve

5.2.5 Dynamic valves as investment

People don't invest in green energy systems unless it saves them money (Strick, 2016). With 11-14% estimated energy savings, dynamic valves can be bought as an investment next to creating a more healthier and comfortable climate (Section 4.1.2).

5.2.6 How does it work?

Dynamic valves measure data and receive instructions on desired opening distance. Desired settings are applied through the BEN, so that updates and optimalisations can be performed after the product is installed (Figure 5.10).

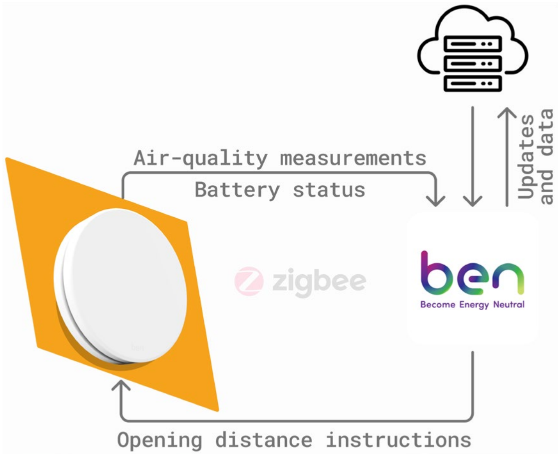
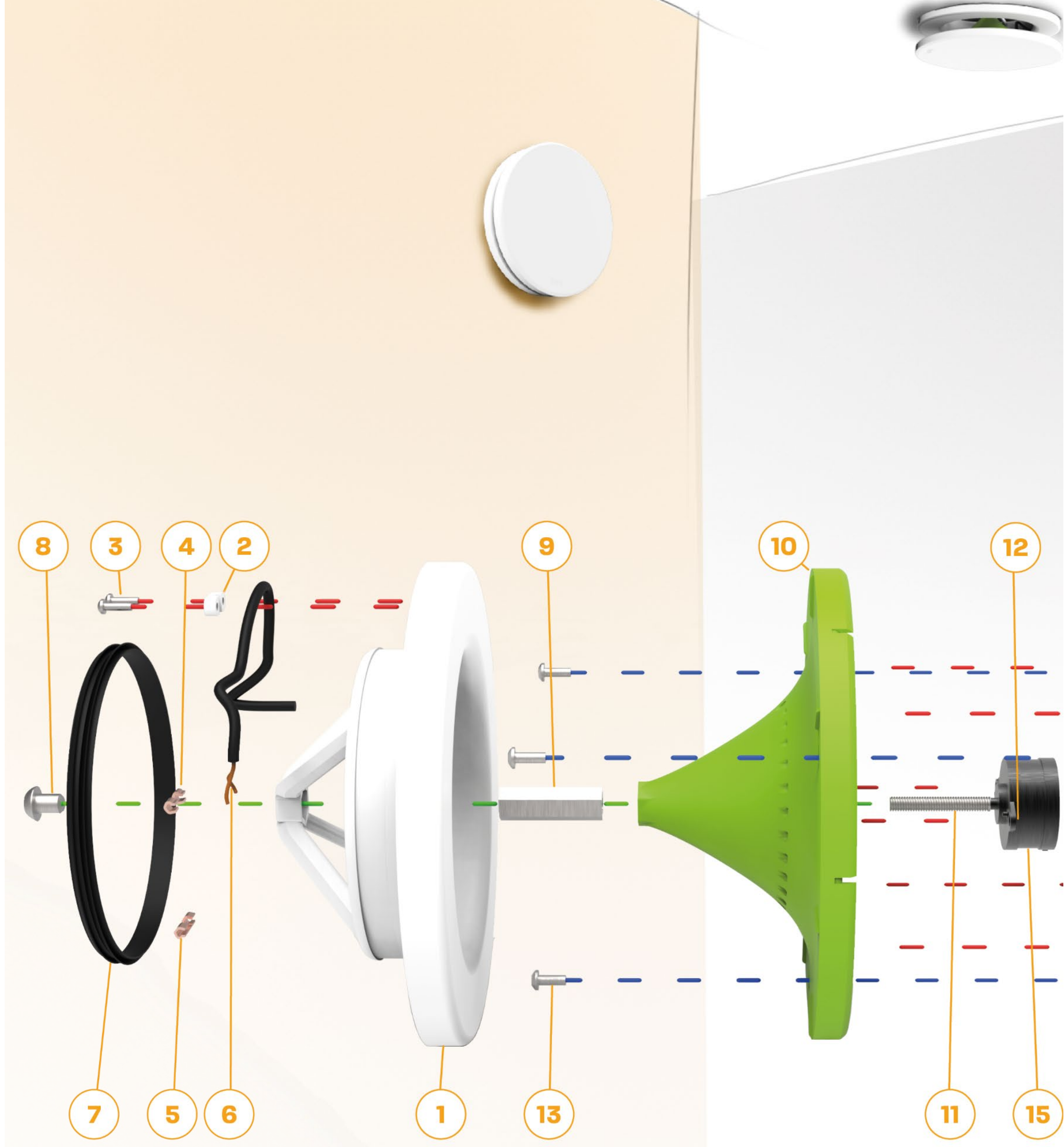


Figure 5.10: Instruction and communication order

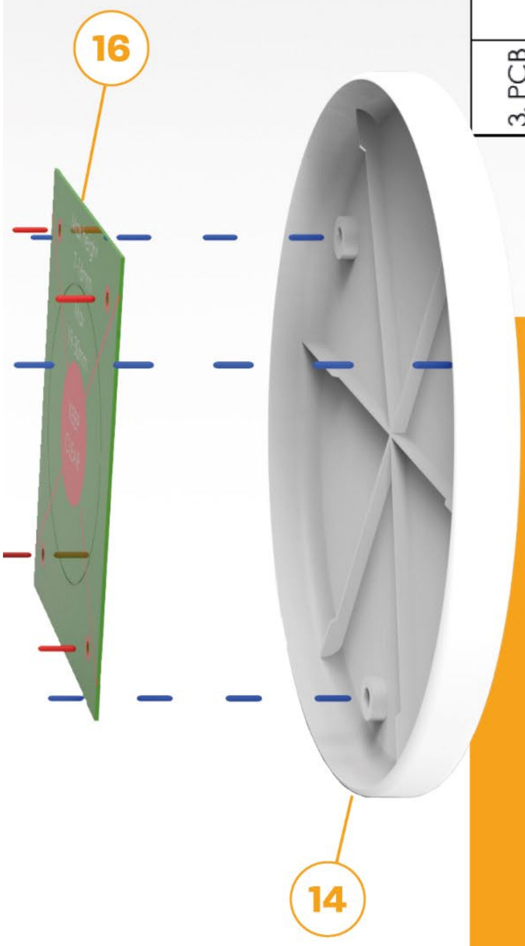
(5.3) Product



BOM - BEN Dynamic Valve

AREA	ITEM NO. 18	DESCRIPTION	Material	QTY. 21	Mould price € 74,000	Price (per part)	Price (total) € 31.84
1. Outer body	1	Outer body	Plastic (ASA)	1	€ 25,000	€ 0.06	€ 0.06
	2	Cable clamp	Plastic (ASA)	1			
	3	Slotted pan head screw (Ø3*10)	Steel (SS)	2		€ 0.05	€ 0.10
	4	Leaf spring AAA battery contact (Single)	Spring steel (Nickel-plated)	2		€ 0.34	€ 0.68
	5	Leaf spring AAA battery contact (Double)	Spring steel (Nickel-plated)	1		€ 0.36	€ 0.36
	6	Cable	Mixed	1		€ 0.05	€ 0.05
	7	Seal	Plastic (TPU)	1	€ 10,000	€ 0.01	€ 0.01
	8	Hex binding head bolt (M8*P(unk.)*8)	Steel (SS)	1		€ 0.12	€ 0.12
	9	Hex bar 12x40 (Adapted)	Steel (SS)	1		€ 0.75	€ 0.75
2. Inner body	10	Steering body	Plastic (ASA)	1	€ 21,000	€ 0.17	€ 0.17
	11	Threaded rod (M6x45)	Steel (SS)	1		€ 0.27	€ 0.27
	12	Hex pan head screw (Ø4*15)	Steel (SS)	2		€ 0.06	€ 0.12
	13	Hex pan head screw (Ø4*10)	Steel (SS)	3		€ 0.05	€ 0.15
	14	Cover body	Plastic (ASA)	1	€ 18,000	€ 0.00	€ 0.00
	15	JT00139 tepper motor	Mixed	1		€ 4.99	€ 4.99
3. PCB	16	PCB (VOC & Wireless)	Mixed	1		€ 24.00	€ 24.00
	17	PCB (VOC & Wired)	Mixed	0		€ 34	€ -
	18	PCB (NDIR & Wired)	Steel (SS)	0		€ 44	€ -

Table 5.12: Bill of Materials (Appendix H)



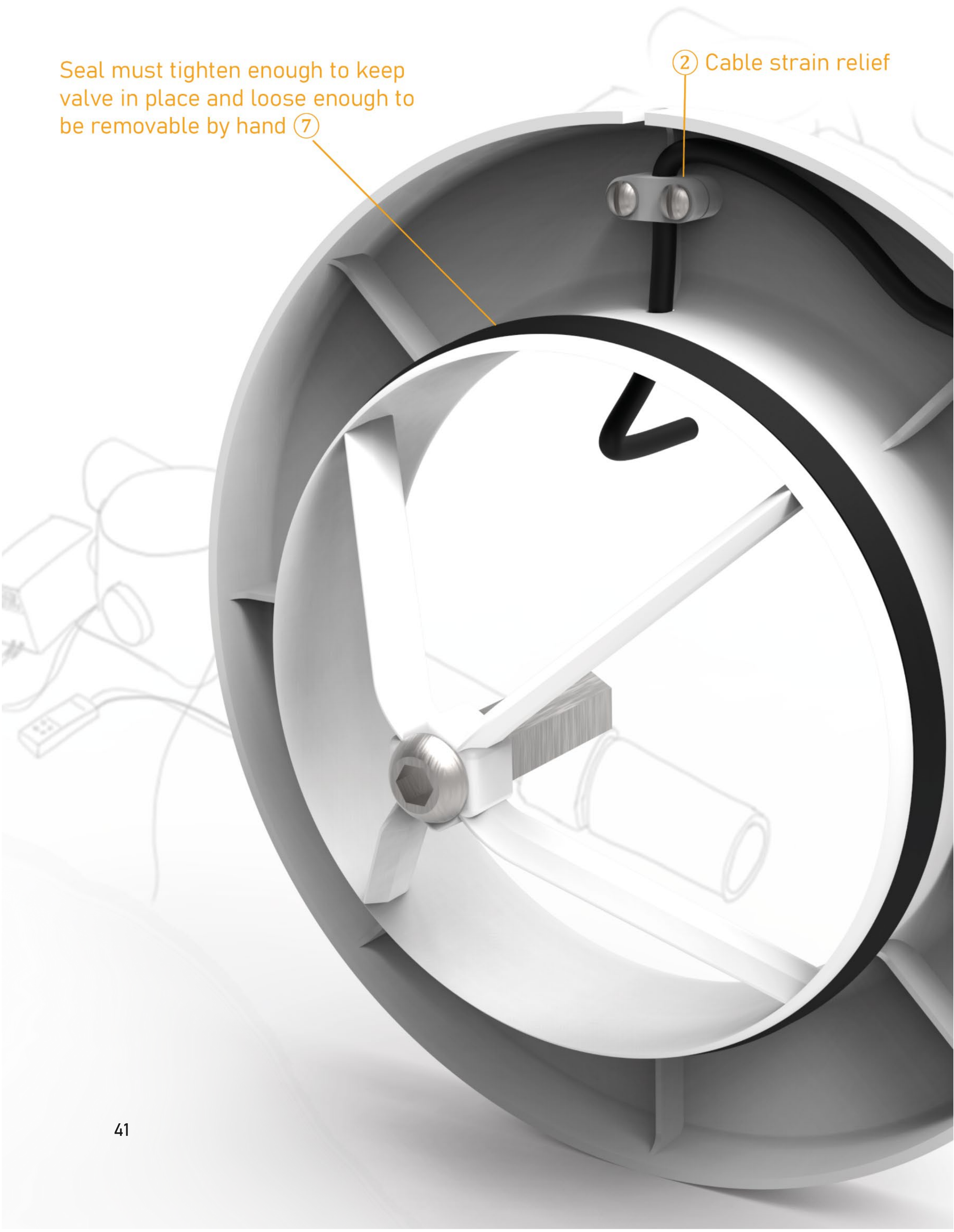
5.3.1 Different versions

To minimize installation effort, the regular version is battery powered. 2 AAA batteries should power each valve for ≈1.5 years (T. van den Berg, Personal communication).

For some buyers, like housing developers, having the system powered by the grid is beneficial. To accommodate this a 2nd version should exist that can be plugged in. The main difference between the standard version and this one is that an adapter is placed in front of the PCB, instead of the AAA batteries. This increases the cost (Table 4.1).

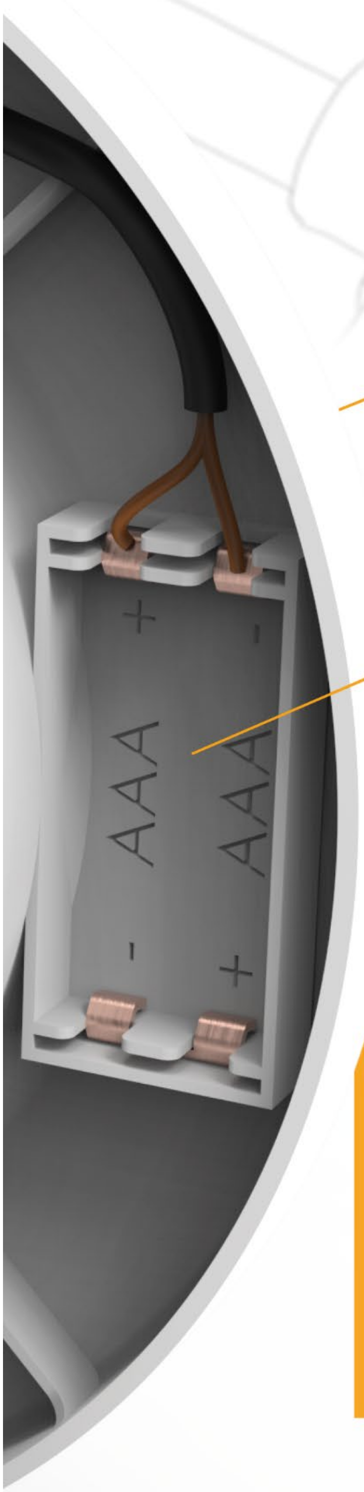
For new buildings, different regulations apply. When steering ventilation through CO2 detection, sensor requirements are more strict. This means a more expensive and energy intensive CO2 detector, the NDIR sensor might need to be used. In the 3th version, the VOC sensor is replaced by an NDIR sensor. This sensor costs more energy to operate, causing this version to be fitted with an adapter as well (Table 5.12).

More information about prices and expected sales numbers can be found in appendix H.


Seal must tighten enough to keep
valve in place and loose enough to
be removable by hand (7)
(2) Cable strain relief

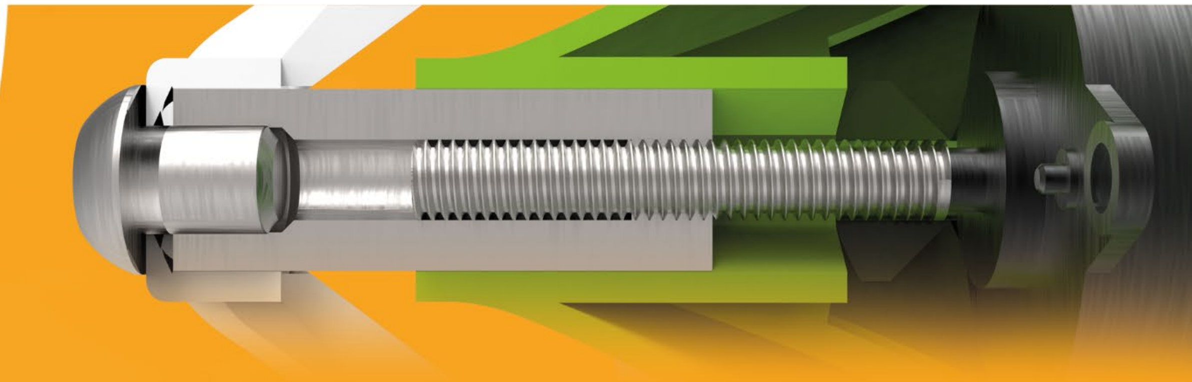
BOM - 1. Outer body

ITEM NO. 18	DESCRIPTION	Material	QTY. 21
1	Outer body	Plastic (ASA)	1
2	Cable clamp	Plastic (ASA)	1
3	Slotted pan head screw (Ø3*10)	Steel (SS)	2
4	Leaf spring AAA battery contact (Single)	Spring steel (Nickel-plated)	2
5	Leaf spring AAA battery contact (Double)	Spring steel (Nickel-plated)	1
6	Cable	Mixed	1
7	Seal	Plastic (TPU)	1
8	Hex binding head bolt (M8*P(unk.)*8)	Steel (SS)	1
9	Hex bar 12x40 (Adapted)	Steel (SS)	1



① ASA (Acrylonitrile Styrene Acrylate) does not discolour much over time

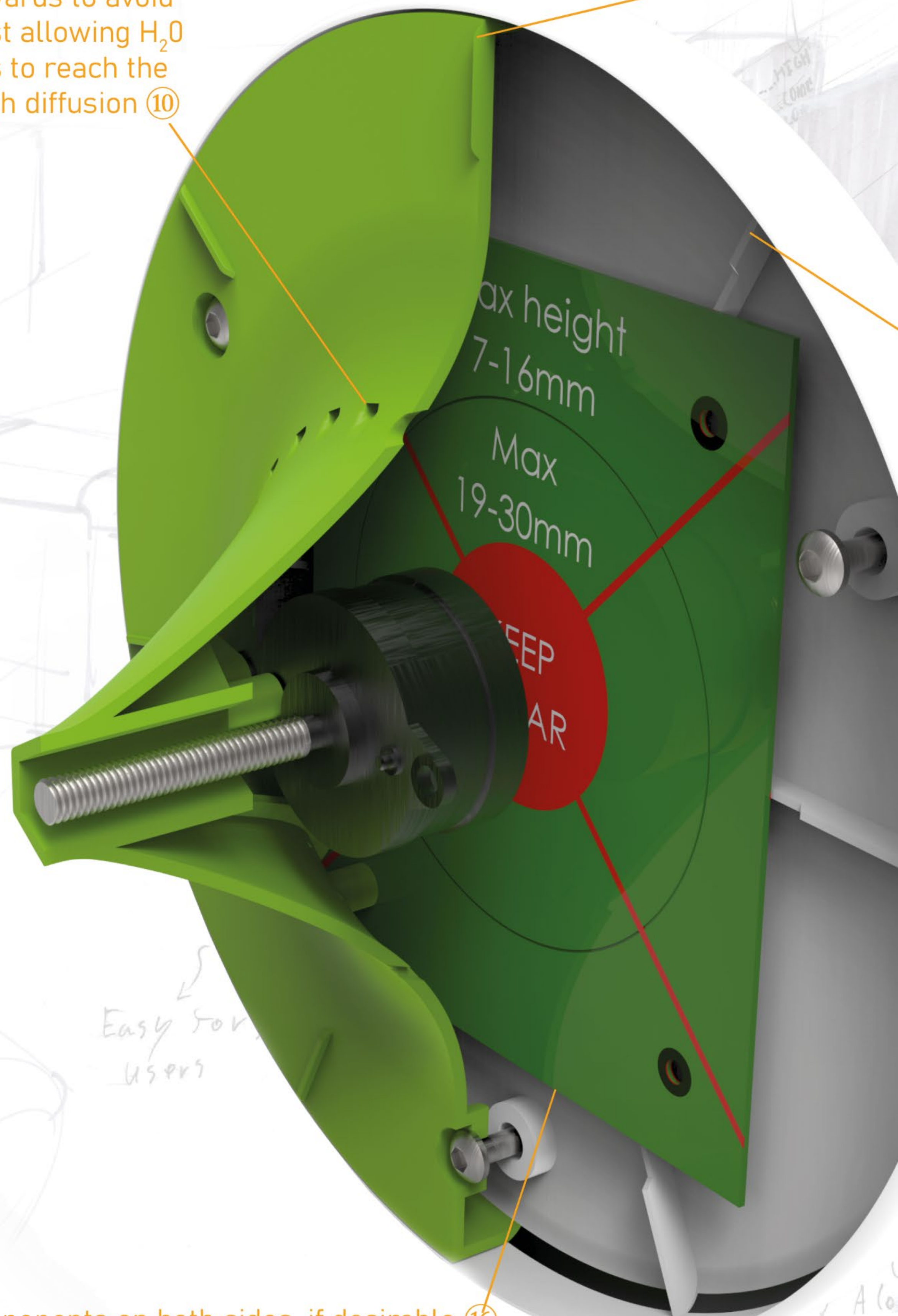
④⑤ If outer diameter ① is deemed to large or battery capacity is too low, battery slots can be split and the number increased



5.3.2 Allignment

Due to tolerances in the thread and the moulding angle, keeping the inner body aligned to the outer body cannot be done with the plastic ①⑩ or threaded ⑨⑪ parts. To keep them properly aligned the middle hole diameter of the hex bar ⑨ is drilled to be the same size as the outside diameter of the threaded rod ⑪.

Holes oriented inwards to avoid dust buildup, whilst allowing H_2O and CO_2 molecules to reach the sensors ⑯ through diffusion ⑩



Has space for components on both sides, if desirable ⑯ there's enough space to change PCB location and size.

⑩ 1,5mm extending legs provide end-stop to avoid complete closure

BOM - 2. Inner body

ITEM NO. 12	DESCRIPTION	Material	QTY. 13
10	Steering body	Plastic (ASA)	1
11	Threaded rod (M6x45)	Steel (SS)	1
12	Hex pan head screw (Ø4*15)	Steel (SS)	2
13	Hex pan head screw (Ø4*10)	Steel (SS)	3
14	Cover body	Plastic (ASA)	1
15	JT00139 tepper motor	Mixed	1

⑭ Can only be placed onto ⑩ in one orientation, minimizing assembly mistakes

1.5 mm 10 mm 30 mm

5.3.3 Movement as use-cue

To achieve dynamic ventilation, a stepper fitted with a threaded rod, pushes part of the valve away from the wall. Opening or closing space avaiable for airflow. The image above shows the a few different positions, illustrating how this movement can be used as visual use-cue that informs the user.

06 - Testing

Shows the results of two final tests for flow and installation.

6.0.1 Chapter introduction

During the project tests have been performed to test the viability of the mechanisms for steering air, determining required flow area, finding influence of flow on sensors etc.. This chapter will discuss two of the final tests, that validate the working of the prototype and its ease of installation.

(6.1) Flow steering capability

6.1.1 Goal of test

The test should validate if the valve's opening and closing motion can be used to influence the direction of flow enough, so that it can be used to achieve similar results as described in section 4.1.2. The test needs to verify the ability to steer air at different airspeeds, so that it can also predict behaviour of valves later in a system.

Next to this the following sub-questions were formulated:

- Can airflow through the valve be limited to 15 m3/h when the fan is blowing at maximum power?
- Can flow through the 2nd opening be controlled by the 1st opening's valve and the ventilation fan, so that it meets the desired ranges as described by section 4.1.2?
- Is the noise produced by the setup noticeably louder then without dynamic valve?

6.1.2 Setup and method

The test was performed using test setup 2 as described in appendix I (Figure 6.1). It has a ventilation fan of which the airflow is measured. Opening 1 contains the valve. Opening 2 is open, but can be partially closed if needed.

1. Increase the amount of power on the fan until the flow exiting the fan reaches the desired value for this round
2. Place the valve into opening 1
3. Measure flow of both flowmeters at opening distances 1, 5, 10, 20 and 30mm
4. Repeat step 1-3 for all rounds
5. Calculate the flow at opening 1 for all opening distances for every round

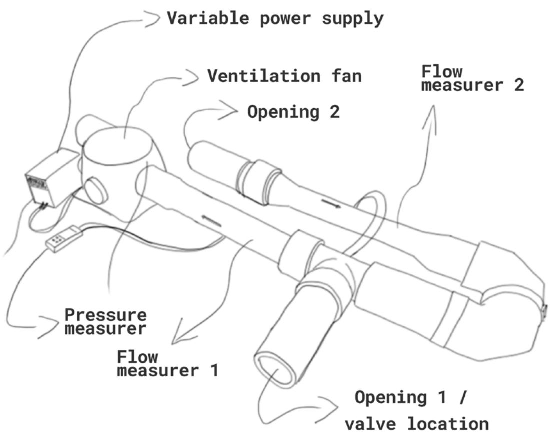


Figure 6.1: Flow test setup

6.1.3 Results, conclusion and discussion

This test validates that the valve is able to steer airflow in most required ranges in a domestic ventilation system (Figure 6.2). An exception is the range of a flow of 306 m^3/h past the first valve. In this case, flow at the first valve can only be limited to ≈30 m³/h. Valves later in the system will see lower minimum flow as flow lowers after each valve. This might still be acceptable for total system performance, as 300 m³/h is not likely to be necessary often with dynamic ventilation. Also, total flow could possibly be dialled down based on percentage of valves requesting high flow. However, if this is indeed acceptable needs to be decided and true total system tests should be performed to confirm this choice.

As all tests were performed without valve at the 2nd opening, this test confirms that passive valves can be used at the end of this system. It's important to note that passive valves can only be added after the last active valve.

During most of the test noise created by the system was significantly less then with a regular valve at higher flow. However, at a flow of 300 m³/h and the valve at 2mm or lower a soft whistling sound could be heard. This was not present in earlier prototypes that were shaped differently, but had similar cross sectional area available for flow. Therefore, the shape of the blocking body and the distance flow travels alongside it is suspected to cause the sound. However, if the project is continued the origin of this whistle must be discovered and resolved before the project can be continued.

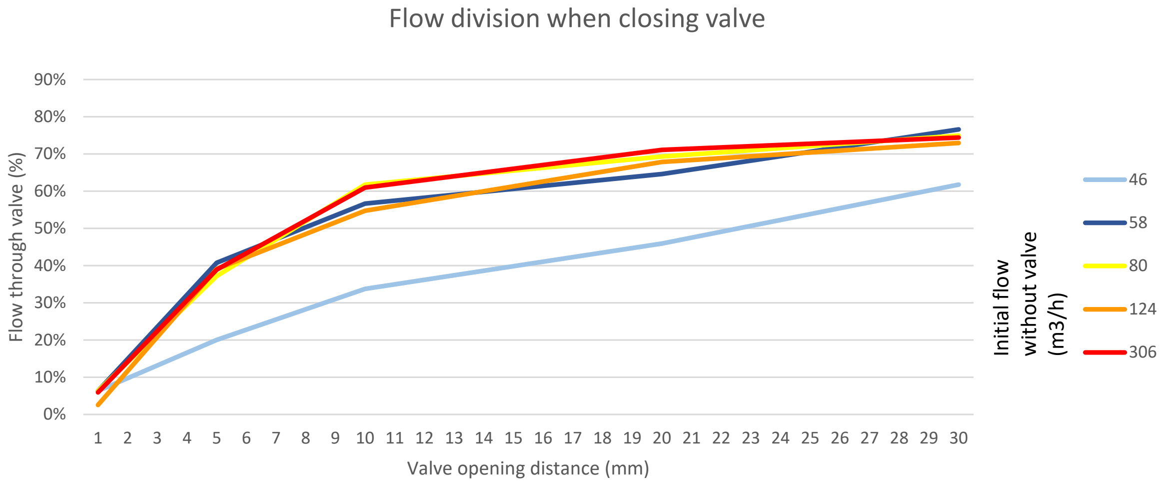


Figure 6.2: Results of flow steering capability test

(6.2) Installation

4.2.1 Goal of test

This test is meant to see if the removal of valves during maintenance and cleaning causes issues for the user or the valve's prolonged operations.

The test is meant as a first indicator, without application nor written instructions. Therefore, although the test provides an indication, it might not be accurate nor cover all bases.

4.2.2 Setup and method

The test was performed with two participants in a studio apartment with balance ventilation (Figure 6.3). The original valve was left in the ceiling at the start of the test and two AAA batteries were placed on the counter. The participants were handed the dynamic valve prototype and asked to install them. When this was done, they were asked to clean the valve and replace the batteries.

Figure 6.3: Test location

4.2.3 Results, conclusion and discussion

Both participants were able to install the valve. One struggled with removing the old 3-legged valve.

The apartment contained both venting and supplying valves. Both participants needed guidance on which valve to replace.

None of the participants placed the batteries into the valve before they were asked to replace them.

When cleaning both participants dusted the valve of. One did this with a moist towel, the other with a dry one. None of the participants tried to open the valve further then its closed position. From observation, it seemed like one of the participants dusted the valve of properly, while the second quickly wiped it. It is unclear if the valve from the second user would have been clean enough.

When removing the valve, both participants pulled at the blocking body. One of the participants mentioned, it did not feel stable.

It might be useful to have a cleaning sequence in the application, that extends the valve so sensor openings are easier to reach.

Making the valve removal feel more stable by having something connect the blocking and lower body might be possible. This would avoid all force transfers through the centre.

07 - Conclusion

Looks into product feasibility, desirability and viability. Advises on the implementation of future development plans.

(7.1) Does it work?

7.1.1 Airflow steering capability

The test shown in section 6.1.1 shows that the steering capability required for dynamic ventilation can be met in all situations, except for the first valve in the system if flow is higher than 300 m3/h. In that case the flow through the valve can only be limited to 30 m3/h instead of the 15 m^3/h the prototype aimed for. This is still acceptable, but should be kept in mind when continuing the project, as it decreases system efficiency of the model in 4.1.2 by ≈1%.

Dynamic valves can work in conjunction with normal valves. Note that adding normal valves before the last active valve in the system would cause the system to be less efficient. Being able to work with normal valves can make the system more affordable and allows for dynamic valves to keep working when set to the 0-position due to low power.

7.1.2 Whistling noise

Noise created by the dynamic valve prototype was less than that of a normal valve. However, at a flow of 300 m3/h and the valve <2mm open a soft whistling sound could be heard. The whistling noise needs to be resolved before this project is continued.

7.1.3 Conclusion

Yes, the product is feasible, although the prototype in its current form does not yet suffice. More development is needed, which chapter 8 will provide more information on.

(7.2) Value for consumers

7.2.1 Costs and benefits

Production cost are €33-53 per unit (Table 7.1). The amount of dynamic valves that need to be fitted differ per residence. The sales price is dependent on Joule's pricing strategy. Comparable products of competitors can be bought for €140-350. However, dynamic valves have lower average installation costs.

Sensor type	Power supply	Production cost per unit	Heating savings
VOC	AAA batteries	€33	11-14%
VOC	Power plug	€43	
NDIR	Power plug	€53	

Table 7.1: Estimated cost and energy savings for different dynamic valve versions and use situations (Appendix E&H)

Energy savings are 11-14%, dependent on user behaviour and amount of occupants. The type or size of residence does not influence the percentage as much. However, it does influence the final average energy savings (Table 7.2).

Type of residence	Average heating energy per year (kWh)	Reduction in energy with DV (kWh)
Apartment	4850	530-580
Terraced (Mid)	6610	730-790
Terraced (End)	7700	850-920
Semi-detached	8790	970-1050
Detached	11210	1230-1350

Table 7.2: Potential average heating energy savings with dynamic ventilation in Dutch houses (Centraal Bureau voor de Statistiek, 2025)

7.2.2 Health, comfort and usability benefits

As the system would improve air quality and inform user better. Health, comfort and usability benefits are likely. However, these claims have not been quantified during this project and should be tested if the project continues.

7.2.3 Ease of installation

Installing this part of the system can be done quickly and without professional help. Only calibration might require a professional to have a look at the system.

Replacement is much easier than competitors' systems and could fill a gap in the market for retrofitting existing systems. Although this project is now designed to work together with BEN, this product can be adapted to also work with other climate control systems, as long as mechanical ventilation is present in the residence

7.2.4 Conclusion

Although more pricy then initially expected, bringing dynamic ventilation to the market would create a viable, interesting proposition. Both for the Joule group and consumers.

The increased ease of installation, air-quality and climate system operation cost savings make the product desirable.

(7.3) Value for Joule

7.3.1 Distinguishing the BEN brand

The addition of dynamic valves into Joule's BEN lineup would clearly distinguish BEN from other heat-pump systems. Claims for improved air quality, comfort and health aspects can now be clearly illustrated.

Minimized energy loss through ventilation would strengthen the general position of BEN's system efficiency.

The movement of the valve would be a start for indicating what the system is doing in a simplistic way. Adding this to more parts of the system would make sure BEN is not only distinguished through its health, comfort and financial aspects. It would also distinguish itself as an understandable, user friendly brand.

08 - Recommendations

Summarises the steps required to continue the project and an evaluation on the value of continuation. Provides the opinion of the author on project continuation and general BEN positioning.

Remaining design challenges

8.1.1 Steps towards bronze

Currently the dynamic valve is at TRL 3 (Technology readiness level). The work done had the goal of providing the groundwork to make a valid decision whether further investment is worth it. Several steps are required to get towards a first bronze/TRL7 version.

1. The whistling noise needs to be resolved
2. The seal needs to be replaced by legs and foam
3. A VOC CO_2 sensor needs to be tested on accuracy
4. An automated prototype with sensors should be created
5. A full scale system test should be performed
6. The product look and feel should be adapted and tested

At a flow of 300 m^3/h and the valve at 2mm or lower, a soft whistling sound could be heard. This sound was not present in other prototypes with similar opening distances under the same conditions. Therefore, it is expected to be caused by the product's shape, specifically the distance at which it travels in between the blocking and outer body (Figure 8.1). This distance could be equal to the wavelength of a vocal note. Other changes that might influence the whistle would be a surface pattern, surface texture or a softer material.

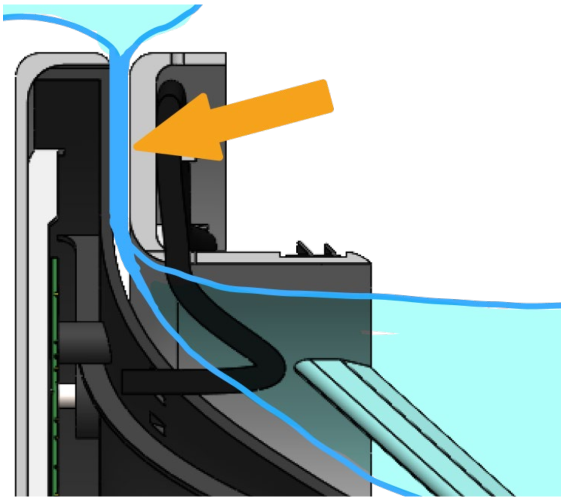


Figure 8.1: Expected whistle location

The seal currently used in the design works well with newer structures. However, as found during testing, this seal is not suitable for existing structures as duct openings differ in size due to putty. Therefore, an alternative version should be created (Figure 8.2). This could be done while the whistle problem is adapted, as both require remodelling.

If measuring CO_2 with a VOC sensor is sufficient needs to be decided. Currently Joule is testing a VOC sensor for their thermostat, if this test cannot conclude if the VOC sensor is accurate enough to steer with CO_2, a separate test should be performed. If steering with a CO_2 sensor is allowed, no version with an NDIR sensor should be made. If the VOC sensor does not suffice, a wireless version of the product is not viable. Thus only the version with a NDIR sensor can be created.

A prototype should be created that has sensors installed to test if the sensors can sense the required room changes in adequate time and set a reference to see how often measurements should take place. This is required both to see if the sensor entrances are sufficient and to make an estimation on the amount of AAA batteries are required to power the system for more than 1,5 years.

First a manual, and later an automatic (Bronze/TRL7) full system test should be performed. The valves can be placed in the ventilation system of an existing residence and the effect of opening and closing different valves at different locations in the system should be tested to do a final feasibility check.

If the previous steps have been completed the product look and feel need some last attention. The outer shape of the product should be adapted to properly match with the Joule style and a mock-up of the changes in the application should be created. The goal for creating these is to perform a user test. Especially the opening distance and influence of the colour should be tested on intuitiveness and disturbances caused in a room. Furthermore, this test should provide insight on issues caused by cleaning.

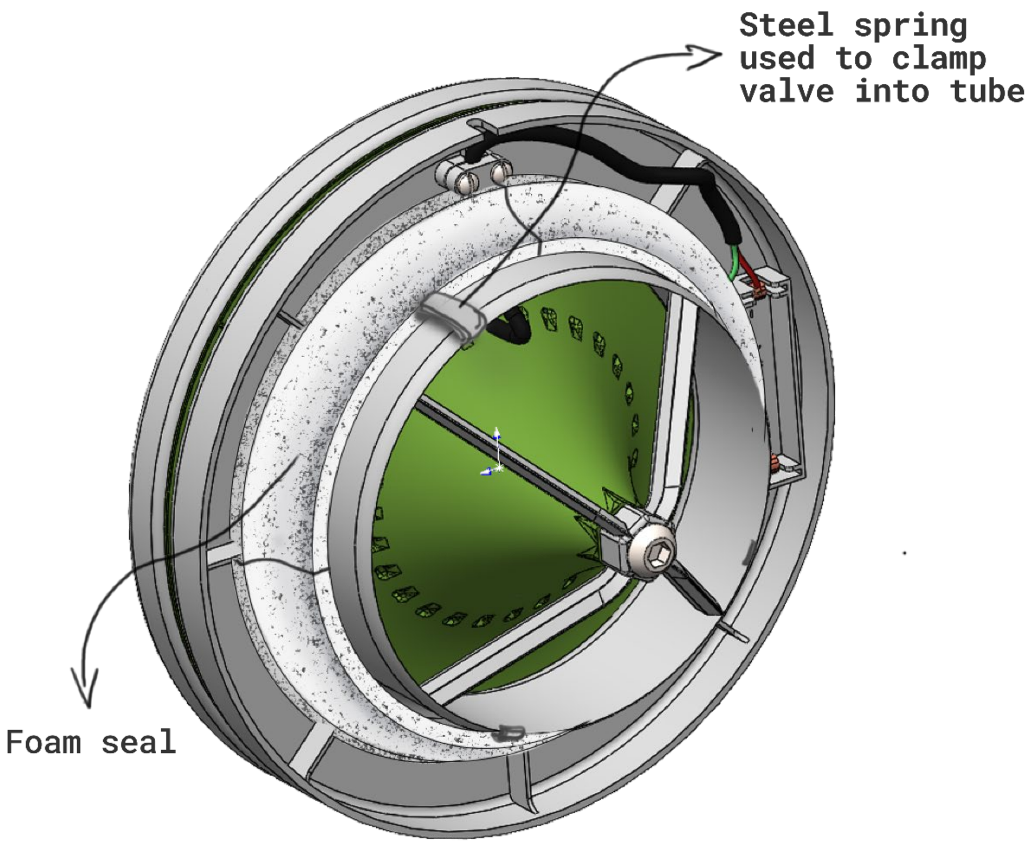


Figure 8.2: Sketch of proposed future changes for dynamic valve

Client advise

After working on this project for half a year, I believe that further exploring dynamic ventilation would be beneficial for Joule. Improvements in the BEN environment should continue to include both the BEN itself and the direct enhancement of air quality through surrounding products (e.g. more precise control).

The system could benefit from a global focus on simple communication. Users don't need to fully understand what is happening, but with subtle use cues, significant progress could be made to better inform the average user. This combined with clearly differentiating the system's form language and/or design from that of gas-powered systems, is where most of the market is currently lacking.

Focus on simple communication to users would enhance user understanding, making it easier for users to accept BEN's choices to help regulate their in-house climate. Thus making the BEN system more user-friendly, further distinguishing the BEN brand.

References

Asim, N., Badiei, M., Mohammad, M., Razali, H., Rajabi, A., Haw, L. C., & Ghazali, M. J. (2022). Sustainability of Heating, Ventilation and Air-Conditioning (HVAC) Systems in Buildings—An Overview. International Journal of Environmental Research and Public Health/International Journal of Environmental Research and Public Health, 19(2), 1016. https://doi.org/10.3390/ijerph19021016

Branco, P., Alvim-Ferraz, M., Martins, F., & Sousa, S. (2019). Quantifying indoor air quality determinants in urban and rural nursery and primary schools. Environmental Research, 176, 108534. https://doi.org/10.1016/j.envres.2019.108534

Carrer, P., Wargocki, P., De Oliveira Fernandes, E., Hänninen, O., Kephalopoulos, S., Allard, A., Asimakopoulos, D., Asimakopoulou, M.-N., Bischoff, W., Braubach, M., Brelik, N., reannan, D., Fanetti, A., Hartmann, T., Héroux, M.-E., Jantunen, M., Leal, V., Mustakov, T., Palkonnen, S., Popov, T., Rolland, C., Salari, M., Santamouris, M., Santos, H., Savli, R. and Seppänen, O. (2020). European Collaborative Action - Urban Air, Indoor Environment and Human Exposure, Report No 30, Framework for health-based ventilation guidelines in Europe, EUR 27640 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-79-54143-8, doi:10.2788/17476, JRC88207

CBS Statline. (2024). https://opendata.cbs.nl/#/CBS/nl/dataset/84948NED/table

Centraal Bureau voor de Statistiek. (2022, 2 oktober). Steeds meer warmtepompen bij woningen. Centraal Bureau Voor de Statistiek. https://www.cbs.nl/nl-nl/nieuws/2022/40/steeds-meer-warmtepompen-bij-woningen#:~:text=Van%20alle%201%2C3%20miljoen,met%20ongeveer%2050%20procent%20toegenomen.

Centraal Bureau voor de Statistiek. (2025). *Energieverbruik particuliere woningen; woningtype en regio's*. Centraal Bureau Voor De Statistiek. https://www.cbs.nl/nl-nl/cijfers/detail/81528NED

Clahsen, A. (2019, September 12). Energiezuinig huis verdient zich terug bij verkoop. Energeia. https://energeia.nl/fd-artikel/40084605/dnb-economen-energiezuinig-huis-verdient-zich-terug-bij-verkoop

column-het-belang-van-goede-inregeling. (2019, February 6). https://www.vakbladwarmtepompen.nl/4302/column-het-belang-van-goede-inregeling?login=true

Doornbos, G. J., Ter Steeg, R. T. M., Van Beek, M. G. M., & Van Gorp, M. D. (n.d.). ONTWERP van een WARMTEPOMP voor de NL MARKT: 2.3 GeertDoornbos_WPvoorNL situatie_Keuzesessie23_WPcongres9okt2019_4.pdf. Nederlands Warmtepomp Congress 2019, 's Hertogenbosch, Brabant, Netherlands.

Kamerpoort. (2023). Duurzame optiesBijlagen Kamperpoort. In Drive: Joule Technologies > General.

Ma, N., Aviv, D., Guo, H., & Braham, W. W. (2020). Measuring the right factors: A review of variables and models for thermal comfort and indoor air quality. Renewable and Sustainable Energy Reviews, 135, 110436. https://doi.org/10.1016/j.rser.2020.110436

Murena, F. (2004). Measuring air quality over large urban areas: development and application of an air pollution index at the urban area of Naples. Atmospheric Environment, 38(36), 6195–6202. https://doi.org/10.1016/j.atmosenv.2004.07.023

NEN. (2020). NEN-EN 1081:2018+A1:2020. In NEN (No. 1081). https://www.nen.nl/nen-en-1081-2018-a1-2020-en-276195

Reinders, U. (2020, 27 februari). Steeds meer belangstelling voor geluidsarme alternatieven. vakbladwarmtepompen.nl. https://www.vakbladwarmtepompen.nl/opinie/artikel/2020/02/steeds-meer-belangstelling-voor-geluidsarme-alternatieven-1015636

Rijksdienst voor Ondernemend Nederland. (2022). Monitor Verduurzaming Gebouwde Omgeving.

Rijksoverheid. (2024). Integrale Nota van Toelichting behorende bij Besluit Bouwwerken Leefomgeving - Artikelsgewijs. BRISbblonline. https://www.bblonline.nl/docs/wet/bbl-nvt/artikelsgewijs

RVO. (2022). Voorbeeldwoningen 2022: bestaande bouw (RVO-231-2022/BR-DUZA). Rijksdienst voor Ondernemend Nederland.

Steenbekkers, A., & Scholte, S. (2019). Onder de pannen zonder gas: Woningeigenaren en hun afwegingen voor aardgasvrije alternatieven (978 90 377 0920 9). Sociaal en Cultureel Planbureau. https://www.narcis.nl/publication/RecordID/oai%3Ascp.nl%3A8576e440-2baf-41b2-b8c6-78a24dd16a5b

Strick, M. (2016). Het promoten van energiebesparende producten: Onderzoek naar het effect van het inspelen op financiële motivatie versus duurzame motivatie op de mate van bereidheid tot aanschaf van energiebesparende producten. https://studenttheses.uu.nl/handle/20.500.12932/22586

Tunderman, S., De Kluizenaar, Y., Visser, D., De Bruyn, S., & Van de Poll, F. (2024). Bredewelvaartsanalyse van woningisolatie. Centraal Planbureau Planbureau voor de Leefomgeving Sociaal en Cultureel Planbureau.

Veltman, K. J. (2022, 27 juli). stakeholders [Presentatieslides; Drive: Joule Technologies > Innovation Management >Stakeholders (users)].

Ventilatieland. (z.d.). De grootste ventilatie webshop van Nederland - Ventilatieland. https://www.ventilatieland.nl/

Note on the use of AI

NotebookLM was used to help increase the literary study speed and find extra connections between articles. All articles where hand-picked before use and no results have been directly used.

ChatGPT was used to check and shorten parts of the text. All results have been checked for correctness, and adapted accordingly.