Automate user behavior to reduce energy demand and improve indoor air quality of residential buildings

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Abstract

In 2013, national agreements have been made to stimulate a healthy and sustainable growth of the Dutch society and economy. These agreements include that, on average, all buildings need a label A by 2030. However, the calculated energy savings for all energy labels do not correspond with the actual energy savings, which is partly due to user behavior. The occupants, not buildings, are the primary energy consumers because they behave proactively and to perform energy related tasks in order to seek comfortable personal conditions. The general aim of this research is to advance the knowledge base on ways of saving energy and increase indoor air quality by addressing user behavior characteristic with an automated building product. This study could offer alternative options for energy saving methods and thereby contribute to the current efforts in sustainable design research. By providing knowledge on thermal loss due to user behavior, occupants can implement such strategies to create more comfort while reducing their energy consumption.

This concept focuses on reducing the thermal loss due to the increase of the air change rate resulting from window operation. The additional energy consumption due to window operation during heating season can be significant, but is difficult to quantify. Ventilation and window opening characteristics become more important due to renovation trends favoring air tight buildings. These high performing and air tight buildings can lead to an indoor accumulation of air pollutants and high humidity's, which can cause multiple health symptoms. A combination of calculations, simulations and prototype testing is used to determine a way of automating window operations in an ideal way. The final prototype is installed in the PDlab where it was used for testing its cooling and air cleaning potentials.

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01

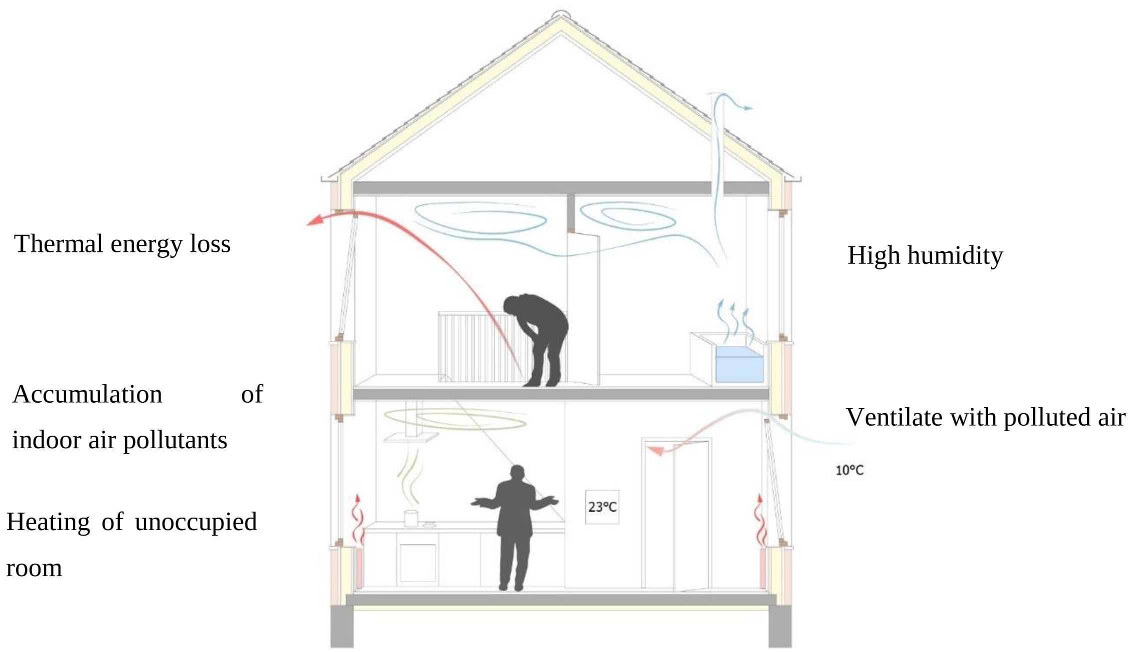
INTRODUCTION

This research framework helps to identify the objectives and focus of the research effort.

1.1 Introduction

Buildings are responsible for approximately 40% of the total energy consumption and 36% of the CO_2 emissions in the EU. About 35% of the EU's buildings are over 50 years old, where 75% of the building stock is declared energy inefficient. Only 0,4 to 1,2% of the building stock is renovated each year. Increasing this renovation rate of existing building has the potential to lead to significant energy savings (European Commission, 2018). In 2013, national agreements have been made to stimulate a healthy and sustainable growth of the Dutch society and economy. Agreements have been made that, on average, all buildings need a label A by 2030 (Sociaal-Economische Raad, 2013). However, the calculated energy savings for all energy labels do not correspond with the actual energy savings. An energy label A building should save around 81% energy on gas, compared to an energy label G building, but is only an average of 38% in practice. Calculating the energy saving potential of a building is difficulty due to unknown U-values, air infiltration and user behavioral characteristics. Behavioral characteristics includes the usage of appliances, thermostat and airing the house (Majcen & Itard, 2014).

Airing the house becomes more important for air tight buildings. High performing buildings can lead to accumulation of indoor air pollutants and high humidity's, which can lead to many different health symptoms. On average, we spent 87% of our times indoor (Milner, et al., 2017). Opening a window and ventilating at a regular basis could create a healthier indoor environment. The opening of windows can cause a significant additional heat loss in air tight and higher performing houses. In normal usage, the opening of windows increases the heat loss coefficient for a building that meets the minimum requirements for the Dutch building codes, by 5 to 10%. This will increase to 35% for intensive usage of the windows (Jack, Loveday, Allinson, & Lomas, 2015). A lot of research has been done on the effect of operable parts on indoor comfort and quality. Francesca Stazi, professor Building science and Technology at Università Politecnica delle Marche, developed an automatic system for window openings, based on thermal comfort and indoor air quality for classrooms. Indoor air quality is a relevant issue in school classrooms, because students usually suffer from high CO_2 levels. The main target in school classrooms is preserving students attention, efficiency and health while attending the lessons. From an indoor climate perspective, this can be translated into reaching and maintaining a satisfactory perception in terms of air temperature and indoor air quality. Theofanis Psomas, research assistant at the Aalborg University in Copenhagen, has done research on the automation of window openings to diminish the thermal discomfort and overheating risk of a dwelling during cooling periods in temperate climates. No research has yet been done in how automated windows could assist an occupant to saving energy in a sustainable and acceptable way.



The general aim of this research is to advance the knowledge on ways of saving energy and increase indoor air quality by addressing user behavior. This study offers alternative options for energy saving methods and thereby contribute to the current efforts in sustainable design research. By providing knowledge of thermal energy loss due to user behavior, occupants can implement such strategies to optimize their own building on heat loss and indoor air quality.

The objective is to identify what behavior and situations influence the indoor air quality and heating demand. This will identify which parameters should be enhanced in order to reduce the overall energy consumption and improve the indoor air quality. A system will be designed that will assist the occupant in adjusting the chosen parameters in order to create a safe and comfortable indoor climate. A typical Dutch rowhouse, a “doorzonwoning”, at the Ramplaankwartier in Haarlem will be used as a case study to determine the potentials of the proposed system and to form criteria for the final product. The final product will be a mechanism that functions as the proof of concept, a strategy that will determine the actions that the mechanism should perform based on measured parameters and a set of boundary conditions. The result could be used to start a new building product line up for companies that want to offer a feasible renovation strategy of residential buildings.

1.2 Approach and methodology

Common sustainable interventions for buildings addresses the building envelope or installing sustainable installations. The final energy savings do not match the initial calculated energy saving potentials and indoor climate could be uncomfortable or unsafe, which could lead to frustration by the occupant and therefor misuse of the building. This vicious circle could discourage current building owners to improve their real-estate, which slows down the ambition to make the current buildings more sustainable. Therefore, the aim of this study was to answer the following question:

In which way can a new system effectively assist users to reduce the energy demand for heating and cooling of a residential building, while creating a safer and more comfortable indoor air quality?

The research project will be based on a top-down approach, called system engineering approach, whereby the design will play a central role in order to gain new knowledge and create criteria for the final product. This will have the following steps:

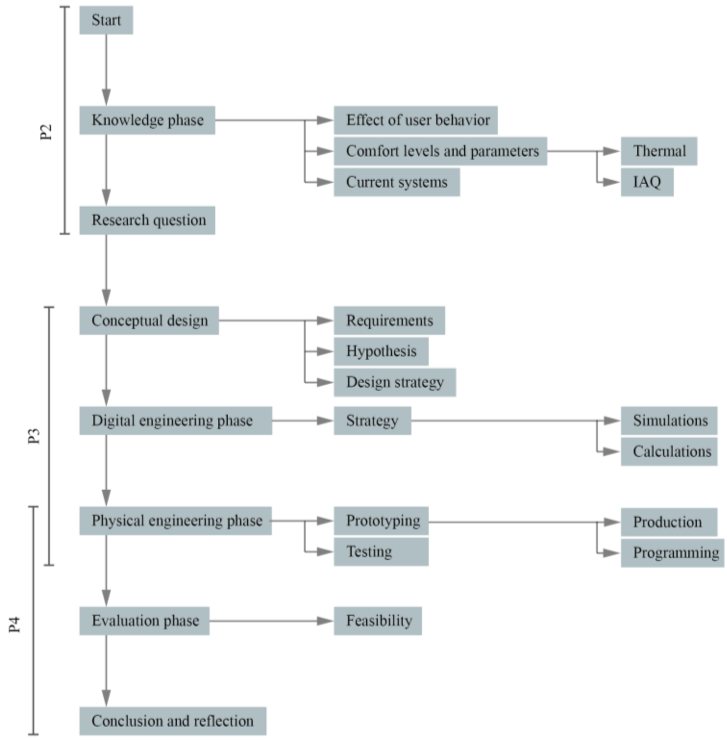
Step 1: system requirements (the demands and wishes)
Step 2: conceptual design (technical requirements)
Step 3: preliminary system design (experimenting with the technical requirements)
Step 4: detail system design and development (detailed drawings and prototyping)
Step 5: production and construction phase
Step 6: operational use and system support phase (systems operation, modifications and maintenance)
Step 7: system retirement and disposal
(Bluyssen, 2009)

These steps are not consecutively performed during the research, but are used as a guideline to ensure that all stakeholders are included with their wishes and demands. During the design phase, a bottom up approach will be used in order to create various iterations and create a data driven solution. Step 1 is considered as the knowledge phase, which will be initiated through an literature study on the current knowledge on heating loss due to window opening behavior and indoor comfort or safety. Different parameters will be determined in order to create indoor comfort and safety. Step 2 is the conceptual design phase, where the technical requirements are determined. These requirements are determined from the research that has been done during step 1 and research through design. Step 3 is the digital engineering phase. Calculations and simulations will be done with the technical requirements in order to determine an efficient strategy that will reduce the energy demand for heating and cooling by operating user operable elements, while improving the IAQ. A residential building in the Ramplaankwartier will be used for these calculations and simulations. Design Builder will be used in order to determine theoretical energy demand of a residential building in the Ramplaankwartier. Uniec is a EPG, Energie Prestatie Gebouw, software tool that is used to calculate energy labels and the energy performance coefficient of buildings. This theoretical energy demand will be compared with the actual energy demand in order to see the influence of user behavior characteristics. Simulations and calculations will be done to verify the results and create an optimal ventilation design for a residential home, located in the Ramplaankwartier. The software that will be used for the simulations will later be determent. The results of the simulations will be transferred into products and drawings. Step 4 is the physical engineering phase, where a prototype be created. This prototype will be function as a design tool, where multiple iterations will end up with a proof of concept. The final prototype will installed in the PDlab, which will be open for people to use. The test that will be conducted in the PDlab is based on the methodology from precedent research done by Francesca Stazi.

1. Data collection in one free-running room
2. Data analysis and testing comfort models
3. Automatic system development
4. Parallel monitoring in both the classrooms and data analysis

(Francesca, Naspi, Ulpiani, & Di Perna, 2017)

This research will only analyses if the system can create comfort and react according to parameters via an the algorithm. A survey will be used to gather information on the comfort levels of the users. Temperature and IAQ will be adjusted during the test in order to create a system that creates comfort while having energy saving potentials. Step 5 and 6 will consider during all steps, which will be investigated during evaluation phase. This phase includes analyzing the ease of installation, production of the proposed product, if modification is possible, how well it can be maintained and how the system can be retired. Step 7 will be replaced with an feasibility analyses, which is part of the main objective in creating this alternative renovation concept. The product should be very feasible, which means a low initial investment, low maintenance and low user inconvenience. After this phase, a conclusion and reflection will be made on the proposed design. The design will be further improved if necessary.



1.3 Focus and restrictions

The influence of user behavior on the heating demand and air quality will be restricted to the effect of operable windows. These parts of the building can be operated by a user and have a high influence on the heating demand and air quality. A system will be designed that assists an occupant in creating a *safe* and *comfortable* indoor climate by performing an *effective action*. This research will only look at the indoor air quality to determine a *safe* and *comfortable* indoor climate. An *effective action* is an action that influences or assist the behavior of the occupant sustainable and reliable, which creates the best outcome in the long run. This action may differ per occupant or level of *safety* and *comfort*.

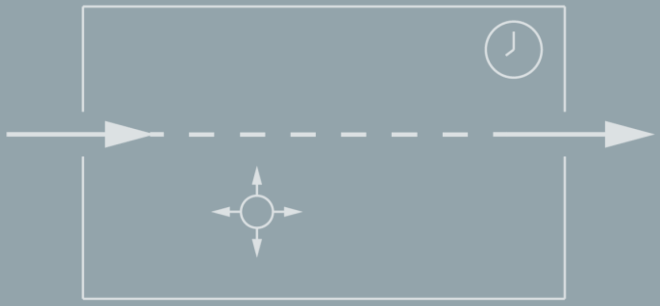
The removal of these operable openings will not be investigated due to Dutch building codes oblige temporarily high air flow for air pollutants removal purposes (Rijksoverheid, 2018). For dwellings, this is almost always done with operable windows, because it doesn't require additional ventilation systems. Also, occupants feel more comfortable when they have control over the ventilation system and windows give a familiar system of ventilation. Therefore, most developers create buildings with operable openings, otherwise it can hinder the salability.

No simulation or algorithm will be created that reflects user behavior. This research focusses on the creation of a new renovation concept that can assist users to behave more sustainable, not predict user behavior. A concept for a building product will be developed that fits the current building stock, but especially the dwelling that will be renovated in the future. A standard Dutch residential building at the Ramplaankwartier in Haarlem will be used for the calculations and simulations. The majority of the houses in the Ramplaankwartier were built between 1920 and 1970, around a third of the current housing stock is built in this period (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2016). These buildings have a high level of gas consumption, due to the low amount of energy awareness during this time. These building types undergo intensive renovations in order to make them meet the new set goals and requirements. The people that live in these buildings experience a change in their homes from a poor performing building to a building with a high insulation value with sophisticated installation. Occupants with old unsustainable habits should be assisted in their new high performing building in order to meet the calculated energy demands.

02

Literature

Window opening is a commonly used method for controlling temperature in dwellings, but is also often used to control other conditions such as humidity, air quality and odors. During the winter heating season, this window operation can cause an increase in heat loss, which will depend upon the duration and extent of opening (Akerkar, Andersson, & Castra, 2015). This chapter will investigate design strategies, the energy impact of user behavior and how indoor comfort can be obtained.



2.1 Design strategy

Design strategy refers to an integrated planning process that examines the relationships between the design approach for user assistance.

2.1.1 Design approach

A traditional focusses on defining threshold values for indoor environmental parameters is called a bottom-up approach. The sources and other influencing factors are identified, with corresponding effects, and thresholds are determined for recognized dangerous substances. These thresholds form the point of action in order to satisfy the end-user. The most dominant stakeholder determines the results, which can result in discomfort by the end-user. In order to establish the wishes and demands of the end user and the communication process required to facilitate the design, production and maintenance, a top-down approach is required. The needs and wishes of an end user have to be understood, both for now and in the future. The context should be understood, including the responsibility and involvement of each stakeholder in the creation of a comfortable indoor environment. This requires communication through all stakeholder, also to understand the full spectrum of the indoor environment, building, outdoor environment, interaction, users etc. This research will combine the top down approach, in order to create a clear understanding of the context, and the bottom up approach, in order to determine an optimal and data drive solution. The research will be based on a top down approach with the following steps:

Step 1: system requirements (the demands and wishes)
Step 2: conceptual design (technical requirements)
Step 3: preliminary system design (experimenting with the technical requirements)
Step 4: detail system design and development (detailed drawings and prototyping)
Step 5: production and construction phase
Step 6: operational use and system support phase (systems operation, modifications and maintenance)
Step 7: feasibility (Bluyssen, 2009)

During the design phase, a bottom up approach will be used in order to create various iterations and create a data driven solution (Figure 2-1).

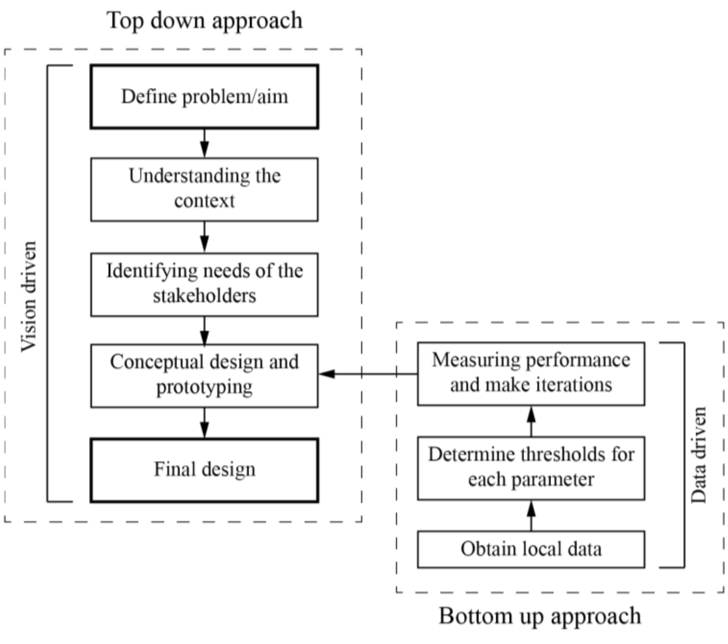


Figure 2-1 Design approach

2.1.2 User assisting strategy

For many products, the `in-use” phase produces for the greatest environmental impact and there are many examples of how the impact can be reduced through ingenious design (Bluyssen, 2009). Nevertheless, the focus has been directed at matters beyond the user’s control, for instance home improvements with insulation, energy efficient appliances and heat pumps. To further reduce the impact of the “in-use” phase lies within the user’s control. The effectiveness of a product lies mostly in the interaction with the product. Therefore, the aim of this chapter is to identify and categorize promising design strategies for sustainable behavior.

K. Lidman and S. Reström, PhD students of the Division of Design & Human Factors of Chalmers University of Technology, investigated and assessed five different strategies on long-term acceptability and effectiveness to induce sustainable behavior, four are focused on behavior adaptation and one is focused on product adaptation (Lidman & Restrom, 2011). These five strategies are:

- Enlighten, behavior adaptation
- Spur, behavior adaptation
- Steer, behavior adaptation
- Force, behavior adaptation
- Match, product adaptation

The purpose of enlighten is to induce sustainable behavior by informing the user, either through information or by reflection. This is mostly done by giving the user a positive attitude towards performing the desired behavior or by informing the behavior of others in order to form a positive subjective norm an attitude. This design strategy has a fair acceptability and effectiveness, but users can lose interest verily quickly.

Figure 2-2 enlighten (Eragon, n.d.)

The purpose of spur is to motivate the user to use a product in a sustainable way. This can be done in the form of rewards and social incentives. The effectiveness and acceptability of this design strategy are weak.

Figure 2-3 spur (Alifrio, n.d.)

The main principle in steer is to guide a user toward the desired behavior. The undesired behavior can be constrained through making it physically or cognitively challenging and the desired behavior can be encouraged through making it easy to perform. This design strategy has a good acceptability and effectiveness, but it creates a low level of awareness.

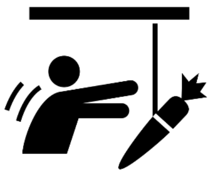


Figure 2-4 steer (Prado, n.d.)

The principle of force is to compel the desired behavior upon the user, through limited functionality or restrictions, which could result in undesired behavior. The difficulty lies in developing products in such a way that the users accepts the hindrance or limitations that are design in the product that prevents undesired behavior. The effectiveness and acceptability of this design strategy are good.

Figure 2-5 force (BomSymbols, n.d.)

The purpose of match is to facilitate sustainable behavior that the users already want to perform but consider themselves unable of doing. The effectiveness of this design strategy is unpaired, but the acceptability depends on the interaction with the product. The product will be accepted if the system adepts to the needs of the user (Lidman & Restrom, 2011).

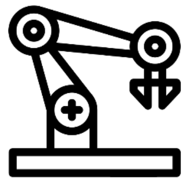


Figure 2-6 match (Corredor, n.d.)

Two main questions can be asked when designing a product for sustainable assistance, according to Lidman and Restrom;
How can barriers towards sustainable behavior be identified most accurately? And
How should design strategies be chosen to successfully overcome barriers towards a sustainable behavior?

In order to answer the first question, there is not a clear consensus of what an acceptable level of intervention for behavioral adaption is, or how multiple interventions result in different behaviors, according to D. Lilley, senior lecturer at the Loughborough University. The 'consequences of use' differs from one product to another, therefore, to enable designers to identify and rate product specific impacts they should observe how people use and misuse existing products (Lilley, 2009). A comparable product that an occupant uses in order to create their indoor conditions will be used as a case study to investigate the effectiveness of a user assisting product for a residential building. This product is a the smart thermostat.

A smart thermostat provides knowledge on energy usage, the indoor temperatures and much more, while heating and cooling the building. These current energy related information can be monitored on a display, in order to inform the user about its energy usage. Thermal adjustments in the building can be done via programmable schedule or an application on a smartphone. Smart thermostats can also suggest maintenance to HVAC systems, warning users when air filters need to be replaced. So the smart thermostat has three key features that should encourage sustainable behavior, it has a programmable schedule, it has sensors that monitor parameters and it has internet connectivity.

Programmable schedule - Steer and match

Research has been done on the energy saving potential and usability of a programmable thermostats. The energy saving potentials of programmable schedules look promising, but have to be set correctly by the user. Lopes and Agnew discovered that participants with a programmable schedule increased their energy consumption for thermal comfort by around 12%. This was contradicting to the what the participants expected and wanted from this product. Around 5% of the participants had to drop out during testing due to misunderstood functionalities (Lopes & Agnew, 2010).

Sensor and monitoring - Enlighten and spur

A smart thermostat provides advanced and detailed information on energy consumption, which is controllable by the users from a the thermostat, PC, smartphone or tablet. Some really advanced smart thermostat can connect to sensors that monitor and control humidity and volatile organic compounds. The main disadvantage of systems with advanced metering and automation is cost. Consumers have to invest in additional sensors, energy displays or software to achieve near real-time feedback. Energy saving potentials are high, but demonstration projects have not been conducted to provide a scientific basis for these claims. This system only saves energy if the user is an active participant within this system. The real effectiveness of this system is unclear and mixed (McCoy, 2012).

Internet connectivity - Enlighten, spur and match

A smart thermostat can be connected to the internet, making it possible to compare energy related data with other smart thermostat users. This enlightens and spurs a user to behave sustainable due to social incentives. Internet connectivity creates the possibility to operate the thermostat from a distance, making it possible to climatize the building while not at home, which increases the energy demand.

The three features of a smart thermostat have advantages and disadvantages. In order to answer the last question, made by Lidman and Restrom, the main barriers towards a sustainable behavior for the smart thermostat is the user participation and input that is necessary for this product to work successfully. After research, this product is more like a gadget than a tool in order to create a more sustainable environment. A smart system should not rely on the input from a user, but should perform desired actions by itself. Therefore, product adaptation should be used as a user assisting strategy for the proposed design, which is described as ‘match’ (Lidman & Restrom, 2011).

2.2 Influence of user behavior

Buildings in the Netherlands lose thermal energy during heating season due to ventilation. But some form of ventilation in a building is essential, to remove moisture and provide fresh air for the occupants. This energy loss due to ventilation can be calculated with the given formula;

$$Q_{vent} = \frac{\rho\ c\ V\ \boldsymbol{n}\ \Delta T}{3600} \tag{1}$$

Q_{vent} = energy loss (W)
ρ = density of air (kg/m^3)
c = specific heat (J/kg K)
V = volume (m^3)
n = air change rate (ACH)
ΔT = temperature difference (°C)

Window opening behavior can have an impact on the air change rate of a building, thus influencing the energy loss due to ventilation. Most homes are required to have operable windows in most rooms of the house and have the potential to provide the ventilation necessary to meet current codes.

Elham Delzendeh, Song Wu, Angela Lee and Ying Zhou, researchers at the Innovative Design Lab Research Centre, have done an extensive review on multiple reports on the effect on energy usage due to user behavior on residential buildings, offices, commercial buildings, educational and other types of buildings. They determined different parameters that influence occupancy energy behavior and their respective probability, which are mostly climate and psychological related (Figure 2-7).

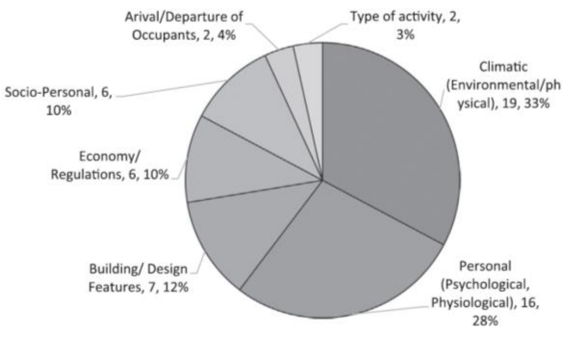


Figure 2-7 Influential parameters on occupants energy behavior (Delzendeh, Wu, Lee, & Zhou, 2017)

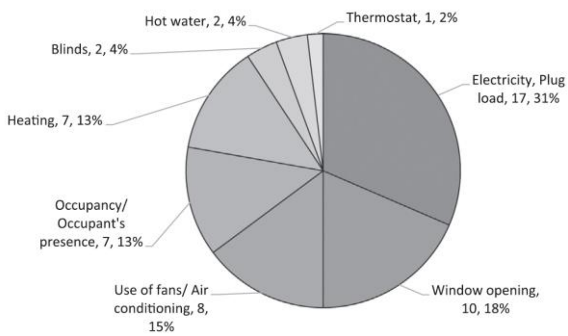


Figure 2-8 Different types of occupants interactions (Delzendeh, Wu, Lee, & Zhou, 2017)

The most performed activity that is performed by the user that influence energy demand is electricity and wall plug related, around 17 to 33% (Figure 2-8). Window opening is the second most performed activity, with 10 to 18%. Activities, that influence energy demand, related to cooling a building is performed 8 to 15% of the time that an activity is performed (Delzendeh, Wu, Lee, & Zhou, 2017). These results originate from multiple researches, done in different climates. Making them not directly applicable for the Dutch oceanic climate.

Several studies on window opening behavior and ventilation are reviewed by Liddament, researcher at the University of Warwick, where he discovered that windows were most likely to be opened under the following conditions: sunny days, higher occupant density, higher outdoor temperature, low wind speed, during cleaning or cooking activities and when smoking. However, there are also many circumstances when opening a window is not practical such as noise, rain, high wind speeds, outdoor pollutants, cold drafts, privacy, security and safety issues, energy loss or when a window may be difficult to operate. Which suggest that window operation is not always in response to ventilation needs (Liddament, 2001).

Window opening behavior is hard to simulated, because user actions are reactions on different parameters. Multiple attempts are made in order to simulate the effect on user behavior on energy demand. Stochastic and probabilistic models are made that calculate the probability that a window is opened or closed in different situations. These models do not have a fixed air change rate, but a variable indoor and outdoor parameter that drives the probability of opening windows. This results in variations in ventilation losses between deterministic and probabilistic scenarios. This deviation varies per climate, but the influence of user behavior has a negative effect on the energy demand compared to the controlled system in every type of climate. In warm climates, energy demand can go up to 61% higher than the controlled system. In colder climates, this deviations is 13% to 35% higher than the controlled systems (D'Oca, Corgnati, Fabi, & Andersen, 2014). Some models show that during winter, the energy demand in warm climates can increase by 196%, and in summer decreased by 5%. In subtropical continental climates, this energy demand during winter is increased by 61% and during summer decreased by 14%. Users in warmer climates tend to open the windows more frequently than people in colder climates, which has an effect on the energy demand (Moghadam, Soncini, Fabi, & Corgnati, 2015).

The effect of window opening on the measured heat loss of a single detached house is quantified by the department of Civil and Building engineering at Leeds Beckett University in Loughborough. The paper uses an experimental approach with different kinds of window opening behaviors. The heat loss of the house is measured by co-heating tests, which provides insight into the relative effect that window opening. Co-heating is a widely used method to measure the thermal performance of a dwelling. It involves measuring the energy required to heat the interior of a house to a constant temperature, typically 25 degrees, for an extended period, typically around two weeks.

The test house is a small, timber framed, detached building, with a total floor area of $60m^2$ and an envelope surface area of $166m^2$ (Figure 2-9). It has insulated cavity walls and loft insulation, the Rc-value is unknown. The infiltration of the building is measured at $15m^3/h/m^2$, which is higher than the $10m^3/hm^2$ limit required for new dwellings with the current building regulations in the United Kingdom. The total Heat Loss Coefficient (HLC) for this residential building is in theory 180W/K, but is in practice around 170W/K.

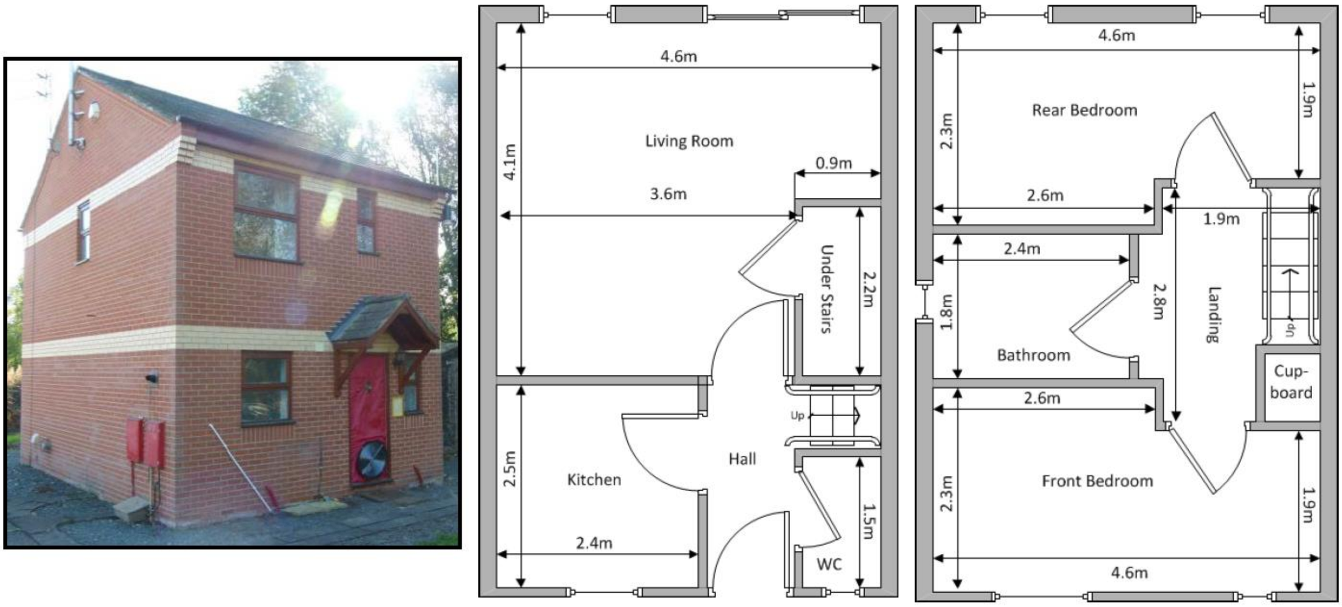


Figure 2-9 test house (Jack, Loveday, Allinson, & Lomas, 2015)

A linear relationship between the additional infiltration and the openings can be measured of 3,8 air changes per hour for each additional square meter of open area. The increase in air infiltration has been used to create Figure 2-10, which shows the additional heat loss that a variety of window opening positions could cause. A window opening of 0,92m^2 for 24 hours would double the heat loss coefficient of this building. This behavior was deemed unrealistic, a more likely scenario was calculated with the following behavior:

- kitchen window is opened between 18:30-18:45 (during cooking)
- bathroom window is opened between 7:30-8:00 (during washing)
- windows are opened in both bedrooms between 8:00-8:15 (after sleeping)

An additional heat loss in this scenario is 4.1W/K, which is 2,4% of the total heat loss coefficient of the building (Figure 2-10). Unfortunately, no user error or ignorance was added to the simulated 'user behavior', making this strict schedule of window operations unrealistic.

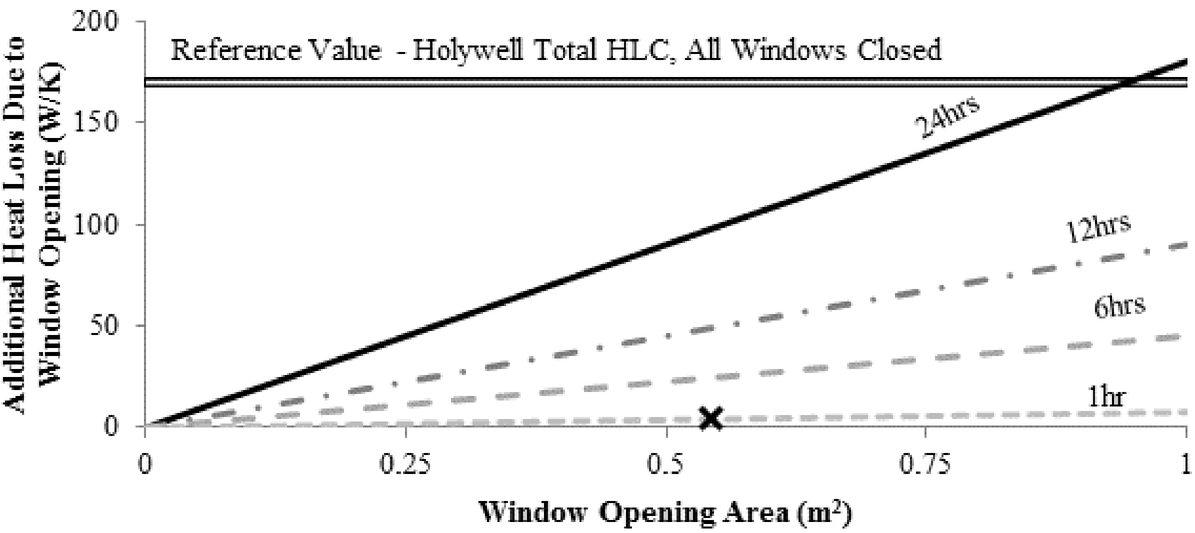


Figure 2-10 heat loss due to window opening (Jack, Loveday, Allinson, & Lomas, 2015)

The different window opening scenario show the potentials and the effect of window opening behavior. The relative impact of window opening will depend on window opening behavior and the performance of the building. For buildings with a lower HLC, high performance building, the same window opening behavior will be more significant in comparison to a building with a higher HLC (Jack, Loveday, Allinson, & Lomas, 2015). This is verified by calculations and simulation (Appendix A).

2.3 Comfort

The occupants, not buildings, are the primary energy consumers because they behave proactively and to perform energy related tasks in order to seek comfortable personal conditions (Hong, Yan, D'Oca, & Chen, 2016). There are four enviceronmental factors in the indoor environment that influence the perception and effect of the physical and mental state of an occupant. These four factors are;

- thermal comfort
- visual or lighting quality
- air quality
- acoustical quality

(Bluyssen, 2009)

Thermal comfort and air quality effect the heating demand due to window opening behavior. Visual or lighting quality and acoustical quality can also affect the heating demand due to window opening behavior, but are smaller and only occur in limited conditions. Therefore, only the thermal comfort and air quality for comfort will be investigated for this research. Dutch building codes form the threshold for the visual or lighting quality and acoustical quality.

2.3.1 Thermal comfort

Opening and closing windows can contribute to thermal comfort, as shown in equation 1 in chapter 2.2. There are two main methods to asses and predict thermal comfort; the predicted mean vote method, which calculated local thermal comfort, and the adaptive thermal comfort algorithm. It seems that it is easier to create thermal comfort in a natural ventilated building. Field experiments have proven that occupants in naturally ventilated buildings accept a higher bandwidth of temperature than those predicted by the PMV (NEN-EN_ISO 7730, 2005).

2.3.1.1 Predicted mean vote

The parameters that influence or determine indoor thermal comfort of an occupant can be described according to:

- air temperature and radiance
- air velocity and turbulence
- occupant metabolism and clothing
- relative humidity

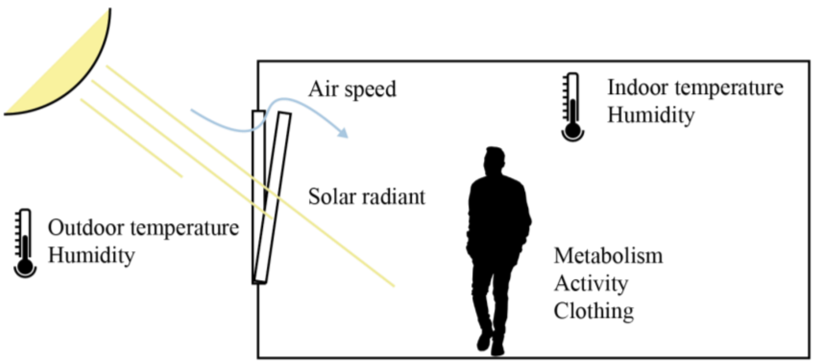


Figure 2-11 thermal comfort parameters (own illustration)

In order to determine the thermal state of a body, both in terms of comfort and heat or cold stress, it is important to evaluate the thermal balance of the human body. The thermal energy balance of a person can be defined as; Heat production = heat dissipation. Heat production is the metabolic rate of a human body and heat dissipation is the heat transfer via conduction, convection and radiation from the clothed body. Also heat loss from sweat evaporation and respiration can be taken into account. To provide comfort, the main skin temperature has to be within certain limits. That limit is subjective, and differs per person, activity and many more factors. The international standards presents methods for predicting the general thermal sensation and degree of discomfort of people with a predicted mean vote (PMV) index. This index predict the mean value of the votes of a large group of persons on a 7 point thermal sensation scale, which is based on the heat balance of the human body (heat production = heat dissipation).

The PMV may be calculated for different combinations of metabolic rate, clothing insulation, air temperature, mean radiant temperate, air velocity and air humidity. The metabolic rate can be estimated with ISO 8996 and thermal resistance of clothing and chair can be estimated using ISO 9920. Other parameters can be measured using sensors or should be entered manually. Thermal sensation varies per individual, so it is useful to be able to predict the number of people likely to feel uncomfortably hot or cold. This is called the “predicted percentage dissatisfied” (PPD). This index establishes a quantitative prediction of the percentage of thermally dissatisfied people that feel too cold or warm. The international Standard have given this thermally dissatisfied a 7-point thermal sensation scale.

This system will not be used in order to determine thermal comfort, due to the many inputs that are necessary from the occupant. As discussed in chapter 2.2, a smart system should not rely on the input from a user, but should performance desired actions by itself.

2.3.1.2 Adaptive thermal comfort

The outside air temperature influences our behavioral adaptations to the indoor thermal environment, according to the adaptive thermal comfort algorithm. The comfortable air temperature can be calculated with the follow formula;

$$Tc = 0{,}255 \times Tout + 18{,}9 \qquad (2)$$

Tc	=	comfort temperature (°C)
Tout	=	running mean outdoor temperature (°C)

This equation was determined using a database with field studies on 21,000 sets of raw data compiled of field studies in 160 buildings on four continents in varied climatic zones (de Dear & Brager, 2002). A range of temperatures around Tcomf correspond to 80 or 90 percent of thermal acceptance (Figure 2-12). This algorithm can be used under the following circumstances:

- Naturally conditioned buildings, in which thermal comfort is regulated by operable façade openings.
- Spaces can have a heating, but can’t be in operation
- No mechanical cooling
- Spaces can have a mechanical ventilation with unconditioned air
- Outdoor temperature range of 10 - 33°C

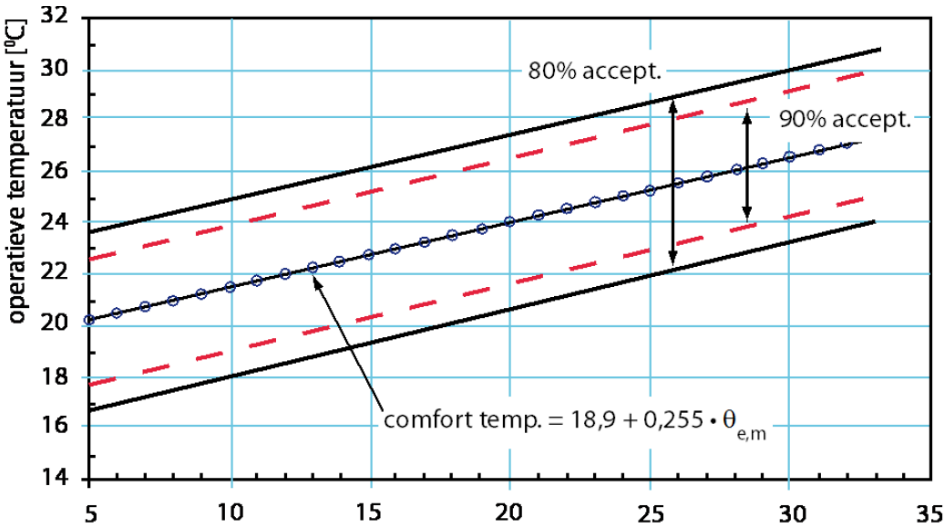


Figure 2-12. Proposed adaptive comfort standard (NEN-EN 15251, 2007).

This doesn't mean that this algorithm is the best solution from an energy point of view. Occupants that have control over the indoor climate with natural ventilation prefer a wider range of conditions, that reflect outdoor climate patterns. The indoor environment changes due to this algorithm, which prevents a too homogeneous environment, that will lead to discomfort (Vroon, 1990).

Heat discomfort can also depend on the humidity, which can vary due to relative humidity of the air. Humidity of the air is effected by evaporation of water molecules into the air as a result of a temperature change or vapor pressure. This relative humidity can be used to increase or decrease the temperature of the indoor air (Bluyssen, 2009). The amount of water varies from zero, which is called dry air, to a maximum, which is called saturation. Dry-bulb temperature is the temperature measured while shielded from radiation and moisture. This 'apparent' temperature is measured by most thermometers, but doesn't represent the temperature that an occupant experiences. In shaded areas, an heat index, which is a combination of dry-bulb temperature and relative humidity, could be used to posit a human-perceived equivalent temperature. This index is calculated with an algorithm and is used in many environmental health studies (Anderson, Bell, & Peng, 2013). The heat index(HIC) can be determined with the following formula:

$$HIC = T - 0.55 \times (1 - 0.001H)(T - 14.5) \tag{3}$$

T	=	temperature (Celsius)
H	=	humidity (%)

The wet-bulb temperature is the temperature read by a thermometer that is covered in a water-soaked cloth over which air is passed. Relative humidity is the ration between the vapor partial pressure in the air and the saturation point of the dry bulb temperature (Engineering Toolbox, 2019). In summer, evaporative cooling can be used to decrease the dry-bulb temperature by increasing the humidity to the saturation point. The psychometric chart can be used to characterize an air-water vapor mixture (Figure 2-13).

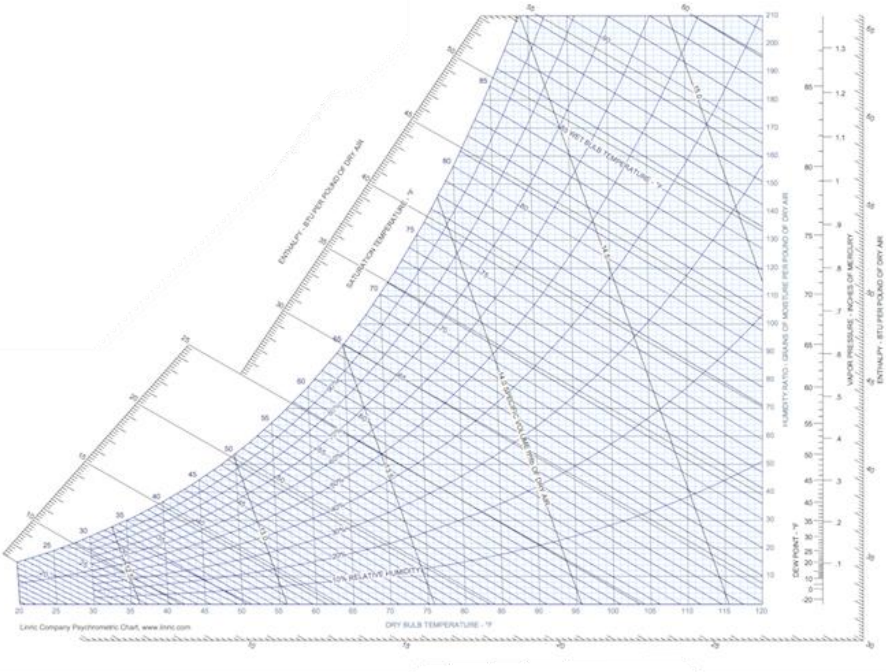


Figure 2-13 psychrometric chart (The Engineering Toolbox, n.d.)

2.3.2 Indoor air comfort

Hazardous substances emitted from indoor and outdoor sources, such as cooking or heating, lead to discomfort, a range of health problems and can even be fatal. National Emission Ceilings Directive sets emission limits for man-made emissions, that are harmful for human health and the environment. Internationally, the issue of air pollution is also addressed by the UNECE Convention on Long-range Transboundary Air Pollution. Due to these legislations, emissions have been decreased over the years. Due to the complex link between emissions and air quality, emission reductions do not always produce a corresponding drop in atmospheric concentrations. This is especially for NO2, PM^{2}.5, PM_{10} and O3, whose concentration levels depend on year by year variations in weather conditions including sunlight, natural emissions or very local emissions (European Environment Agency, 2014). Therefore, air quality measurements only determine the pollutants level in the air in that location. Location specific measures are presented in the NSL, Nationaal Samenwerkingsprogramma Lucht (Rijsoverheid, 2009).

Understanding of the hazards of these substances is the first step in identifying the actions necessary to avoid and reduce the adverse impacts of these pollutants on comfort and health. Air quality is not only important for the health of the occupant, but also the durability of the building (World Health Organization, 2010; World Health Organization, 2009). The exposure of an individual to pollutants present in a space determines the air quality. This exposure can be defined as the concentration of the pollutants in µg/m^3. The parameters influencing the indoor air quality are;

- the production of the pollutants in the space
- the concentration of pollutants in the ventilation air
- the air exchange rate of the space
- time
- volume of the room

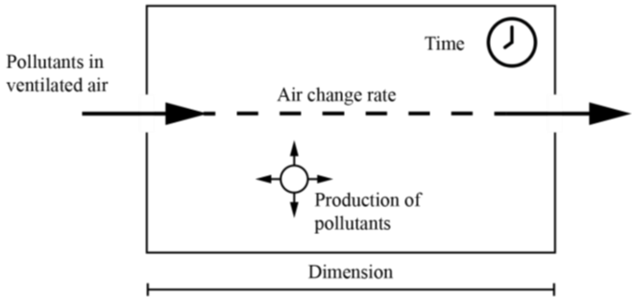


Figure 2-14 pollutants diagram

An occupant can influence various parameters, such as the production of the pollutants in space, by their activity, and air exchange rate of the space, by opening and closing windows. Those parameters will be investigated in this chapter.

2.3.2.1 Indoor pollutants

Occupant-related activities and buildings materials cause most of the production of indoor air pollutants. Occupant-related activities include tobacco smoking, cleaning, cooking and laser printing. Building materials include insulation, plywood, paint, particle board and floor/wall coverings. The production rate of air pollutants varies from activity and building material and is therefore difficult to predict. Pollutants in the incoming air can originate from outdoor sources and ventilation system components. Sources include traffic or industry related activities and components, such as filters, ducts and humidifiers. Both new and old air filters emit volatile organic compounds, due to the used materials. Oil residuals in air ducts, used during the manufacturing process, are the dominant source of growth of microorganisms and dust/debris accumulation (World Health Organization, 2009).

The main groups of pollutants, found in indoor air, are chemical and biological pollutants. Gases and vapors (inorganic and organic) are distinguished among the chemical group. The biological group consists out of dust particles that originate from bacteria, viruses, moulds, insects, bird, pollen and animals. Most of these gases and vapors can’t be smelled at a unsafe dosage(Table 2-1).

Fume	Source	Odor detection level	Safe doses	
Benzene	Fuel	300 mg/m^3	0,17 μg/m^3	
Carbon monoxide	Incomplete combustion	No detection	100 mg/m^3	1/4h
			35 mg/m^3	1h
			10 mg/m^3	8h
			7 mg/m^3	24h
Carbon dioxide	Burning fossil fuel	70200 mg/m^3	2250 mg/m^3	
Formaldehyde	Building materials	1,47 mg/m^3	0,1 mg/m^3	1/2h
Naphthalene	Mothballs	0,44 mg/m^3	0,01 mg/m^3	Avg.
Nitrogen dioxide (NOx)	Combustion of fossil fuel	2 mg/m^3	200 μg/m^3	1h
			40 μg/m^3	Avg.
Ozon			40 μg/m^3	Avg.
Polycyclic aromatic hydrocarbons	Incomplete combustion	Unknown	0,012 mg/m^3	
Radon	Radioactive matter	No detection	0,000006 Bq/m^3	
Trichloroethylene	Solvent for organic matter	1,134 mg/m^3	2,3 μg/m^3	
Tetrachloroethylene	Solvent for organic matter	5,2 mg/m^3	0,25 mg/m^3	Avg.

Table 2-1. Hazardous gasses odor detection level (American Industrial Hygiene Association, 2013) and safe doses (World Health Organization, 2010).

Particulate matter (PM) is a collective name for all small solid and fluid particles in the air that can be breathed in by a human. These particles originate from chemical reactions, mechanical actions and nature. These particulate matters are classified in $pm_{2.5}$ and PM_{10}, which means the size of the particle is below 2,5μg or 10μg. The smaller the particles, the deeper they will penetrate the air channels of the human body. Most particles that are 10μg or bigger will be captured in the nose or throat. Particles of 10μg till 2,5μg will get stuck in the upper air channels where they can be breathed out. Particles below 2,5μg will penetrate until the alveoli, where the smallest particles will enter the bloodstream (Gezondheidsraad, 2018). Table 2-2 shows the save doses of the particulate matter that can be found indoor and outdoor.

Particulate matter	Source	Safe doses
pm^2.5	Mostly chemical reactions	15 μg/m^3
PM_{10}	Mostly mechanical actions	50 μg/m^3

Table 2-2 Safe doses of particulate matter (World Health Organization, 2010).

2.3.2.2 Research on indoor pollutants

Blauw Research measured the concentration of CO_2, $PM_{2.5}$, relative humidity and air temperature in 749 households over a period of 9 months. The conducted research showed an unacceptable air quality for one in every seven households. Especially for CO_2 concentration, that rises higher than the save value for one in every ten households for longer than a quarter of a day. Of all the tested households, 90% of the residents aren't aware of the air quality in their homes (Blauw Research bv, 2018).

The TNO has done research on the indoor sources of particulate matters. They measured particulate matter in the living room and kitchen of nine different dwellings with an optical particle counter during heating season. The following graph shows the data that they recovered from an average household on a Wednesday. Small PM_{10} spikes are the results of children playing, but the largest spike is from making pancakes at 18:30 (Figure 2-15). The indoor air is ten times more polluted than the outdoor air during cooking. The mechanical ventilation takes four hours to dilute the indoor air until it reaches the same concentration as the outdoor air.

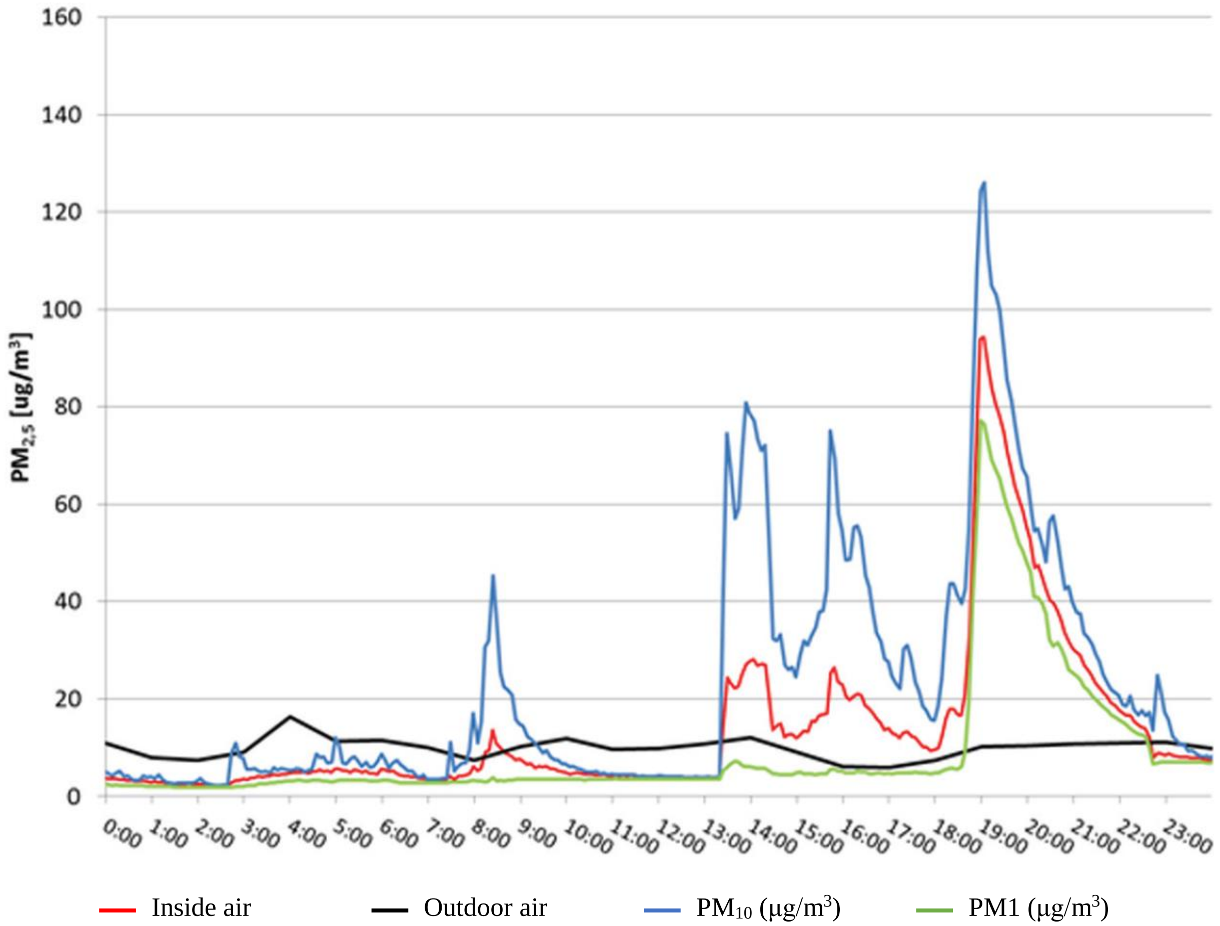


Figure 2-15 PM concentration during the day (Jacobs, Fijnstof bronnen in en rondom woningen, 2017)

Cooking can increase the concentration of particulate matter in the indoor environment significantly. Not only has it a high concentration, but it is an activity which is part of a daily routine. PM concentration between 18:00 and 23:00 can be increased with less than 1 μg/m^3 for residential buildings with an motorized mechanical extractor hood. This can increase to 10 μg/m^3 for an unmotorized extractor hood (Jacobs, Fijnstof bronnen in en rondom woningen, 2017). Figure 2-15 also shows that the pollutants level can be lower than the outdoor pollutants. This is not only due to absorption of particulate matter in surfaces, but also because this residential building is outfitted with M6 filters in front of the mechanical inlets.

2.3.2.3 Air exchange

Natural ventilation and mechanical ventilation are the main systems to exchange indoor air with fresh air. Natural ventilation is a passive way to exchange air with the outdoors, where wind and air density difference results in airflow through ventilation openings. Advantages of natural ventilated dwelling are:

- general well appreciated by an occupant, they understand and control it easily
- low initial investment, running and maintains cost
- very large airflow rates are possible

Drawbacks of a dwelling with a natural ventilation system:

- outdoor noise and air pollution can form discomfort
- efficiency depends on depth-to-height ratio and location of in-and outlets
- heat recovery is possible, but can be difficult
- airflow rate varies with the meteorological conditions

Nowadays, there are many different types of natural air inlets available. From simple system, which are basically a operable hole in the façade, to complicated automated systems that are regulated by wind pressure or demands. Infiltration of air which occurs through gaps and crack in the building, is not a proper way to ensure natural ventilation since the airflow rate through this infiltration cannot be controlled. Table 2-3 shows the different types of natural ventilation inlets.

Type	Principle	Remarks
Standard grill - user operable		higher wind pressure leads to higher ventilation rates
Pressure regulated grill - programmable	Opening of the grill depends on wind pressure, ensuring a maximum ventilation rate	
Noise insulation grill - user operable	Added acoustical performance	Can be bulky
Demand regulated grill - programmable	CO_2 or timer operated grill	Sensors are required

Table 2-3 natural ventilation inlets

The two main drivers causing natural ventilation flows are pressure differential due to temperature difference and pressure differential due to wind. Ventilation can also be driven by a mechanical source, such as a fan. Mechanical ventilation is mainly used when natural ventilation cannot meet the requirements, due to outdoor conditions (noise or pollutants) or high energy reduction ambitions, or location in the building (difficult to naturally ventilate).

- it can filter outdoor noise and pollutants
- finer control of the indoor climate
- it allows ventilation in rooms that are inaccessible with natural ventilation
- heat recovery from exhaust is easier

Drawbacks of dwellings with a mechanical ventilation system:

- often not well accepted by occupants, due to lack of control
- system consist out of large parts, up to 25 percent of the building volume
- installation, maintenance and operation cost
- it can be noisy
- air quality depended on maintenance of the system

The ventilation rate for this system doesn't rely on uncontrollable parameters, like pressure difference due to wind and temperature. Pressure is created by a fan, which creates a finer control of the indoor climate. This fan contributes to additional energy usage, which can be calculated with the following equation;

$$Q_{me} = q\ v\ \Delta P / \eta \tag{4}$$

Q_{me}	=	electrical power necessary for ventilation (W)
q_v	=	amount of ventilation (m^3/s)
v	=	flow velocity (m/s)
ΔP	=	pressure difference (Pa)
η	=	ventilator efficiency

Long-term monitoring studies shows that there are large differences in the indoor air quality and energy performance of code compliant residential buildings. Rob van Holsteijn and William Li have monitored the energy performance and CO_2 concentrations in residential buildings with natural ventilation, natural inlet/mechanical exhaust and a mechanical ventilation system with heat recovery. A ventilation system that applies a mechanical component in the air exchange, inlet or exhaust, performs significantly better in energy performance and reducing the CO_2 dose per person. The natural ventilated habitable rooms showed a large variations in their indoor air quality, due to the fact that they have insufficient control over the air exchange rate. Rob van Holsteijn and William Li state that these system require an active occupant, which was not exhibited in the results (van Holsteijn & Li, 2015). The results showed that all the buildings had code compliant ventilation system, but not all code compliant ventilation systems perform comparable on IAQ. The existing building codes do not require any assessment on IAQ-performance, only the energy potentials are calculated. Conducted tests in laboratory, with heating up olive oil up to temperatures in the range of 180 to 220 ºC in kitchens, suggest that the building regulations in the Netherlands with regard to kitchen exhaust is inadequate. A spike of PM1 concentration of 826 $\mu g/m^3$, with an hourly average of 327 $\mu g/m^3$, was measured for a situation that represents the Dutch building codes. Multiple different ventilation strategies were done in order to determine an ideal indoor environment. The effect of an open window during and after cooking was also simulated, where the average PM1 concentration reduced to 67 μg/m^3 at the expense of significant thermal losses. Also, this solution is less preferred by an end user because of possible draught problems and extra heating or cooling demand. An high capacity motorized hood with oversized hood (damp buffer) was also tested, that could extract 160 dm^3/s, with direct exhaust to outdoors. This system almost catches all pollinations (Jacobs, Cornelissen, & Borsboom, 2017).

2.4 System requirements

The system consist out of a mechanism that converts an input into an output via a strategy. Precedent research has found limited knowledge on the mechanism of a similar system. A hypothesis is that this system is a domotica system that consist of an interface for the user that is similar to a thermostat, sensors and the operative components for the windows. A domotica system is mainly used for home automation, which consist out of components that aid a user. These components should be a coherent addition to a residential building, connecting different parameters within the building while not disturbing the comfort or the functionality of the window for the user (Figure 2-16).

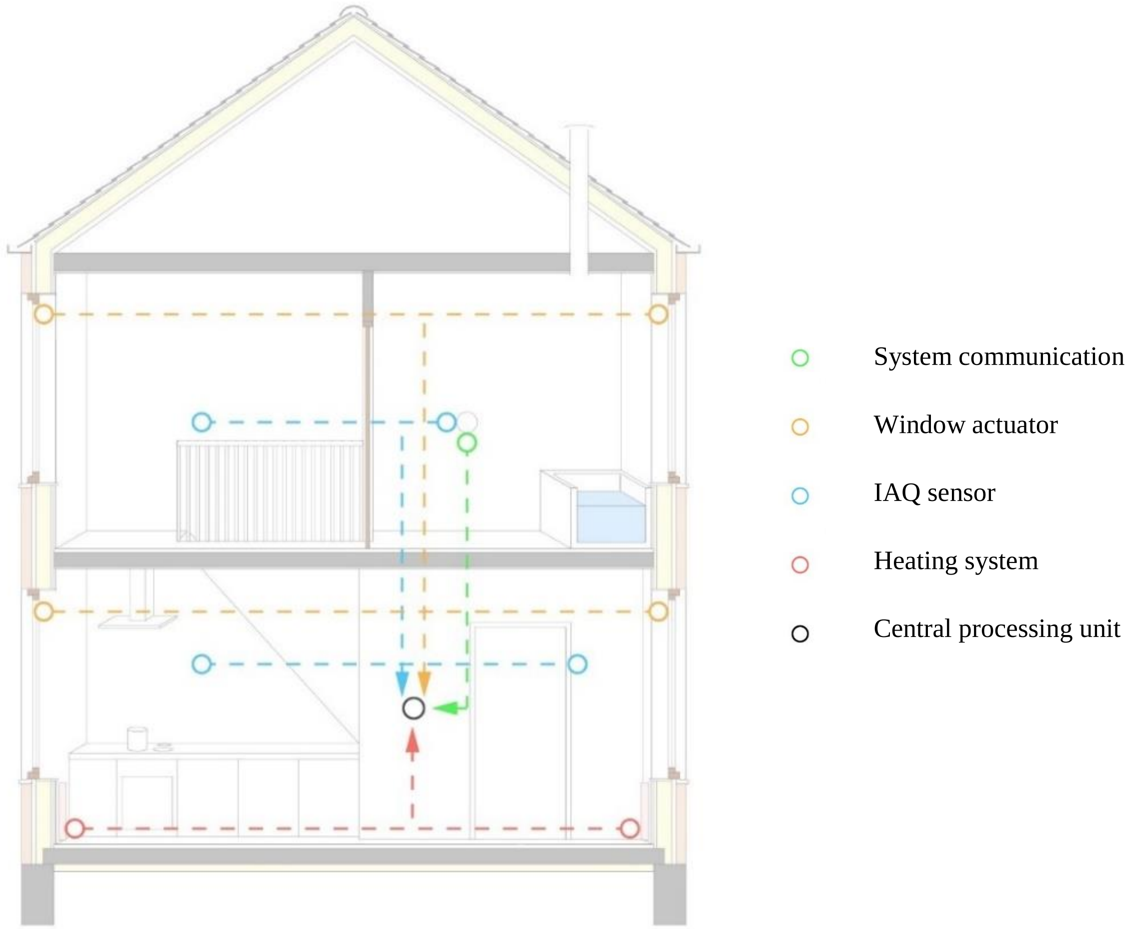


Figure 2-16 Integrated system

In this case, the system is an energy saving system. The concept consist of a domotica system that senses presence of an occupant and create their conditions for indoor comfort in an energy efficient way. A hypothesis is made which will be elaborated via the system engineering diagram, made by Blanchard (Blanchard, 2016). It consist of various mechanisms, such as window actuators, IAQ sensors and thermostats, that communicate with parts of the building, such as the window, radiator and thermostat. Each room will be seen as a separate zone, making decentralized and demand driven actions possible. There are a lot of domotica components already on the market, the current knowledge on these systems will be investigated. According to Benjamin S. Blanchard, Professor of Industrial and Systems Engineering at Virginia Tech, a system has;

- inputs; consumer requirement, stakeholders
- outputs; an effective and efficient action from the system that correspond to the consumers need
- external constraints; technological, social, economic, environmental and political constraints
- required mechanism; materials, software, maintenance

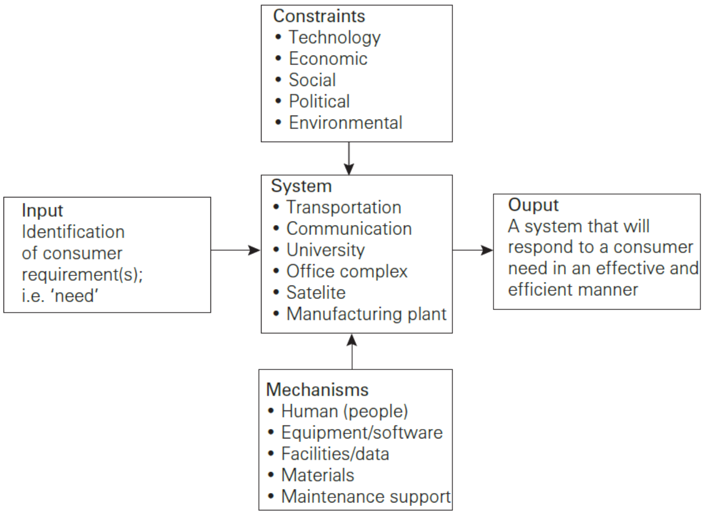


Figure 2-17 System engineering (Blanchard, 2016)

The input, constraints, mechanisms and output will be investigated in order to understand the aspect of creating a system. The output is the result of a ventilation or cooling strategy that determines a reaction to a certain actions or measurements.

2.4.1 Input (stakeholders)

Stakeholders can be classified in multiple ways, such as primary or secondary, owners and non-owners of a firm, resource providers to or dependents of the firm. Jukka Majava, professor at the University of Oulu, describes stakeholders as internal and external stakeholders. Internal stakeholders can be seen as formal members of an organization or a project that create a product. External stakeholders are not formal members, but can influence or be influenced by this organization or a project (Majava, Haapasalo, & Harkonen, 2015).

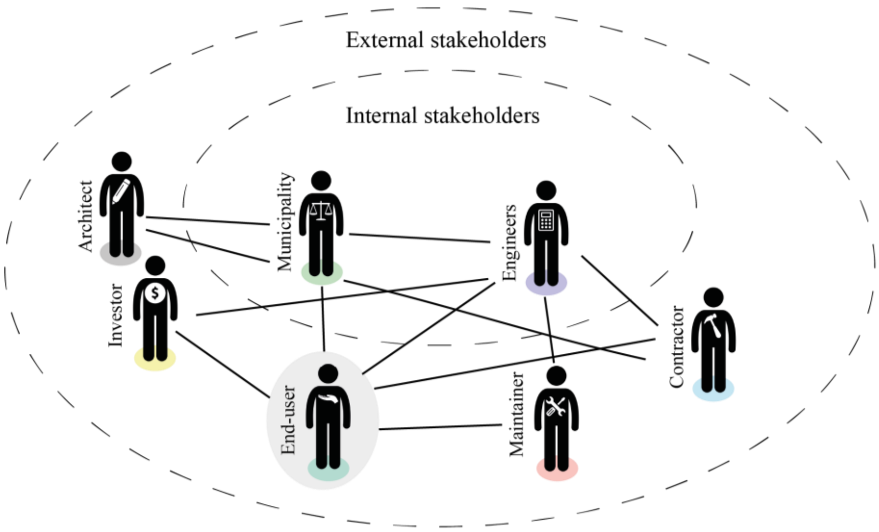


Figure 2-18 Stakeholders (own illustration)

The end-user is the most important stakeholder during the entire life cycle of the system, but this stakeholder has the least influence on the final design of the system. This is done by the product engineers, that tries to design a product that fits the needs of every external stakeholder within the regulations of the municipality. The end user of the building does not always say what he or she means, they are not educated to do so. They can also not oversee the consequences of certain demands when they come together (Bluyssen, 2009). Therefore, the final prototype should be tested by an end-user in order to determine its acceptability. Demands and wishes of all the other stakeholders are easier to determine, because they are generally based on rules and policies.

Automation is more common in hospitals and shopping malls, not in residential buildings. The *architects* main focus is aesthetics, the product should look and feel like it is for residential buildings. The interest for the *municipality* is the performance of the intervention and if it is conform the local ambitions, Dutch building codes and NEN-norms, chapter 2.4.2. The main interest of the *contractor and maintainer* is that it can be ordered, built and maintained. The contractor will steer the design towards products that are easy to order, manufacture or install. The initial investment cost should be low and have a favorable exploitation. The system or product shouldn't interfere with the structural integrity of the building, or should improve it. Also, the product should adapt to new standards, ambitions or goals, in order to prevent additional investments.

2.4.2 Constraints

The design process is limited by the regulative framework and their needs to be trusted between the society and the designer. The designer has responsibilities towards the society as a whole, where codes of ethics formulated state that designers should display integrity and honesty in their work if they are to be trusted by costumers and society (van Gorp, 2005). An authority for the ethical use of data and artificial intelligence should be established, according to the Institution for Public Policy Research. This authority should regulate the use of automating technologies within an ethical and regulatory framework. Governing should precede technologies, rather than follow technological development (Commission on Economic Justice, 2017) Thus the regulative framework and ethics within the proposed system will be investigated.

2.4.2.1 Regulations

No regulation on home automation are present in the current Dutch buildings codes, yet. Thus, only the regulative framework for ventilation characteristic will be investigated. The Dutch building codes, Bouwbesluit 2012, state that a residential area must have 0,9 $dm^3/s/m^2$ of ventilation, with a minimum of 7 dm^3/s. A room or place to stay must have a ventilation rate of 0,7 $dm^3/s/m^2$, with a minimum of 7 dm^3/s. A room that is designated for cooking must have a ventilation rate of 21 dm^3/s and wet rooms have a ventilation rate of 14 dm^3/s (Rijksoverheid, 2018). These codes are conformed and expanded in NEN 1087, where dilution factors can calculated the quality of the ventilated incoming air. Complicated calculations are presented in NEN 1087, that do not seem to add value to this research. The Nederlandse Norm provides even more guidelines for indoor air quality in NEN-EN 15251. The required ventilation rate can be higher for very sensitive persons with special requirements like handicapped, sick, very young children and elderly. These ventilations rates are continuously operated during occupied hours.

Category	Air change rate		Living room and bedrooms		Exhaust air flow (l/s)		
	$l/s/m^2$	ACH	l/s/pers	$l/s/m^2$	Kitchen	Bathroom	toilet
High level	0,49	0,7	10	1,4	28	20	14
Good level	0,42	0,6	7	1,0	20	15	10
Acceptable level	0,35	0,5	4	0,6	14	10	7

Table 2-4 Ventilation rates for residential buildings (Normcommissie 351 074 "klimaatbeheersing in gebouwen", 2007)

The recommended ventilation during un-occupied hours, during periods when there is no demand, are lower. A minimum ventilation rate between 0,05 to 0,1 $dm^3/s/m^2$ is recommended, this included infiltration and leakage (NEN-EN 15251, 2007).

It is noted that for renovations, current building requirements are withdrawn and the relevant requirements during the time of construction of the existing buildings must be met. Thus, renovation projects need to meet the ventilation requirements that were used during the time of construction of the building or the already existing ventilation capacity that is used in the current building. The first Dutch norm for ventilation was released in 1975, which was the NEN 1087 (De Gids, 2015). Therefore, all buildings that were constructed before 1975 have no regulations for ventilation.

2.4.2.2 Ethical

This research focusses on the creation of a home automation system. To take into account all ethical issues connected in one way or another to an automated system would be impossible, according to Anke van Gorp, researcher in Ethics, Privacy, and Research Integrity at the Research Centre for Social Innovation and the Institute for Safety and Security. Some questions on automation, which are created by the parliament of the United Kingdom, should be answered while designing. The applicable topics include; (UK Parliament 2016)

- concerns around *privacy*
- ensuring human *safety*
- the extent and necessity of *human control* of autonomous systems

The extent and necessity of human control was discussed in chapter 2.1.2.

2.4.2.2.1 Privacy

Data privacy has received a lot of attention over the past few years. From big data leaks at Facebook to ongoing concerns about data privacy at social media and efforts by governments to give consumers more power to control their own data, the issue of data privacy is at top of mind for consumers, governments, and businesses, according to Doug Cutting, Chief Architect at Cloudera. It's this rise of data that has led to concern over data privacy and ethical use. Data can be used for multiple matters, such as approvals of loans, bias in criminal justice and social security, (Gutierrez, 2019). Arie den Hertog, founder of AirTeq, mentioned that data of air quality monitoring can harm the value of property. Loads of buildings are located in areas near factories, airports and harbors, that pollute the environment in such a way that these buildings become less desirable to life in. Therefore, the proposed product should be offline, where data can’t be checked, even by the occupant. This also increases the safety of this product, making it impossible to hack without physical interaction with the system.

2.4.2.2.2 Safety

This system comprises a set of interrelated components that work together with a common objective, which is lowering the energy demand of a residential building in a comfortable and safe way. Safety has the highest priority, which is safe indoor air quality and safe operation of the windows and doors, an unsafe environment for the occupant and building should be prevented. This means that window operations are limited to tilting a window-pane.

Not only the reaction of the system should be ethically justified, also the type of communication that the system uses needs to be safe. The smart buildings in the built environment rely on automated processes to control multiple different tasks, that have to work without a glitch and withstand attacks. A group of researchers from Tencent Security Platform mentioned during their

Hack in the Box Conference that the security of smart building equipment is not given enough attention at present. KNX, a network communication protocol for building automation, that is often used in large public spaces such as stadiums, hotels and airports, is easy to attack. Yong yang, HuiYu Wu and YuXiang Li of the Tencent Blade Team demonstrated an attack on the Marriot hotel and succeeded in controlling the lighting, air conditioning, curtains and other equipment (Yang, Wu, & Li, 2018). This same protocol, KNX, reached the Dutch news at February 21, 2019, where they state that around 1300 buildings are prone to these attacks (Schellevis, 2019).

Figure 2-19 News article February 21st 2019 (Schellevis, 2019)

KNX is an 24-year old standard, which is still used in order to make ‘smart’ buildings. According to Daan Keuper, ethical hacker at the security company Computertest, these devices are connected to the internet in order to remote control them, but this feature creates the opportunity to hack the device (Schellevis, 2019). Also other protocols, such as Zigbee networks are easy to tamper, according to Yong Yang, HuiYu Wu and YuXiang Li.

2.4.3 Mechanism (Operative components of the windows)

The concept for the proposed system consist out of a controller, some form of computer that receives an input and generates an output, various sensors, to measure indoor parameters, and window actuators. All these different elements have to communicate to each other in order create a system that functions like it is intended.

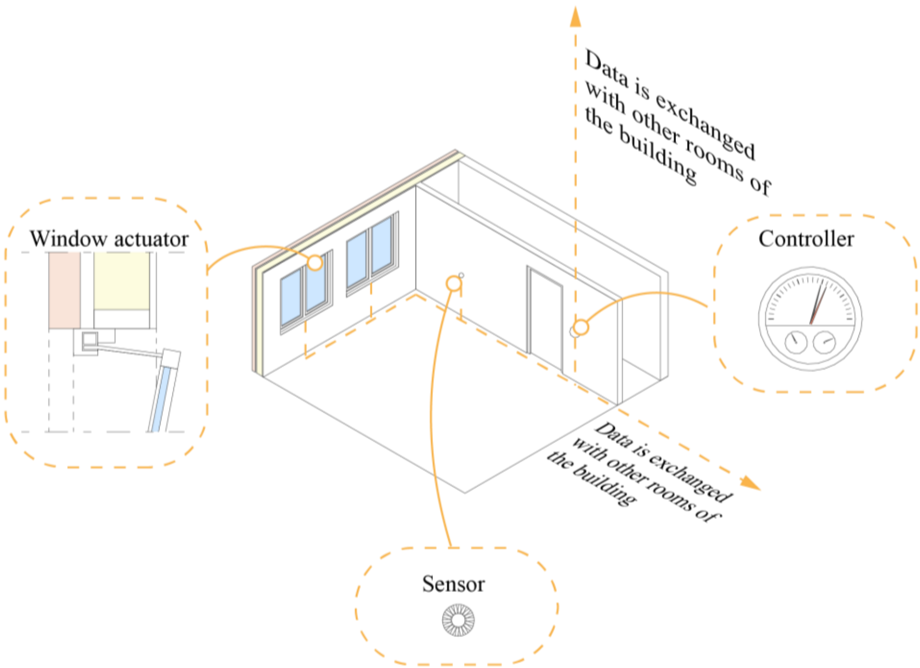


Figure 2-20 Mechanism

2.4.3.1 Controller

The controller for most climatization system in residential homes is a thermostat, which comes in different varieties. Traditional thermostat senses the temperature of a room and performs actions in order to change the rooms temperature near the desired setpoint. This action is mainly done by increasing or decreasing the waterflow through the radiators and floor heaters or changing the temperature of incoming air. The interface of these thermostat are minimalistic, where the setpoint is controlled by a single operable knob (Figure 2-21). A newer iteration of the thermostat is the programmable thermostat, which is designed to adjust the temperature according to a series of programmed settings. A user can set the temperature as a schedule for different times of the day, which the thermostat will follow automatically. The latest iteration of thermostat is the smart thermostat (Figure 2-22). Smart thermostats is similar to a programmable thermostat, but also contain additional features, such as sensors and WiFi connectivity and it can be used with home automation and domotica systems. Users can see their energy usage, indoor temperatures and much more date from the screen of the device and from an app on their smartphone. As discussed in chapter 2.1.2, these additional features requires active participation of the user and accurate inputs in order to be beneficial.

Figure 2-21 Round T87F (Honeywell, n.d.)

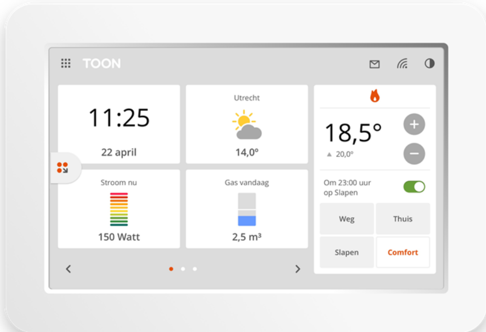


Figure 2-22 Toon (Toon, n.d.)

The controller of climatization systems has been changed from an analog knob, to set the desired temperature, to a touchscreen, with multiple applications that expand the functionality.

somfy.

A leading company in home automation is Somfy, which is partly due to their home automation controller called TaHoma box and their user friendly Somfy application. Somfy is a French industrial group founded in 1969. Historically located in Cluses in Haute-Savoie, it is today one of the world leaders in motorization and automation of building elements. The company's main focus is on automation of window blinds and shutters, lighting, music and observation for safety. They partner with other companies like Honeywell and Philips in order to offer "do it yourself" packages to completely automate different activities which is driven and programmed with the TaHoma box and a Somfy application for a smartphone, tablet or pc. This box creates the infrastructure for the communication between different smart device or their own made motors, that can be used for inside and outside window covering and openers. This communication works with different protocols, such as IFTTT, Zigbee, Z-wave and Bluetooth, and different applications, Google assistant, Amazon Alexa and Apple HomeKit.

The main target audience of Somfy is electronic enthusiast or offices, where they are used in order to create more convenience for the user. There is a slight increase in the amount electricians that approach Somfy, unfortunately this is still not very common. These products could also be deployed purely for their energy saving potentials.

Contact:
Mark Pekelharing

2.4.3.2 Sensor

Traditionally, air quality monitoring has been constructed for two purposes: surveillance and research. These air pollution concentrations are monitored by professional personnel using static monitoring stations equipped with certified instruments. The sensors are relatively large, heavy and expensive, with prices ranging between €5000 and €30.000. per device. These sensors are subject to strict routines of maintenance and calibration, to ensure high quality data (Castell, et al., 2016). It is unfeasible and undesired to have these high maintenance and expansive instruments for the occupants. But due to the current trend to collect air quality data beyond reference monitoring stations, new low cost platforms are currently available and new devices are continually introduced.

Sensors for measuring indoor humidity levels, temperature and air quality need to be placed near the locations of the sources of the pollutants or near in the middle of the room at a height of 1,1m above the ground. This is a recommendation of the location of the sensor measuring the pollutants at head level when sitting, according to EN ISO 7726:2001.

Two types of sensor platforms are currently available for monitoring air pollutants, those that measure gas phase species and those that measure particulate matter. Commercially available gas sensors operate by measuring either the electrochemical interaction between the sensing material (Figure 2-23) and the pollutant or the absorption of light (Figure 2-24). Particulate matter is measured by light absorption or scattering, where algorithms relate the signal to the particle size or composition. These sensors range from €1 to €200. New types of commercially available sensors are increasing at a rapid pace, so new measuring techniques and prices may come down in the near future.

Figure 2-23 electrochemical sensor (Winsen, n.d.)

Figure 2-24 light absorption sensor (Winsen, n.d.)

Semiconductor gas sensor (methane)
- type = MQ-5
- cost = €1 - €12
- dimensions = 20 x 16,4 mm
- expected life span = 2 years
- average energy consumption = unknown
- accuracy = unknown
(HANWEI ELECTRONICS, n.d.)

Infrared Gas Sensor (methane)
- type = MH-440D
- cost = €129 - €167
- dimensions = 20 x 21,4 mm
- expected life span = >5 years
- average energy consumption = unknown
- accuracy = unknown
(Gas-sensor, n.d.)

The performance of these sensor are tested, in a laboratory, against traceable gas and particulate matter under accurately and reproducible controlled conditions. These controlled conditions are impossible to get in a dwelling, where humidity and temperature can fluctuate. Researchers at the Norwegian Institute of Air research have investigated the accuracy of the measurements of these low-cost commercial sensors that measure traceable gasses (CO, NO, NO2 and O3) and particulate matter

(PM_{10} and PM^{2},5). The results show that even for identical sensors and platforms, the performance can vary from sensor to sensor. According to Aleixandre and Gerboles (2012), this inaccuracy is due to interference of the electrochemical sensor with the temperature and the relative humidity. The stability is probably the worst problem for these kinds of sensors. The response changes over time and the sensors needs to be recalibrated. Manufactures do not provide much information about the drift or stability. Each low-cost sensor behaves uniquely, it is therefore important to evaluate every sensor before deploying it in the field (Curto, et al., 2018). Tests show that commercial low-cost sensors are promising, but for now, only sensors measuring NO and PM_{10} are capable of offering coarse information about air quality (Castell, et al., 2016).

A company that specializes in measuring indoor air quality of residential buildings is Netatmo. Founded in 2011, Netatmo is a French company that manufactures consumer smart home solutions. Their product line-up focusses on a safer, healthier and more comfortable home. Their weather station, thermostat and camera have been awarded by the "CES Innovations Design and Engineering Awards" in 2013, 2014 and 2015. Their weather station gives live data on CO_2 concentration, temperature, humidity and sound with a grading system if comfort is created or suggestions in order to restore comfort. Netatmo products can be programmed with a Netatmo applications, but also with third party interfaces like Google assistant, IfThisThenThat, Amazon Alexa and Apple HomeKit, which communicates via wifi.

Netatmo’s products are mainly used by electronic enthusiast for their good looks and energy saving potentials. Their product line-up is engineered and designed to create an ‘apple’ like product, with the good looks and ease of use, therefor making it a successful consumer product that can be bought in electronic stores. Netatmo’s product line-up could be an interesting for electricians or plumbers, unfortunately they only learn how to install more main stream and conservative installations, according to their sales manager Edwin Aartman. The large amount of jobs, in current market, generates enough work for an electricians that prefer to install more conservative systems that they know, understand and trust. Netatmo has future ambitions to be approached more by contractors and electricians, in order to be part of the built environment. Netatmo has been asked to present their products at the Bouwbeurs, one of the biggest trade fair for building related products in the Netherlands, but they declined this offer. Apart from the big expense to have a stand on the Bouwbeurs, they prefer to present their products as a part of an integrated system. That’s why they partner with companies, such as Velux (manufacturer of skylights) and Samsung (multinational electronics company), in order to co-create smart home solution.

Contact:
Edwin Aartman

2.4.3.3 Actuators

There are a large range of various types of brackets, for concealed, semi concealed or built-on solutions. Three different actuators are available on the market, a gear operated, the chain operated and automated door closers.

Gear operated windows are normally seen in industrial applications, like green houses, or cheaply made retrofits (Figure 2-25). These give great functionally and adjustability in opening and closing of the window. The robustness can make it a durable system if done correctly, but the open gears and the dimensions of this system makes it undesirable from an aesthetic point of view in a residential building. An operable part that is outfitted with a gear operated actuator cannot be operated by hand. The chain operated windows are the most common used for residential buildings (Figure 2-26), because they are small and concealable in window frames, according to Jochem de Langen, area project manager at Schuco Nederland. These systems are normally installed where operable windows are inaccessible by a user. Operating this system can only be done with buttons, therefor limiting the functionality of the window by making operation by hand impossible. The automated door closers are mainly used in publicly accessible buildings, where doors need to be opened quickly. An operable part that is outfitted with an automated closer cannot be operated by hand.

Figure 2-25 gear operated actuator (Vektiva, n.d.)

Figure 2-26 chain operated actuator

Figure 2-27 automatic door closer (HBopeners, n.d.)

Some companies that make window actuators are Schuco and AXA. These companies offer a different actuator for a different target group.

Schüco International KG develops and markets window and façade elements for the built environment. As a system provider, they offer consulting and support for architects, planners, investors and other clients. Their product range includes profiles and accessory systems for the construction of windows, doors and facades. Schüco develops innovative system, that are designed for fire, burglary protection and products for building automation. They developed an automated turn-tilt window with integrated and fully concealed chain actuator, named “Tiptronic”. Schüco TipTronic SimplySmart is the concealed mechatronic fitting for automating Schüco aluminium window systems, which combines energy management, building automation and security. The actuator of the window becomes an integral component of the building. These windows are currently mostly applied in location where the user can’t reach the window, but still needs to be operated.

The Schuco Tiptronic turn/tilt window frame can be operated as a traditional mainly operated window, but also has an automated tilt mode to open and close the window. When opened as a traditional ‘turn’ window, the windowpane is disengaged from the actuator and can only operate by hand. The actuator is reengaged automatically when the window is closed.

Figure 2-28 Tiptronic window (Schueco, 2019)

This way, an occupant can still have influence on the effectiveness of the system by simply opening a window as a traditional 'turn' window, instead of tilting the window-pane. The window should be operable by hand, which could increase the acceptability of this system, but the actuator should not disengaged when the window is opened by an occupant. According to Jochem de Lange, it is currently not possible to use a chain actuator to operate the window frame in two directions, turn and tilt.

The system only needs full control over the tilt function, which allows the window to remain open with little ability to maneuver the window fully open by unwanted quests. The turn function of the window will, due to this reason, not be used by the mechanism. The only operation that the proposed system should have over the turn function is closing it if an occupant opened it, making it reengage with the chain actuator that can ventilate a room in a safe manner. This could be done with an additional motor.

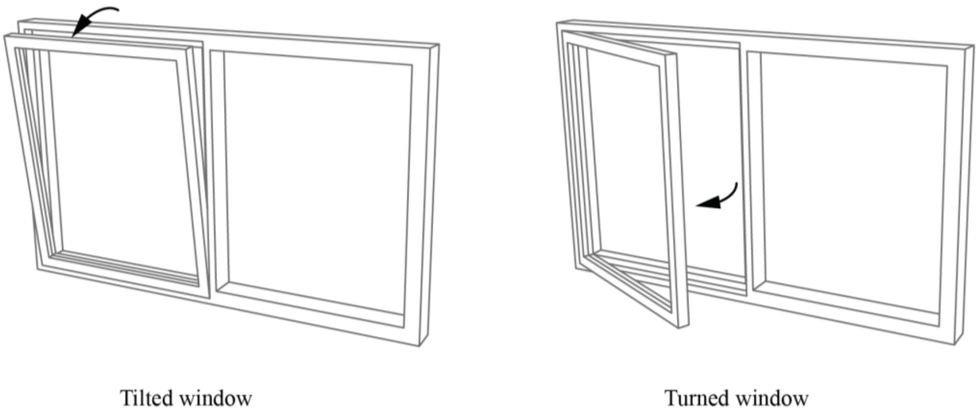


Figure 2-29 Different window operations

Contact:
Jochem de Langen

AXA home security offers a totally different actuator, which is more focused on safety and ease of assembly and installation. AXA is part of the Allegion group, which is a global pioneer in safety and security cooperating with CISA, Interflex, LCN, Schlage, SimonsVoss and Von Duprin. AXA developed a window actuator, the AXA Remote 2.0, that could be fitted to a swivel window as a retrofit (Figure 2-30). This actuator is currently mostly used by home owners for windows that they can't reach. The police mark of approval gives confidence that this product provides safe operation of the window. This actuator can be modified to be mounted to a tilt window.

Figure 2-30 AXA Remote 2.0 (AXA home security, 2019)

The downside of this system is that it removes the convenience of window operation by hand, only the motor can tilt the window open or close. The turn function of the window will be completely removed when installing the AXA Remote 2.0. This will lower the acceptability for this system, because the occupant can't seek comfort by opening or closing the window by itself.

This system works with an infrared sensor in order to perform a requested action. It isn't connected to the internet or any home automation protocol. This makes it difficult to include into a smart home solution without modifying the actuator or the remote. A small and cheap ESP2866 like chip could make this system smart and ready for automated home solutions, but this can also make it prone to hackers.

The actuator also reduces the airtightness of the window frame by removing the locking mechanism of the window that pushes the windowpane in the rubber seals. An alteration of the automatic smart handle from SimonsVoss, partner of Allegion, could be added to the AXA Remote 2.0 when implement for higher performing window frames with rubber seals.

Contact:
Menno Bouwens

2.4.4 Output (strategy)

All different inputs, constraints and mechanisms form an output, based on a strategy. In the end, the strategy determines if a window should open or close. Research has been done on the effect of operable parts on indoor comfort and quality. Francesca Stazi, professor Building science and Technology at Università Politecnica delle Marche, has done research on the development of an automatic system for window openings, based on thermal comfort and indoor air quality for classrooms. Indoor air quality is a relevant issue in school classrooms, because students usually suffer high CO_2 levels. The main target in school classrooms is preserving students attention, efficiency and health while attending the lessons. From an indoor climate perspective, this can be translated into reaching and maintaining a satisfactory perception in terms of air temperature and indoor air quality. A window operation strategy was created based on these criteria (Figure 2-31).

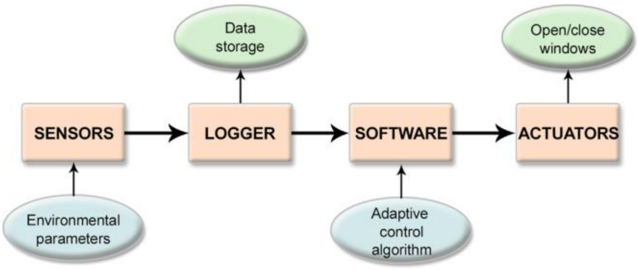


Figure 2-31 automated window diagram (Francesca, Naspi, Ulpiani, & Di Perna, 2017)

Before creating the strategy, data is collected in one free-running classroom by recording indoor and outdoor environmental parameters, occupancy patters, thermal sensation and user actions on windows. This data was analyzed and tested in models, evaluating trigger parameters for window use. An automatic system was developed with sensors, a data logger, an adaptive thermal comfort algorithm and window actuators (Figure 2-31). This system was installed and monitored in multiple classrooms for 10 days.

The automatic system guaranteed a more comfortable environment, with CO_2 concentration below 1500 ppm, and increase in thermal satisfaction. But the automatic system efficacy in CO_2 reduction was greater during windy days, since it cooperated with a positive combination of wind speed and direction (Francesca, Naspi, Ulpiani, & Di Perna, 2017). No research has been done on its energy saving potentials, because this research had a different goal and strategy.

Theofanis Psomas, PhD researcher at the Aalborg University, has done research on the automation of window openings to diminish the thermal discomfort and overheating risk of a dwelling during cooling periods in temperate climates. The research concluded that passive and hybrid ventilation methods, techniques, strategies and technologies may significantly decrease the environmental impact of residences and creation of an healthy and comfortable indoor climate.

A cooling algorithm for the integrated window system was created with different statements that determined the actions which will be performed by the window (Figure 2-32). Multiple strategies, the rate of opening of the windows and the determination of the desired temperature, have been compared and showed potential.

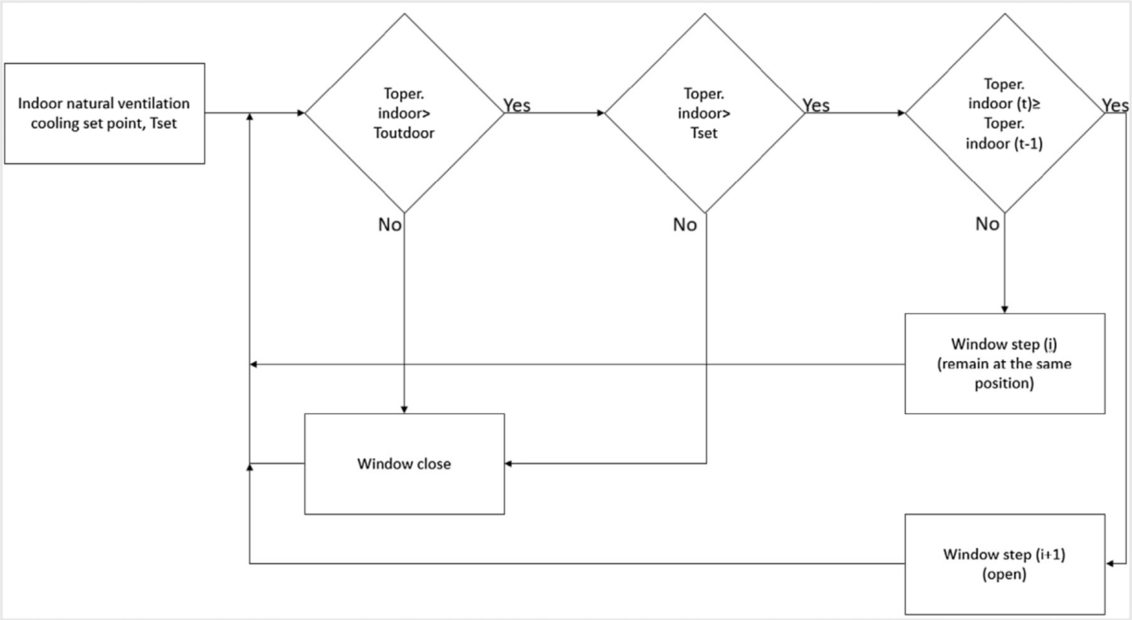


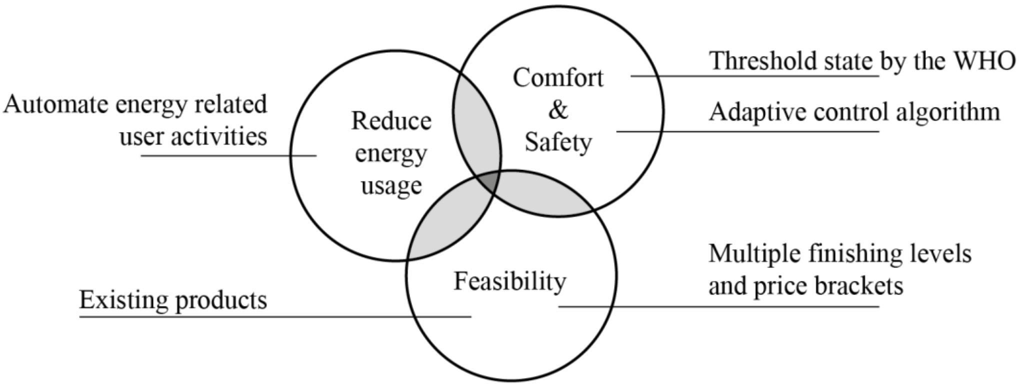
Figure 2-32 automated window system algorithm (Psomasa, Fiorentini, Kokogiannakis, & Heiselberg, 2017)

This research was done with ESP-r and BCVTB simulations, not with the real world tests. They used a typical 1930 Danish floor plan for their simulation house (Psomasa, Fiorentini, Kokogiannakis, & Heiselberg, 2017). Also, no research has been done on the energy saving potentials.

2.5 Conclusion

Literature study showed that user behavior has an unknown effect on the final energy usage of a building, because the user behaves proactively in creating a comfortable and safe indoor climate. These indoor conditions are reached by operating the thermostat, opening windows, operating mechanical ventilation and much more. These systems can be misused by a user due to ignorance or negligence.

Window operation is the second most performed energy related activity, where excessive window operation has an negative effect on the energy consumption that is difficult to quantify. Lack of window operation can also have a negative effect, due to accumulation of indoor pollutants, which can lead to many different health symptoms. A new system should be proposed that assist users with window operation. This system doesn't need an input of an occupant in order to function correctly and is nearly impossible to misuse. The system should only operate within the comfort limits of an occupant, which will increase the acceptability of the designed system. Comfort is effected by multiple parameters, this research will focus on comfort due to IAQ and thermal comfort. Our own sensors, nose, eyes, ears etc., are not accurate enough to detect an unsafe IAQ, which can result in unnoticeable high indoor pollutants that have an negative effect on the health of the occupant and the building. The World Health Organization has created thresholds for pollutants concentration for a safe IAQ, which shouldn't be exceeded for long periods. Therefore, the thresholds of the World Health Organization will be used to determine a safe, and thus also comfortable, IAQ. Thermal comfort can be reached by using the adaptive thermal comfort algorithm in order to reach thermal comfort. This method determines thermal comfort based on outdoor parameters. No input from the user is necessary, minimizing misuse of the system. The last ingredient in which could affect the success of this design is the feasibility of this product. The product should meet the needs and wishes from all stakeholders.

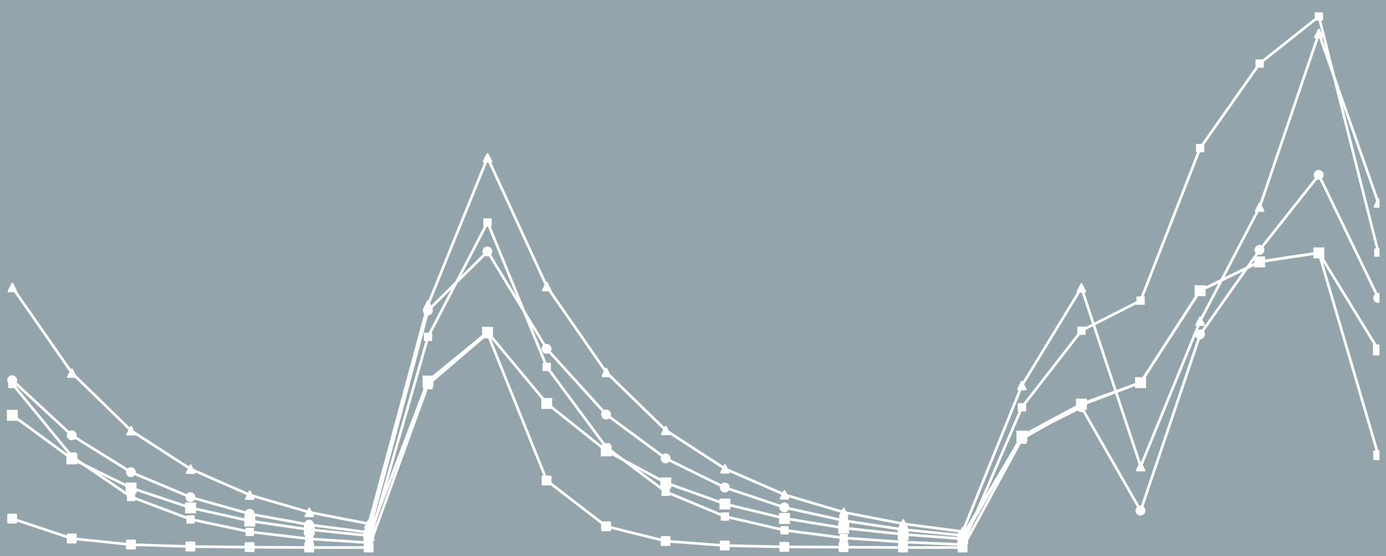


The system should be designed for buildings that are constructed before 1975, when no regulations on ventilation capacities existed. Ethical issues, such as data leaking and safety, can be minimized by keeping the system simple and offline. The mechanism consist out of a controller that functions as the brain of the entire system. Multiple inputs from sensors and actuators feed the controller with indoor and outdoor parameters. The system reacts to certain activities, by measuring indoor pollutants, humidity levels, temperature and window operations. There are no physical buttons or program that can be set on the mechanism. The user is free to operate any window, the system determines based on various parameters if this window should stay open or should be closed after a period of time. There are various companies that could collaborate in order to create this system.

03

CASE STUDY

Case-study analysis is used to investigate this topic in depth. Models and strategies will be created that provide information and identify problems. This chapter compares and determines the potentials for different ventilation strategies in a typical Dutch rowhouse. A mechanism will be constructed, based on literature studies, that could perform the ventilation strategies.



3.1 Location

The Ramplaankwartier will be used as a case study for designed product. The Ramplaankwartier is a neighborhood in the south-west of the city center of Haarlem. The majority of the houses were built between 1920 and 1970. These building have a high gas consumption, due to the low amount of energy awareness during this time. Many of these residential buildings have been renovated which improved their energy label (Figure 3-1).

Figure 3-1 certified energy labels Ramplaankwartier (Meer Met Minder, 2019)

Most of the buildings in the Ramplaankwartier have an energy label G, but will be improved in the near future. The TU Delft proposed a “Wijkwarmteplan” for these building, with improvements on the building and neighborhood scale. Collective heat and cold storages, low temperature heating grid, high insulation values and PVT panels will upgrade this area in an affordable to a gas free and sustainable neighborhood that makes use of locally energy sources.

Dwellings that were built in 1946 and 1974 have an average gas consumption of $1500m^3$ to $1560m^3$ per year. Modern day dwellings have an average gas consumption of $1000m^3$ (Milieu Centraal, 2019). The average energy consumption of the 1960’s dwellings in the Ramplaankwartier is almost $1800m^3$. Therefore, these buildings are in need of an intensive renovation. The building that will be used for the case study is located at Rollandslaan 84, which is an row house with neighbors on either side (Figure 3-2). This building was built around 1964, with a back facing the South at a 20 degree angle and front facing the North at an angel of 20 degrees. The building has an uncertified energy label F (Meer Met Minder, 2019)

Figure 3-2 Rollandslaan 84 (Google, 2019)

The house has a typical Dutch floorplan, a “Doorzonwoning”. The first floor consist out of a living room that spans the entire depth of the building with an open kitchen and a door towards the garden. It has a relatively small entrance with adjacent toilet. A staircase in the entrance leads to the first floor. 5 rooms are accessible via the landing, two large bedrooms, two smaller rooms and a bathroom. The two rooms at the south side share a balcony facing the garden. The stairway continues to the attic, where 4 more rooms are located. The total floor plan is $122m^2$. All the rooms, except the bathroom, have access to an operable façade element. Drawings of the building can be found in Appendix B.

The production of particulate matter and carbon dioxide is mainly based on the presence and activity of an occupant. Therefore, it is important to understand when occupants are present and what kind of activity they perform. For this dwelling, a household of three has been assumed. This household consist of two parents that work full time and a child that goes to school. During midweek, no activity takes place during 09:00 and 16:00 in the dwelling. All members of the household stay at home during the entire weekend (Appendix C). At 19:00, the occupants cook for an hour, an activity that is repeated every day. The building has six potential bedrooms, one bedroom will be occupied by both parents and one bedroom will be occupied by the child. The rest of the bedrooms will only be ventilated during the weekend and holidays, to simulate a high amount of overnight guest.

3.2 Air change rate

A poor performing building has an air infiltration rate of 6 to 12 ACH at 50 pascal (Xella, 2019). Due to the high energy consumption of the building, it is assumed that the air infiltration rate of the current building is poor and will be set to 12 ACH at 50 pascal. Design builder has been used to determine the corresponding fixed air exchange rate that can be used for the hand calculation by checking the energy consumption for heating. A constant infiltration of 0,8 ACH creates similar results for zone sensible heating as an infiltration rate of 12 ACH at 50 pascal in the building that is used for the case study.

Infiltration	Zone sensible heating (kWh)
12 ACH at 50 pascal	3.210 kWh
0,8 ACH constant	3.301 kWh

Table 3-1 Infiltration with similar energy consumption for heating

The proposed building product replaces existing window frames. Some of the existing window frames are dated and do not provide the air tightness that new window frames can provide. The improved situation will have an air infiltration rate of 7 ACH at 50 pascal, which is the air infiltration rate of an average house (Xella, 2019). A constant infiltration of 0,4 ACH creates similar results for zone sensible heating as an infiltration rate of 7 ACH at 50 pascal in the building that is used for the case study. Meaning that an infiltration rate of 0,4 ACH will be used for the hand calculations and an infiltration rate of 7 ACH at 50 pascal will be used for the simulations.

Infiltration	Zone sensible heating (kWh)
7 ACH at 50 pascal	2.642 kWh
0,4 ACH constant	2.669 kWh

Table 3-2 Infiltration with similar energy consumption for heating

The potential air change rate that can be created by opening a window has to be determined in order to see if the necessary air change rates can be met for each ventilation strategy. The two main drivers causing natural ventilation flows are pressure differential due to temperature difference and pressure differential due to wind. Only the pressure differential due to wind will be used to determine the effective opening of the window, because the pressure differential due to temperature difference is too small. The pressure differential due to wind is given by;

$$P_{wind} = \frac{\rho v^2}{2} C_p \qquad (5)$$

P	=	pressure (Pa)		
ρ	=	density of air (kg/m^3)	=	1,2kg/m^3
v_a	=	flow velocity (m/s)		
C_p	=	wind pressure coefficient		

$$v_a = v_{boundary} \left(\frac{h}{h_{boundry}}\right)^{\alpha} \qquad (6)$$

$$v_{boundary} = \frac{v_{10}}{\left(\frac{10}{h_{boundry}}\right)^{\alpha}} \qquad (7)$$

Surroundings	α	$h_{boundary}$ (m)
Free field	0,11	250
Trees and shrubs	0,15	300
Built environment	0,25	400
Urban city	0,36	500

Table 3-3 coefficient of velocity profiles

The building in the Ramplaankwartier is located in a “Built environment”, therefor α will set to 0,25 and hboundary will be set to 400 meters. The height of the window opening will be set at 1 meter for the calculations. The wind pressure coefficient, Cp, depends on the position of the building on the envelope, wind direction and building geometry. Its value is usually positive at the luff side and negative at the lee side, sidewalls and roof. In practice, it is difficult to determine the Cp value due to the complexity of the shape of the building and the environment having a large influence on the Cp value. This can be simplified by altering the geometry to a simple isolated rectangular building, where Cp0 is the wind pressure coefficient at the front side, which is approximately 0,6.

$$C_p = C_{p0} \ln\left(\begin{matrix} 1{,}248 - 0{,}703 \sin\left(\frac{\alpha}{2}\right) - 1{,}175 \sin^2(s\alpha G) + 0{,}769 \cos\left(\frac{\alpha}{2}\right) \\ + 0{,}07G^2 \sin^2\left(\frac{\alpha}{2}\right) + 0{,}717 \cos^2\left(\frac{\alpha}{2}\right) \end{matrix}\right) \qquad (8)$$

When the pressure difference is calculated, the orifice equation can be used to calculate the airflow rate through a given opening.

$$Q = C_d A \sqrt{\frac{2 \Delta P}{\rho}} \qquad (9)$$

C_d	=	turbulent flow	=	0,8
A_{eff}	=	opening (m^2)		
P	=	pressure (Pa)		
ρ	=	density of air (kg/m^3)		

Ventilation can occur in different air exchange efficiencies, depended on the location of the in-and outlet in the room. The efficiency expresses how fresh air is distributed in a room, which dilutes the polluted indoor air with clean air. Short-circuit (Q1) is the situation in which the air supplied is almost immediately exhausted, resulting in a low air exchange efficiency of around 0 (Figure 3-3). Mixing (Q2) is when incoming air is uniformly mixed with the interior air mass, which results in a good air exchange efficiency of around 0,5. Displacement (Q3) provides the highest air exchange efficiency of around 1, where the incoming air displaces the polluted indoor air. A combination of mixing and displacement is most common in practice. While from an air quality aspect displacement is the most optimal solution, due to the high air exchange rate, very precise operating conditions are mandatory. Occupant behavior and activities can impair these systems, making them unusable for residential buildings (Bluyssen, 2009).

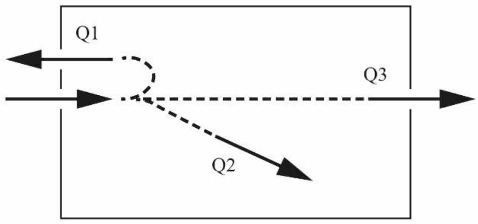


Figure 3-3 ventilation efficiency (own illustration)

$$Q_1 = short - circuit$$
$$Q_2 = mixing$$
$$Q_3 = displacement$$

The window opening strategy will aim for the highest air exchange efficiency by opening windows opposite to each other, creating as much displacement of polluted air as possible. This will never reach an air exchange efficiency of 1, due to occupant activities and comfort. This ventilation strategy will reach an air exchange efficiency higher than 0,5 because mixing is kept to a minimum. Therefore, an air exchange of 0,8 will be used during the calculations of the living room, which is the air exchange efficiency for a combination of mixing (0,5) and displacement (1). This air exchange efficiency can't be reached in the bedroom, because operable window elements are only on one side of the room. Therefore, an air exchange efficiency of 0,5 will be used for the calculations of the bedroom, which is similar to mixing. Air infiltration will also have an air exchange efficiency of 0,5. The air exchange efficiency will only be used during the calculation of the pollutant levels. This efficiency will be multiplied with the air change rate in the calculation, lowering the effective air change rate and thus reducing the effectiveness of the cleaning potentials of the ventilation strategy.

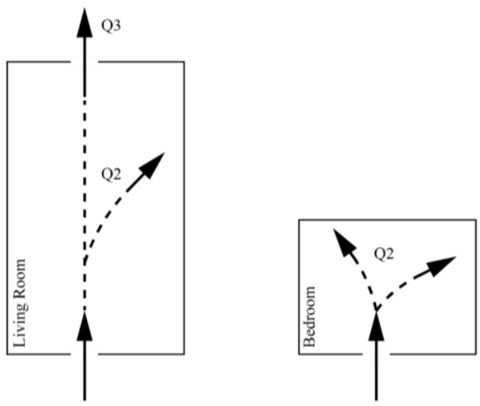


Figure 3-4 ventilation efficiency per room

$$Q_2 = mixing = 0,5$$
$$Q_3 = displacement = 1$$

3.3 Ventilation strategies

Hand calculations will used to determine different ventilation strategies and their potential to reduce the indoor air pollutants. Hand calculations are the preferred method for this stage of the design, due to the clear understanding of the effect for each parameter. The energy saving potentials will be determined in DesignBuilder, which is a modelling tool to accurately determine energy usage. The ventilation strategy will be determined based on the parameters in the living room with kitchen and the bedroom of the residential building, because these two rooms are most occupied by a user. Ventilation rate or thresholds will be determined for each strategy. The calculated air change rate is additional to the existing air infiltration rate.

Strategy 1, bouwbesluit

No ventilation facilities are built into the residential building, thus the first ventilation strategies is conform the Dutch Building codes, which is 0,7l/s/m^2 (Bouwbesluit 2012, 2018). The room is 2,68 meters in height, therefore a constant air change rate will be set to 0,95 ACH.

$$air\ change\ rate\ = \frac{0{,}7\ *\ 3600}{1000\ *\ 2{,}68} \approx\ 0{,}95\ ac/h$$

The air change rate will increase when cooking with 21l/s (Rijksoverheid, 2018). The total volume of the room is 106m^3, therefore a constant air change rate will be set at 1,7 ACH when cooking. This air change rate will have an higher effectiveness due to the use of an extractor hood, as discussed in chapter 2.3.2.3.

$$air\ change\ rate\ = \frac{0{,}7\ *\ 3600}{1000\ *\ 2{,}68} + \frac{21\ *\ 3600}{106} \approx\ 1{,}7\ ac/h$$

Strategy 2, minimum setting

Most mechanical ventilation systems have three preset settings for the desired ventilation capacity. Setting one should be used for when the building is unoccupied, setting two is mostly conform the Dutch building codes and setting three should be used for when there is visit and the demand for fresh air increases. Research shows that setting one is the most used setting with 89% of households using this setting for 12 hours or longer per day. Setting three is the second most used setting, 57% of households use this setting during cooking. Setting two is the least used setting, where 68% of the households never used it. This manual input of choosing a setting is misused by a user, where the occupant forgets to switch the setting to the appropriate setting or uses setting one because of the lowered acoustical discomfort (Bader & Blaauboer, 2009). This strategy will simulate a passive user with a similar system that seeks comfort on an acoustical level at the expense of IAQ. The ventilation capacity of an ITHO ventilation installation will be used for the calculations and simulation, which is a commonly used installation for residential use. ITHO products have a preset minimum ventilation capacity for setting one of 25m^3/h (Itho Daalderop, 2017). The living room has a volume of 104m^3 and the bedroom has a volume of 35m^3.

$$air\ change\ rate\ in\ the\ livingroom\ = \frac{25}{104} \approx\ 0{,}24\ ac/h$$

$$air\ change\ rate\ in\ the\ bed\ room = \frac{25}{35} \approx\ 0{,}71\ ac/h$$

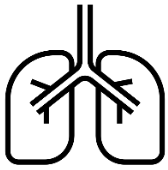
The air change rate for the living room will be set at 0,24ACH and 0,71ACH for the bedroom.

Strategy 3, same exposure

The third strategy is based on reaching similar pollutant exposure and ventilation rate as for the first ventilation strategies, but reducing the air change rate to 0,0 ACH when no occupants are present in the room. This doesn't create a healthier environment for the user, compared to the ventilation strategy conform the Dutch building coded, but has energy saving potentials.

Strategy 4, threshold

The forth ventilation strategy is based on the threshold stated by the World Health Organization, which means that window opening action will occur at pollutants levels of 2,25g/m^3 of CO_2 and 50ug/m^3 of PM_{10} (World Health Organization, 2010). This strategy is similar to the experiment done by Francesca Stazi, which was discussed in chapter 2.4.4.



Strategy 5, own

The last strategy focusses on creating an IAQ which is around the threshold levels, meaning it is allowed to exceed the threshold for limited amount of time if energy can be saved that way. This creates and IAQ which is in between strategy 2 and 3.

3.4 Calculations methods

Hand calculations will be used to determine different ventilation strategies. These calculations will results in an air change rate which is necessary to create an safe or comfortable IAQ. These ventilation strategies have been calculated during the midweek and weekend, because user patterns and performed actions and activities differ during the week.

Based on literature study, carbon dioxide and particle matter will be used as indicators of indoor air quality. A number of factors influence the concentration of indoor pollutants in a confined space. Due to the fact that they all present time variability, CO_2 and PM_{10} concentration indoors considerably varies over time. Equations will be used to determine different ventilation strategies with hourly indoor concentrations and energy losses for an entire week.

3.4.1 CO_2 concentration

CO_2 concentrations can be calculated with a mass balance model (Figure 3-5).

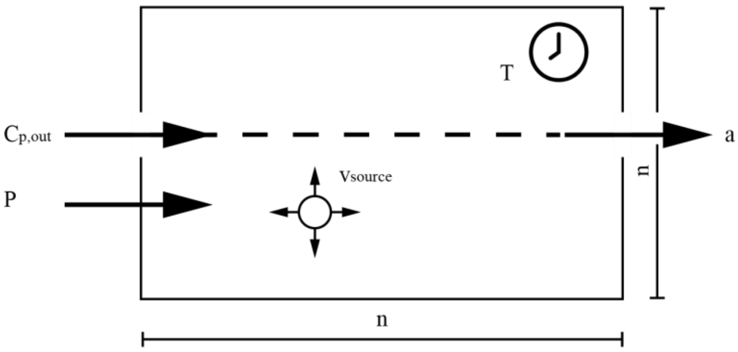


Figure 3-5 mass balance model

$$c = \left(\frac{v_{source}}{a\,V}\right)\left[1 - \left(\frac{1}{e^{a\,t}}\right)\right] + \left(C_{p\,in} - C_{p\,out}\right)\left(\frac{1}{e^{a\,t}}\right) + C_{p\,out} \tag{10}$$

$C_{p,in}$ = indoor concentration of particle mass ($\mu g/m^3$)

$C_{p,out}$ = outdoor concentration of particle mass ($\mu g/m^3$)

t = time (h)

a = air infiltration rate per hour (h^{-1})

P = particle penetration coefficient

V = volume (m^3)

v_{source} = indoor particle generation rate ($\mu g/h$)

(Engineering Toolbox, 2019)

3.4.2 Particulate matter concentration

Assuming that the particle concentration in the living room is uniform, the following mass balance for particulate matter can be written for a naturally ventilated building (Figure 3-6):

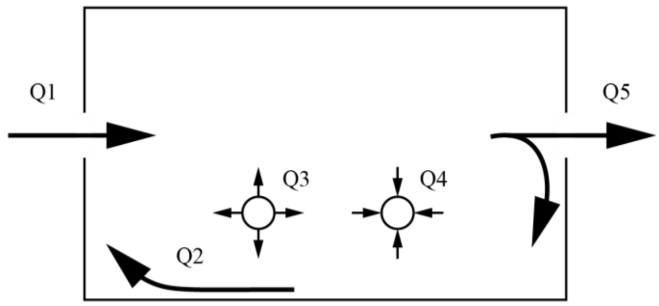


Figure 3-6 mass balance model

$$C_{P,in\,(T+\Delta T)} = C_{P,in\,(T)} + \frac{Q_{added}\ x\ \Delta T}{V} \tag{11}$$

$$Q_{added} = Q_1 + Q_2 + Q_3 - Q_4 - Q_5 \tag{12}$$

$$Q_1 = incomming\ particles = aPVC_{P,out} \tag{13}$$

$$Q_2 = particle\ resuspension = RL_f A_f \tag{14}$$

$$Q_3 = indoor\ particle\ source = v_{source} \tag{15}$$

$$Q_4 = particle\ deposition\ and\ extraction = (a+K)VC_{P,in} \tag{16}$$

$$Q_5 = particle\ filtration = v_{sink} \tag{17}$$

$C_{p,in}$ = indoor concentration of particle mass ($\mu g/m^3$)

$C_{p,out}$ = outdoor concentration of particle mass ($\mu g/m^3$)

T = time (h)

a = air infiltration rate per hour (h^{-1})

P = particle penetration coefficient

V = volume (m^3)

R = particle resuspension rate (h^{-1})

L_f = mass loading of particle on accessible surface ($\mu g/m^2$)

A_f = floor area (m^2)

v_{source} = indoor particle generation rate ($\mu g/h$)

K = particle deposition rate (h^{-1})

(Qian, Ferro, & Fowler, 2012)

All non-ventilation related elements of this equation, except the particle source, are set to'1' during the calculations. These elements are based on unknown parameters, making this formula unnecessarily difficult during this stage. These parameters can be used during a later stage in order to get a more accurate result. The following simplified mass balance is used (Figure 3-7):

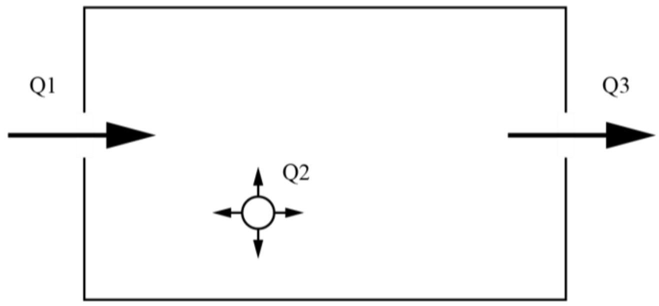


Figure 3-7 mass balance model

$$Q_1 = incomming\ pollution$$
$$Q_2 = indoor\ pollution\ source$$
$$Q_3 = extracted\ pollution$$

These are the exact same parameters as the calculations for the CO_2 concentration, therefor the same formula will be used to calculate the concentration of indoor particles. This method has been discussed and approved by my supervisor Regina Bokel.

$$C_{p\ in\ (T+\Delta T)} = \left(\frac{v_{source}}{a\ V}\right)\left[1 - \left(\frac{1}{e^{a\ \Delta T}}\right)\right] + \left(C_{p\ in} - C_{p\ out}\right)\left(\frac{1}{e^{a\ \Delta T}}\right) + C_{p\ out} \quad (18)$$

$C_{p,in}$	=	indoor concentration of particle mass (µg/m^3)
$C_{p,out}$	=	outdoor concentration of particle mass (µg/m^3)
T	=	time (h)
a	=	air change rate per hour (h^{-1})
V	=	volume (m^3)
v_{source}	=	indoor particle generation rate (µg/h)

The volume of the room that will be calculated is 106m^3 for the living room and 35m^3 for the bedroom. The calculation will be done with an interval of one hour. Other constant values that need a more elaboration are;

- outdoor CO_2 and pm concentration
- generation of indoor pollution
- dilution efficiency

For EU member States, the National Emission Ceiling Directive sets emission limits for man-made emissions, that are harmful for human health and the environment. Internationally, the issue of air pollution is also addressed by the UNECE Convention on Long-range Transboundary Air Pollution. Due to these legislations, the emissions have been decreased over the years, but due to the complex link between emissions and air quality, emission reductions do not always produce a corresponding drop in atmospheric concentrations. This is especially for particulate matter, which concentration levels depend on year by year variations in weather conditions including sunlight, natural emissions or very local emissions (European Environment Agency, 2014). Therefore, air quality measurements only determine the pollutants level in the air on that location. Location specific measures are presented in the NSL, Nationaal Samenwerkingsprogramma Lucht (Rijsoverheid, 2009). The PM_{10} concentration in Haarlem is around 20µg/m^3 on average, but can sometimes exceed to 60µg/m^3 (Rijksinstituut voor Volksgezondheid, 2019). The outdoor concentration will set at 20µg/m^3 as a fixed value during the simulation and calculations. Unknown seasonal variations will change the outcome, but these concentrations are unknown and will give unnecessary complication in this stage. The final system should have a PM_{10} sensor that measures local outdoor concentration.

The global concentration of carbon dioxide in the atmosphere hit 400 parts per million for the first time in recorded history in 2013, according to data from the Mauna Loa Observatory in Hawaii. Before 1950, atmospheric carbon dioxide had never been above 300 parts per million. Carbon dioxide concentration keep rising and reached around 413 parts per million in the beginning of 2019 (National Oceanic & Atmospheric Administration, 2019). This concentration will be used as a fixed value for the simulation and calculations. Carbon dioxide concentration will increase in the future, but to an unknow concentration, this will not be taken into consideration for the simulation and calculations. Thus, an outdoor concentration of 413ppm will be set as a fixed value.

3.4.3 Indoor pollution generation rate

Cooking emissions have long been seen as an odor problem. However recent field studies showed that Particulate Matter (PM) is the main health risk of indoor air and cooking can be a major indoor source of particulate matter (World Health Organization, 2013). Piet Jacobs, researcher at the TNO, has also shown that high concentration of particulate matter are produced during cooking, even when ventilation is conform Dutch building codes. Also, carbon dioxide concentration can increase rapidly when present in a confined space or when a room is full of people. These high concentration can have a great effect on sleep quality and concentration (Strøm-Tejsen, Zukowska, Wargocki, & Wyon, 2015). More pollutants can affect the human health, but will not be taken into consideration during the calculations and simulation. Particulate matter and carbon dioxide are two pollutants that are produced indoors in large quantities, therefor need to be ventilated.

3.4.3.1 CO_2 production

They main indoor source of carbon dioxide is that humans exhale carbon dioxide as part of respiration. Other sources are combustion of fossil fuels for cooking and heating, which will not be taken into consideration because future interventions will eliminate the use of fossil fuels. Combustion of paraffin candles will be taken into consideration during calculations and simulations.

Human production

Calculations will be made for the CO_2 production during breathing by subtracting the CO_2 concentration that is breathed in by the CO_2 concentration that is breathed out. The amount of air inspired per minute, respiratory hourly volume, is normally about 0,36m^3/min (0,5l/ breath × 12 breaths/min) (Barrett, Boitano, Barman, & Brooks, 2010). The inhaled air contains 413ppm of CO_2, as discussed in chapter 2.3.2, which is around 0,74 gram/m^3. The total CO_2 concentration that is breathed in can be calculated by multiplying the respiratory hourly volume with the inhaled CO_2 concentration, which is 0,27gram/h.

Pulmonologist M.G.J.A. van Lanen at Reinier de Graaf hospital in Delft showed that a human in rest exhales around 0,3 to 0,4l/min of CO_2, which depends on their metabolism and physical health. A constant CO_2 production of 0,35l/min will be used during the calculations, which is 21l/h. CO_2 has a molecular weight of 44g/mol, thus 1000 gram of CO_2 is 22,7 mol. The volume of 1000 gram of CO_2 can be calculated with the given formula:

$$V = \frac{nRT}{P} \tag{19}$$

V = Volume (L)

n = moles

R = gas constant = 0.0821 atm L/molK

T = Temperature (Kelvin) = 293k

P = Pressure (atm) = 1 atm

$$V = \frac{22.7 * 0,0821 * 293}{1} = 546l$$

A 1000 gram of CO_2 is 546L, making the exhaled CO_2 around 38,50 gram/h.

$$CO_2 \; mass \; per \; hour = 21 \; x \; \frac{1000}{546} = 38,50 \; gram/h$$

The total added CO_2 can be calculated by subtracting the CO_2 concentration that is breathed in with the CO_2 concentration that is breathed out.

$$CO_2 \; concentration = 38,50 - 0,27 = 38,23 gram/h$$

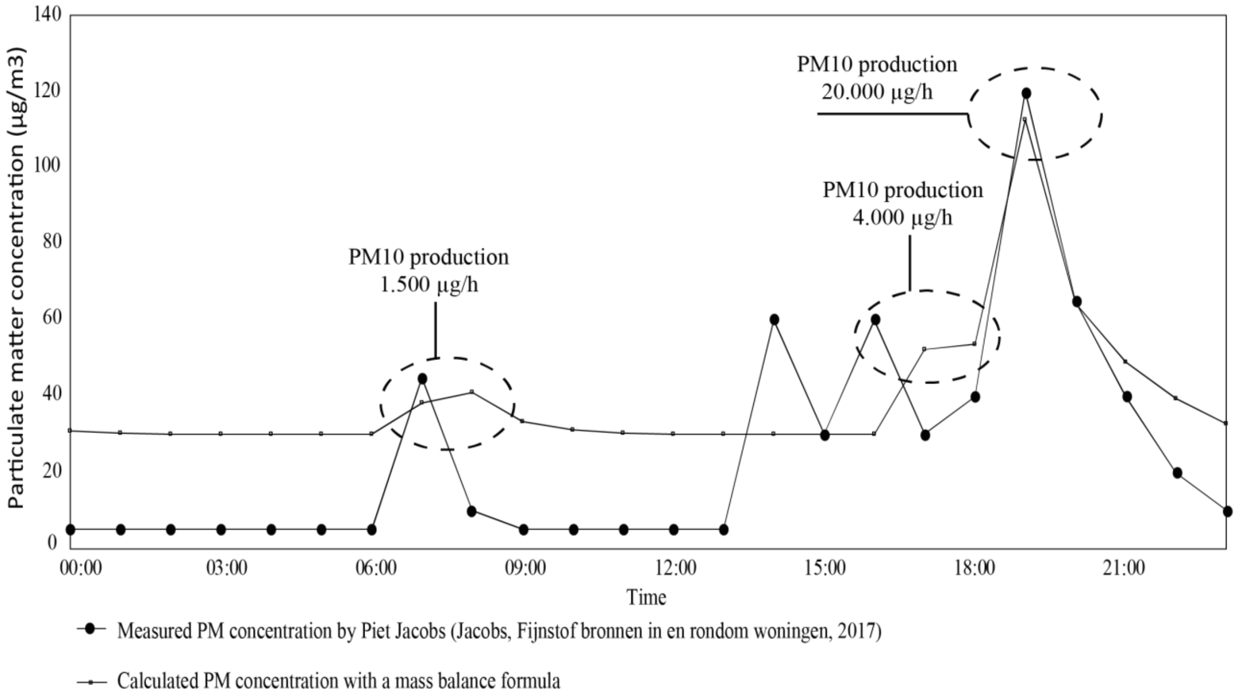
The total CO_2 production per human per hour will be set at 38,23gram/h. Calculations will not include different activities of an occupant that may alter the CO_2 production.

Paraffin wax

Most candles are made of paraffin, a heavy hydrocarbon derived from crude oil. Burning a paraffin candle for one hour will release around 10 grams of carbon dioxide (O'Carroll, 2009). During calculations, three candles will be burned during the night in the Livingroom.

3.4.3.2 PM production

The production of particle matter is difficult to determine. There are multiple actions that can occur in the indoor environment that result in an increase of indoor air pollutants, such as cooking, vacuuming, walking and much more. The increase of indoor air pollutants differs per action and no sufficient scientific evidence could be found on the exact amount of produced particle matter per action. The TNO has done research on the indoor sources of particulate matters. Piet jacobs measured particulate matter in the living room and kitchen of nine different dwellings with an optical particle counter during heating season. Figure 2-15, discussed in chapter 2.3.2.2, shows the average indoor pollutants of nine buildings on a Wednesday. These results will be used to determine the corresponding particulate matter production during the day. The mass balance equation (10) is used to create similar indoor pm concentrations (see figure). There are multiple differences between the calculated and the measured particulate matter concentrations. The building that Piet Jacobs conducted his measurements was outfitted with a mechanical ventilation system with a M6 filter, this resulted in a lower indoor particulate matter concentrations than outdoor particulate matter concentrations. Also, the measured results were from an Wednesday, a day in the week that children come home early from school. The calculated results didn't included this, resulting in different particulate matter concentrations during the afternoon.



3.4.4 Thermal energy loss due to ventilation and infiltration

The ventilation and infiltration loss for each ventilation strategy is calculated for a winter day and a spring/autumn day. An outside air temperature has been determined for each hour of each season (Figure 3-8). Each room will have a setback temperature of 15,6°C, which is an efficient setback temperature (Moon & Han, 2010). The bedroom will be heated to a temperature of 18,9°C, which is a comfortable temperature for sleeping (Wookey, Bone, Carmichael, & Crossley, 2014). The living room will be heated conform the adaptive thermal comfort algorithm, as discussed in chapter 2.3.1.

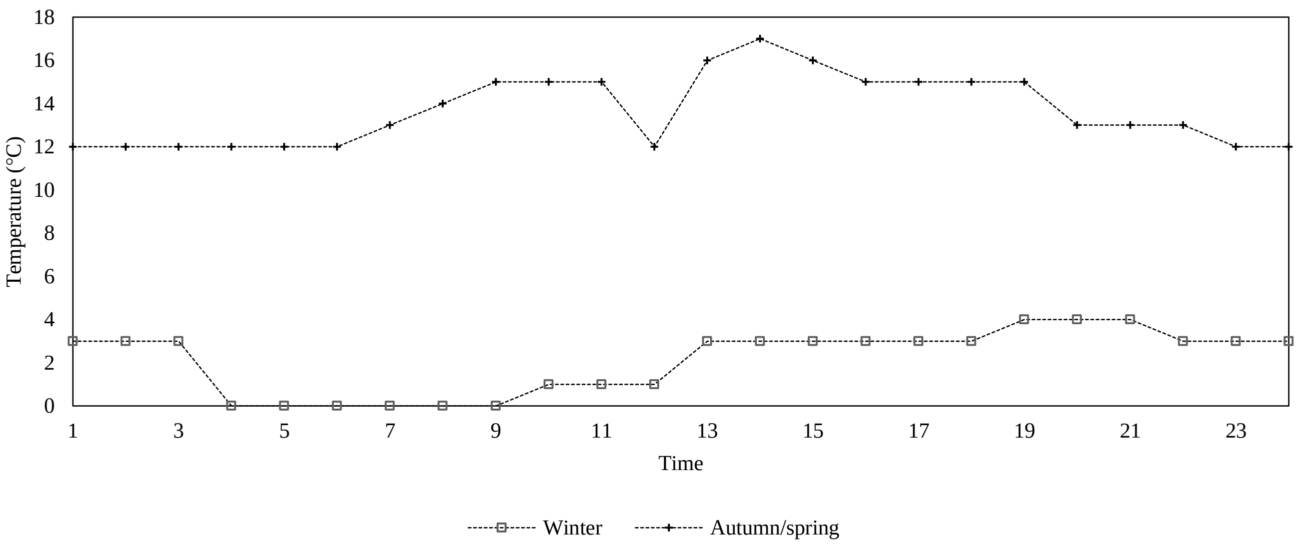


Figure 3-8 Outside temperature, based on average temperatures in winter and spring/autumn days in the Netherlands

Equation 20 will be used to quantify the energy loss due to ventilation and infiltration in the living room and bedroom.

$$Q_{vent} = \frac{\rho\ c\ V\ n\ \Delta T}{3600} \tag{20}$$

Q_{vent}	=	energy loss (W)
ρ	=	density of air (kg/m^3)
c	=	specific heat (J/kg K)
V	=	volume (m^3)
n	=	air change rate (ACH)
ΔT	=	temperature difference (°C)

3.5 Simulation

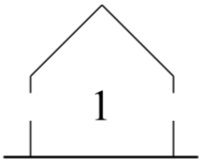
The energy saving and cooling potential of the various strategies will be simulated in Design Builder. Design Builder is a multipurpose program which allows to simulate complex 3D models with multiple input parameters. This gives it the potential to accurately simulate the indoor climates and energy consumption. Design Builder version 5.5.2.007 is used for all simulations. This project is located in the Netherland, therefore matching location and weather data will be used for the model. Data from the building plans and the MSc thesis from ir. L.L. Franx were used to create the model which is used for the simulations (Franx, 2018). By performing a simulation of a year, the annual energy consumption for heating will be calculated.

Figure 3-9 Design Builder model

The results from the hand calculations are used to create an accurate operation schedule for the natural ventilation. Characteristics regarding climate, geometry, zones, HVAC and user schedules have to be manually set under the designated tabs. Amsterdam is the nearest available location file with weather data that is built into Design Builder, which is located around 40km to the east of Haarlem. Therefore, Amsterdam has been set as the location. The air change rate for each ventilation strategies will be inserted in schedules under the natural ventilation tab. Mechanical ventilation will be switched off for the rooms that are tested with the proposed strategies, making natural ventilation via windows the only way of creating a comfortable IAQ.

The geometry has been created with the built-in interface in Design Builder, materials are determined on the model made in the MSc thesis from ir. L.L. Franx (Franx, 2018) and construction drawing received from Regina Bokel (Appendix B). The only change that has been made is the removal of the wall between the kitchen and the living room, creating an open kitchen, which is a common intervention in the Netherlands. This creates a situation where pollutants from the kitchen can flow to the living room, creating a bigger area that is exposed to harmful pollutants and that needs to be ventilated. This will create a more realistic estimation of the potentials of the designed strategies.

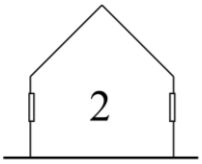
Four simulations will be done per ventilation strategy. The first simulates the potentials of each of the five strategies in the existing building (Table 3-4), simulating a simple retrofit. The second simulates the potentials of the designed strategy in the existing building with improved infiltration, simulating an installment of upgraded windows frames. The third simulates the building with a poor air infiltration, but with a small improvement of the U-values of the building envelop (Table 3-5). The walls, roof and floor will be insulated, without loss of interior space or need of building permits. The cavity in the double layer brick wall, 50mm, will be filled with insulation. The roof and floor will be outfitted with 100mm rockwool, which fits between the wooden rafters. Also the new window frames will have an improved U-value. This scenario will show the potentials of this system in buildings with different properties. The last simulation determines the potentials of the designed strategies in combination with a building that has an improved building envelope and better air tightness, simulating a small renovation.



Simulation 1: Existing building

Properties:

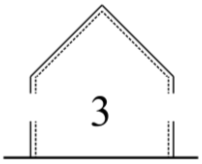
- Poor infiltration rate (12 ACH at 50 pascal)
- Poor insulation (Table 3-4)



Simulation 2: Improved airtightness

Properties:

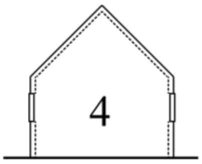
- Improved infiltration rate(12 ACH at 50 pascal)
- Poor insulation (Table 3-4)



Simulation 3 :Insulated envelop

Properties:

- Poor infiltration rate (7 ACH at 50 pascal)
- Improved insulation (Table 3-5)



Simulation 4: Renovated building

Properties:

- Improved infiltration rate (7 ACH at 50 pascal)
- Improved insulation (Table 3-5)

Construction	Structure type	U-value (W/m^{2}K)
External wall	Brick cavity wall	0,98
Wooden ground floor	Wooden floor	0,75
Concrete ground floor	MUWI concrete floor	1,75
Pitched roof	Wooden roof	1,26
Flat roof	Wooden roof	1,36
Dormer wall	Wooden structure	0,55
Dormer roof	Wooden roof	1,36
Doors	Low standard doors	2,82
Glazing	Low standard double glazing	2,76
Frames	Wooden frames	2,62

Table 3-4 Original building properties (Franx, 2018)

Construction	Structure type	U-value (W/m^{2}K)
External wall	Brick cavity wall	0,49
Wooden ground floor	Wooden floor	0,35
Concrete ground floor	MUWI concrete floor	0,35
Pitched roof	Wooden roof	0,45
Flat roof	Wooden roof	0,46
Dormer wall	Wooden structure	0,55
Dormer roof	Wooden roof	0,46
Doors	Low standard doors	2,82
Glazing	Low standard double glazing	1,50
Frames	Wooden frames	2,62

Table 3-5 Building properties after small renovation

Other inputs are similar to the used parameters and standard values during the hand calculations.

3.6 Results

3.6.1 Air change rate potential

The air change rate through a window opening depends on several parameters, several are fixed values that depend on the dimensions of the room and location of the window opening. The volume of the living room is 106m^3 and the volume of a bedroom is 35m^3, the location of the window is set at 1 meter above the ground. The other parameters, windspeed and window opening, are used to create a graph in order to characterize the air change rate in the living room (Table 3-6) and bedroom (Table 3-7).

Living room	Wind speed							
Window opening	1 m/s	2 m/s	3 m/s	4 m/s	5 m/s	8 m/s	10 m/s	15 m/s
50cm^2	0,1	0,1	0,2	0,3	0,4	0,6	0,7	1,0
100cm^2	0,1	0,3	0,4	0,6	0,7	1,1	1,4	2,1
200cm^2	0,3	0,6	0,8	1,1	1,4	2,2	2,8	4,2
300cm^2	0,4	0,8	1,3	1,7	2,1	3,4	4,2	6,3
400cm^2	0,4	1,1	1,7	2,2	2,8	4,5	5,6	8,3
500cm^2	0,7	1,4	2,1	2,8	3,5	5,6	7,0	10,4
1000cm^2	1,4	2,8	4,2	5,6	7,0	11,1	13,9	20,9
2000cm^2	2,8	5,6	8,3	11,1	13,9	22,3	27,8	41,7
3000cm^2	4,2	8,3	12,5	16,7	20,9	33,4	41,7	62,6

Table 3-6 Air change rate potentials in the living room

Bedroom	Wind speed							
Window opening	1 m/s	2 m/s	3 m/s	4 m/s	5 m/s	8 m/s	10 m/s	15 m/s
50cm^2	0,2	0,4	0,6	0,8	1,0	1,7	2,1	3,1
100cm^2	0,4	0,8	1,3	1,7	2,1	3,3	4,2	6,2
200cm^2	0,8	1,7	2,5	3,3	4,2	6,7	8,3	12,4
300cm^2	1,3	2,5	3,7	5,0	6,2	10,0	12,4	18,6
400cm^2	1,7	3,3	5,0	6,7	8,3	13,3	16,5	24,8
500cm^2	2,1	4,1	6,2	8,3	10,3	16,5	20,7	31,0
1000cm^2	4,1	8,3	12,4	16,5	20,7	33,0	41,3	62,0

Table 3-7 Air change rate potentials in the bedroom

These graphs show that the air change rate of fresh air for a room depends on the wind speed and window opening. The window opening can be adjusted by a user or by an actuator in order to adjust the air change rate. The wind speed can’t be adjusted or influenced by a user or actuator, which means that not all air change rates can be created at any moment of time. Additional mechanical pressure can be created with a fan, but will not be investigated during this research.

3.6.2 IAQ strategies

The five different strategies create different air change rates in the living room with an open kitchen with an air infiltration rate of 0,8ACH. These strategies are plotted in a graph for a midweek day (Figure 3-10), the corresponding CO_2 (Figure 3-11) concentration and PM_{10} (Figure 3-12). These strategies are also calculated during a weekends day and in a building with a lower air infiltration rate (Appendix D).

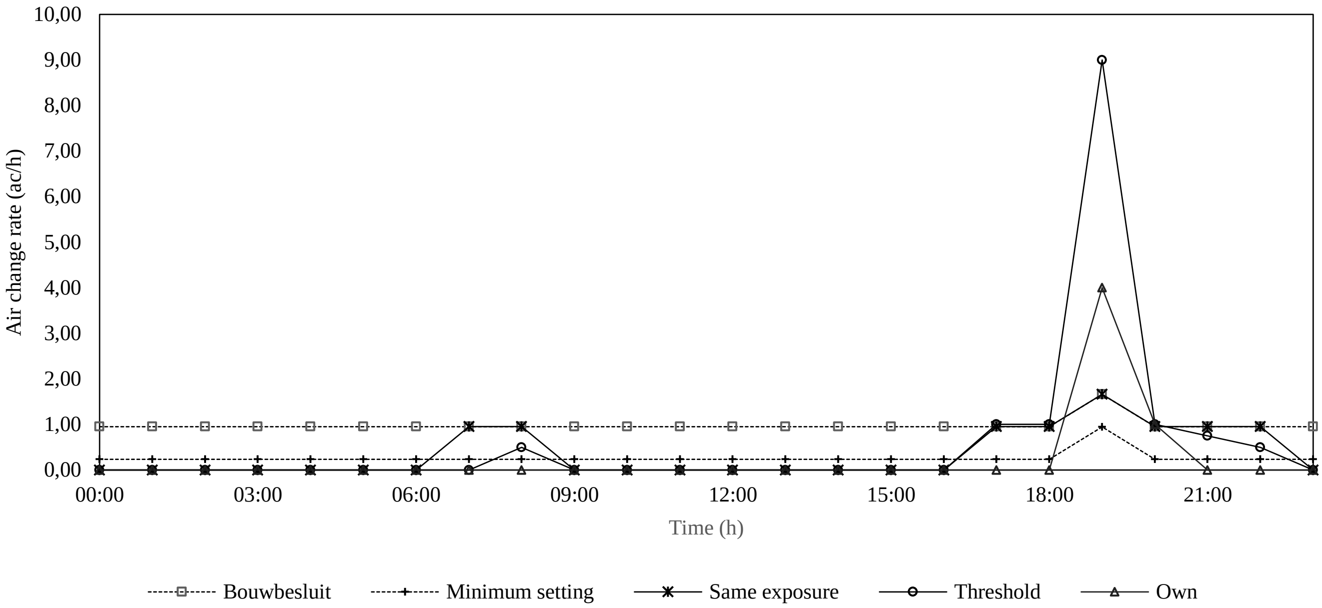


Figure 3-10: Air change rate in the living room with an infiltration of 0,8ACH(midweek)

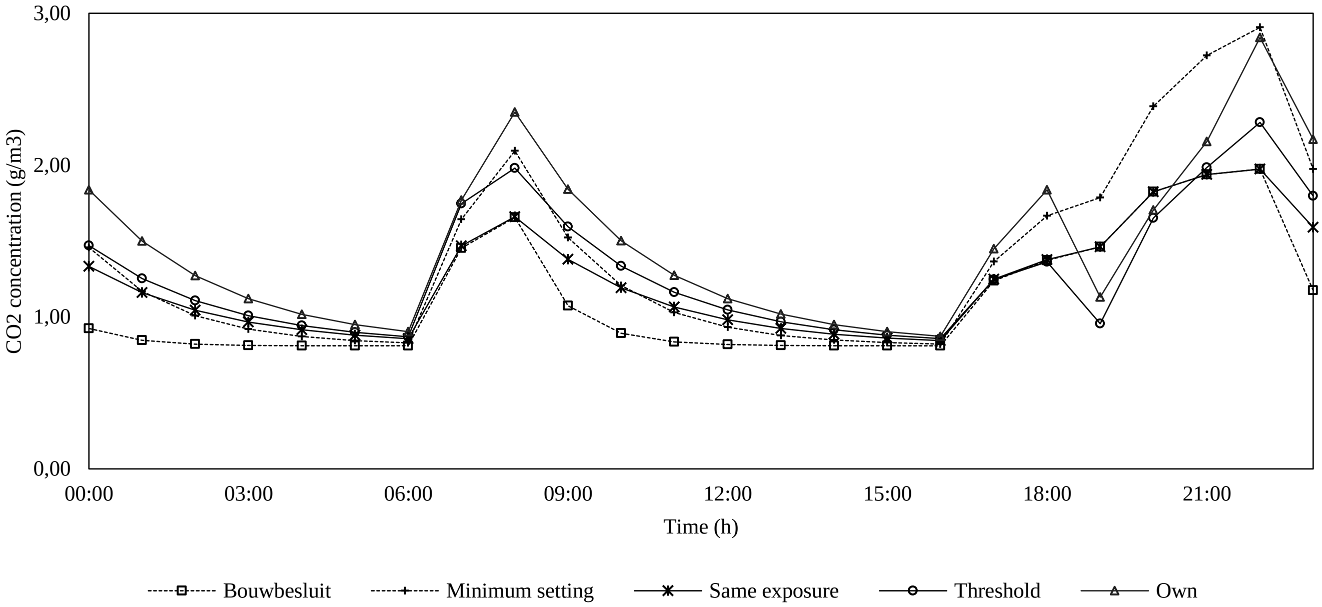


Figure 3-11 CO_2 concentrations in the living room with an infiltration of 0,8ACH (midweek)

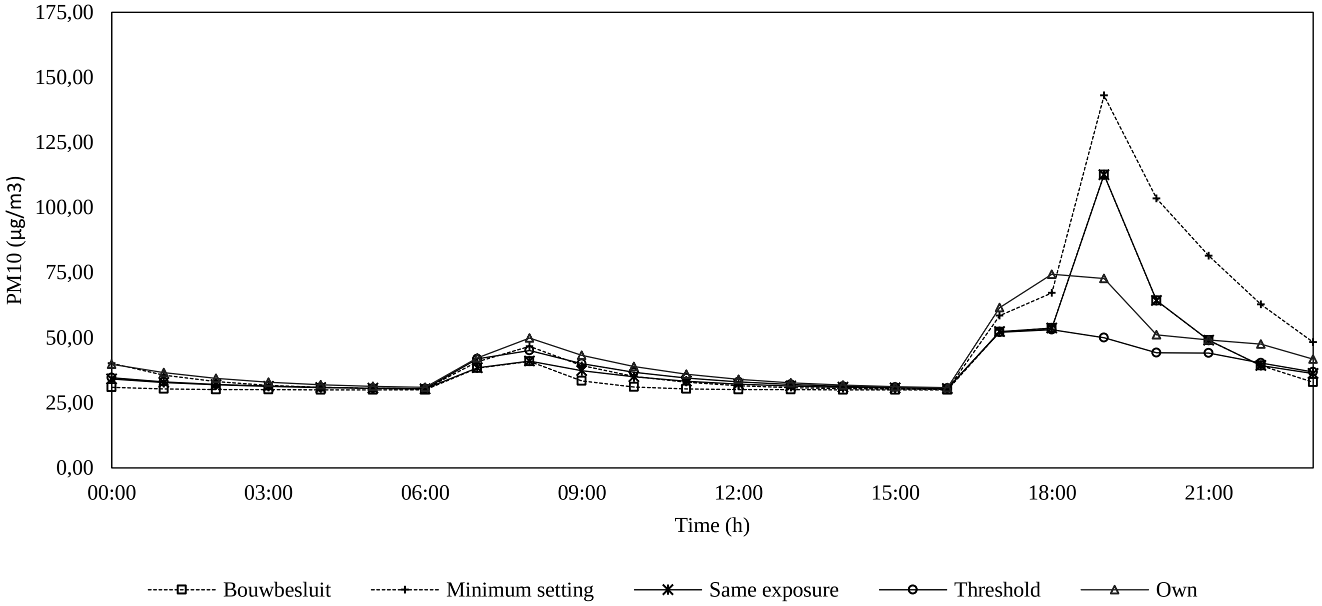


Figure 3-12 PM_{10} concentration in the living room with an air infiltration rate of 0,8ACH (midweek)

The indoor PM_{10} concentration for the strategy "bouwbesluit" has been manipulated by adjusting the PM production to match the graph made by Piet Jacobs (Figure 2-15) as discussed in chapter 3.4.3.2 (Appendix E). The ventilation capacity conform the Dutch building code is able to keep the CO_2 concentrations below the thresholds stated by the WHO, but isn't able to keep the PM_{10} concentration at a safe level. The strategy "min. setting" creates an even worse IAQ, where both the CO_2 and the PM_{10} concentrations exceed the thresholds states by the WHO. The strategy "same exposure" creates almost the same levels of pollution during the entire day, but reduces the ventilation capacity in order to lower the thermal loss. The strategy "threshold" only ventilates when pollutants exceed 2,25g/m^3 of CO_2 or 50μg/m^3 of PM_{10}. High concentrations of particle matter are released during cooking, resulting in an air change rate of 9 ACH during cooking, which can lead to discomfort due to high windspeeds. Strategy "own" allows higher concentrations by lowering the air change rate, which can be beneficial for thermal loss and comfort, due to lower windspeeds during cooking.

The spikes in air change rate are due to the high concentration of particulate matter during cooking. Piet Jacobs, researcher at the TNO, has done research in ventilation strategies during cooking, where he discovered that the shape of an extractor hood can increase the effectiveness of pollutant extraction. Therefore, the air change rate or air flow rate can be lowered. His redesigned extractor hood had an air flowrate of 300m^3/h, air change rate of 3 ACH for a living room of around 100m^3, which resulted in and average particulate matter exposure of 30 μg/m^3 (Jacobs, Cornelissen, & Borsboom, 2017). This will not be taken into consideration during further calculations and simulations, because the designed product doesn't include an upgraded extractor hood. But if discomfort is created due to high air velocities, it can be solved with an extractor hood that is similar to the one that Piet Jacobs used during his experiments.

The five strategies create different air change rates in the bedroom (Figure 3-13), except for strategy which is conform the Dutch building codes. These lines represent the air change rate due to window opening without air infiltration, which is set at 0,8 ACH for these calculations. These strategies purely focusses on the removal of CO_2, not particulate matter, because no particulate matter sources are located in the bedroom (Figure 3-14). The strategy is also calculated in a building with a lower air infiltration rate (Appendix D).

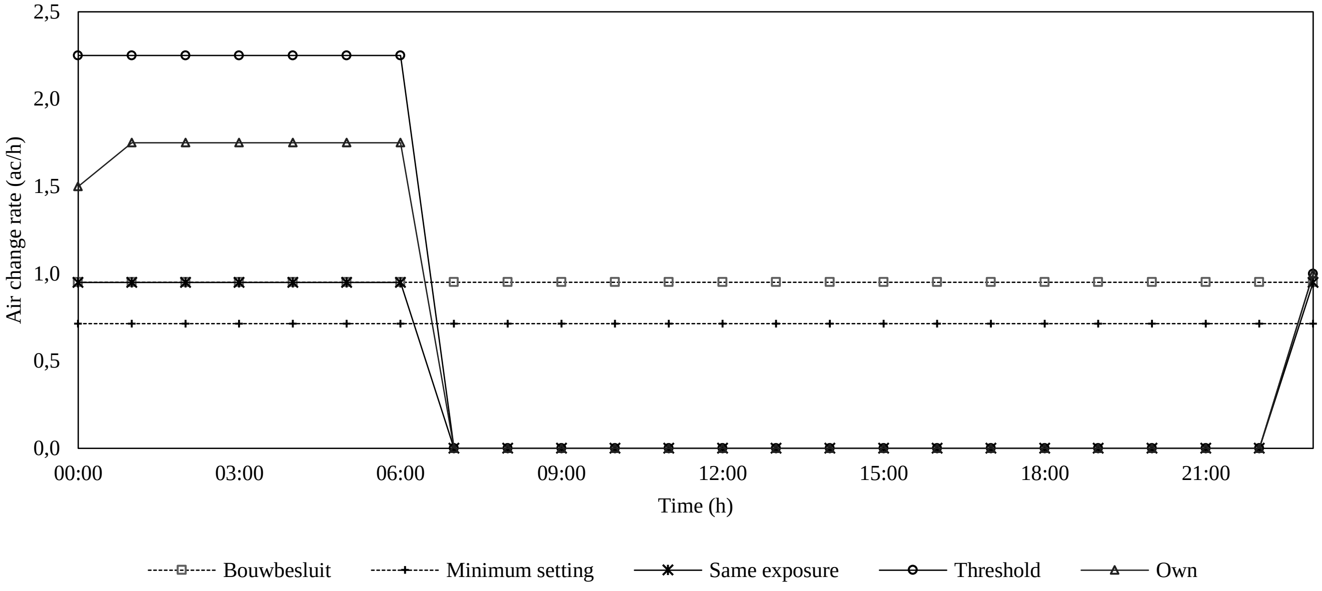


Figure 3-13 Air change rate in the bedroom with an air infiltration rate of 0,8ACH (midweek)

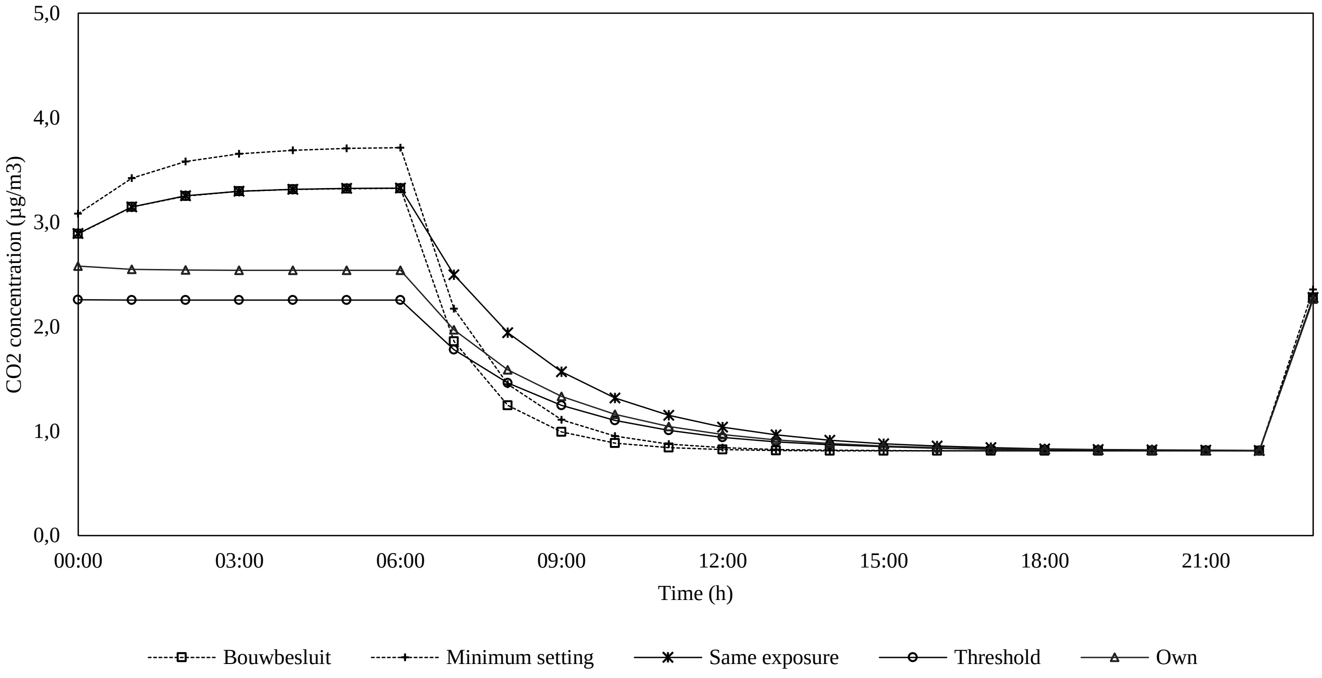


Figure 3-14 CO_2 concentration in the bedroom with an air infiltration rate of 0,8ACH (midweek)

The CO_2 concentrations exceed the threshold stated by the WHO for the strategies “bouwbesluit”, “minimum setting” and “same exposure”. This means that the ventilation capacity stated in the current Dutch building code doesn’t guarantee a healthy IAQ in a bedroom with two people. The CO_2 concentrations are lower for strategy “threshold” and “own”.

3.6.3 Thermal energy loss due to ventilation and infiltration

The ventilation and infiltration loss for each ventilation strategy is calculated for a winter day and a spring/autumn day. The used parameters for indoor and outdoor temperatures can be found in chapter 3.4.4. The used ventilation rates for each strategy and corresponding CO_2 and PM_{10} concentrations can be found in Appendix F. The energy loss due to air infiltration and ventilation in the living room has been calculated for a midweek day, when the occupants work, and for a weekend day, when the occupants are at home for the entire day (Table 3-8).

Ramplaankwartier	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5
Living room	Bouwbesluit (kWh/day)	Minimum setting (kWh/day)	Same exposure (kWh/day)	Threshold (kWh/day)	Own (kWh/day)
Winter(midweek)	22,4	13,4	15,0	17,5	12,9
Winter(weekend)	24,2	14,5	19,8	19,5	17,3
Autumn(midweek)	6,7	4,1	5,5	7,1	4,8
Autumn(weekend)	10,1	6,0	8,8	9,4	7,8

Table 3-8 Thermal energy loss in the living room due to ventilation infiltration (0,8ACH)

Strategies 1, 2 and 3 are conform the Dutch building codes or common practice situations, where ventilation rates will not change when people occupy a room. The additional energy loss due to ventilation during the weekend is only due to the increased time that heat is demanded. The impact of a higher occupancy rate during the weekend has an impact larger thermal loss for strategy 4 and 5.

Ramplaankwartier	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5
Living room	Bouwbesluit (kWh/day)	Minimum setting (kWh/day)	Same exposure (kWh/day)	Threshold (kWh/day)	Own (kWh/day)
Winter(midweek)	17,5	8,4	10,0	13,8	8,7
Winter(weekend)	18,8	9,0	14,4	16,2	12,2
Autumn(midweek)	5,2	2,6	4,0	6,3	3,6
Autumn(weekend)	7,8	3,8	6,6	7,9	5,7

Table 3-9 Thermal energy loss in the living room due to ventilation and infiltration (0,4ACH)

The lowered air infiltration has an positive effect on the energy saving potentials for every strategy. In winter, the energy losses due to ventilation and infiltration are lowered by 5 kWh/day for strategy 1, 2 and 3 and around 4 kWh/day for strategy 4 and 5. During spring and autumn, this energy loss due is lowered by 1,5 kWh/day for strategy 1,2 and 3 and around 0,8 kWh/day for strategy 4 and 5 during midweek. Overall, the lowered air infiltration rate has a larger effect on strategy 1, 2 and 3 than on 4 and 5. The energy losses in the bedroom shows a different characteristic (Table 3-10).

Ramplaankwartier	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5
Bedroom	Bouwbesluit (kWh/day)	Minimum setting (kWh/day)	Same exposure (kWh/day)	Threshold (kWh/day)	Own (kWh/day)
Winter	7,1	6,2	4,8	6,2	5,9
Autumn	1,5	1,3	1,3	1,8	1,7

Table 3-10 Thermal energy loss in the bedroom due to ventilation and infiltration (0,8ACH)

Strategy 2 and 3 have the best energy saving potential for the bedroom, but also create the least comfortable IAQ. Strategy 3 creates the same IAQ as strategy 1, but lowers the energy loss by only ventilating when an occupant is present in the room. Strategy 4 and 5 guarantee a safe and comfortable IAQ, at the cost of a higher energy loss. The effect of lowering air infiltration has a larger effect on strategy 1, 2 and 3, similar to the ventilation strategies that were made for the living room (Table 3-11).

Ramplaankwartier	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5
Bedroom	Bouwbesluit (kWh/day)	Minimum setting (kWh/day)	Same exposure (kWh/day)	Threshold (kWh/day)	Own (kWh/day)
Winter	5, 5	4, 5	3, 2	5, 0	5, 1
Autumn	1, 1	0, 9	0, 9	1, 6	1, 6

Table 3-11 Thermal energy los in the bedroom due to ventilation and infiltration (0,4ACH)

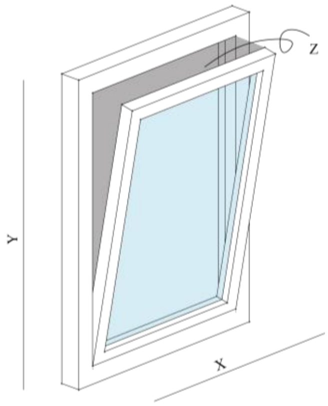
The lowered air infiltration has an positive effect on the energy saving potentials for every strategy. In winter, the energy losses due to ventilation and infiltration are lowered by 1,6 kWh/day for strategy 1, 2 and 3 and around 1 kWh/day for strategy 4 and 5. During spring and autumn, this energy loss due is lowered by 0,4 kWh/day for strategy 1,2 and 3 and around 0,1 kWh/day for strategy 4 and 5 during midweek. Overall, the lowered air infiltration rate has a larger effect on strategy 1, 2 and 3 than on 4 and 5.

While determining the ventilation rate for the different strategies, it showed that by lowering the infiltration rate, the air change rate through the windows had to be increased for the strategies that focusses on creating a better IAQ. Strategy 4 and 5 only ventilate when certain thresholds are met, uncontrolled air infiltration also contributes to the dilution of indoor air pollutants. By lowering the air infiltration rate, the air change rate through the windows had to be increased in order to meet the set indoor air pollution thresholds. This offsets the energy saving potential of the improved air tightness, which has a larger energy saving potential for a building without the designed ventilation strategy or a ventilation strategy that doesn't contribute in creating a more comfortable indoor air quality.

3.6.4 Cooling potential

The cooling potential of the proposed ventilation strategies are compared with a conventional ventilation system that creates an air change rate that is conform to the Dutch building codes. The living room and the bedroom on the south side of a rowhouse in the Ramplaankwartier have been used in order to investigates the cooling potentials on a warm summer day. Two ventilation strategies have been simulated, a ventilation strategies that is conform to the Dutch building regulations and a ventilation strategy based on the adaptive thermal comfort algorithm that tries to keep indoor temperatures within comfort limits. Both of these strategies are simulated in four different building envelop types, as discussed in chapter 3.5.

The maximum air change rate is set at 10ACH for the living room, which was the highest air change rate which was necessary to create a safe and comfortable indoor air quality. This air change rate simulates the potentials of a window of 70cm by 100cm that is tilted open with an average windspeed in July in Haarlem of 4,5m/s (Meteoblue, 2019), see chapter 3.6.1 and Figure 3-15. The maximum air change rate for the bedroom is also set at 10ACH, simulating the potentials of a window of 35cm by 70cm with an average windspeed of 4,5m/s. Larger window openings will be simulated if indoor temperatures rise above comfortable levels.



Location	X (cm)	Y (cm)	Z (cm^2)
Living room	70	100	2000
Bedroom	35	70	500

Figure 3-15 Window opening

The average indoor temperature in the living room of all the different building envelop types has been plotted in a graph (Figure 3-16). The adaptive thermal comfort algorithm tries to keep indoor temperatures below 26,2°C, which is based on a 90% acceptancy with the average outdoor temperature in July of 18,9°C (KNMI, 2019). The indoor temperature stays below 26,2°C for the thermal comfort based ventilation strategy until 10:00, after which solar load increases the indoor temperature 29°C. The thermal comfort based ventilation isn't able to keep the indoor temperature within comfortable limits from 10:00 until 19:00, due to the low air change rate. The ventilation rate based on the Dutch building codes only creates a comfortable indoor temperature between 04:00 and 06:00 in this simulated warm summer day, with an indoor temperatures reaching around 34°C. The thermal comfort based ventilation strategy lowers the indoor temperature by around 5°C, compared to the constant ventilation rate which is based on the Dutch building code, at the warmest moment of the day. Therefore, it contributes significant to thermal comfort, even though it isn't able to keep indoor temperatures within comfortable thermal limits.

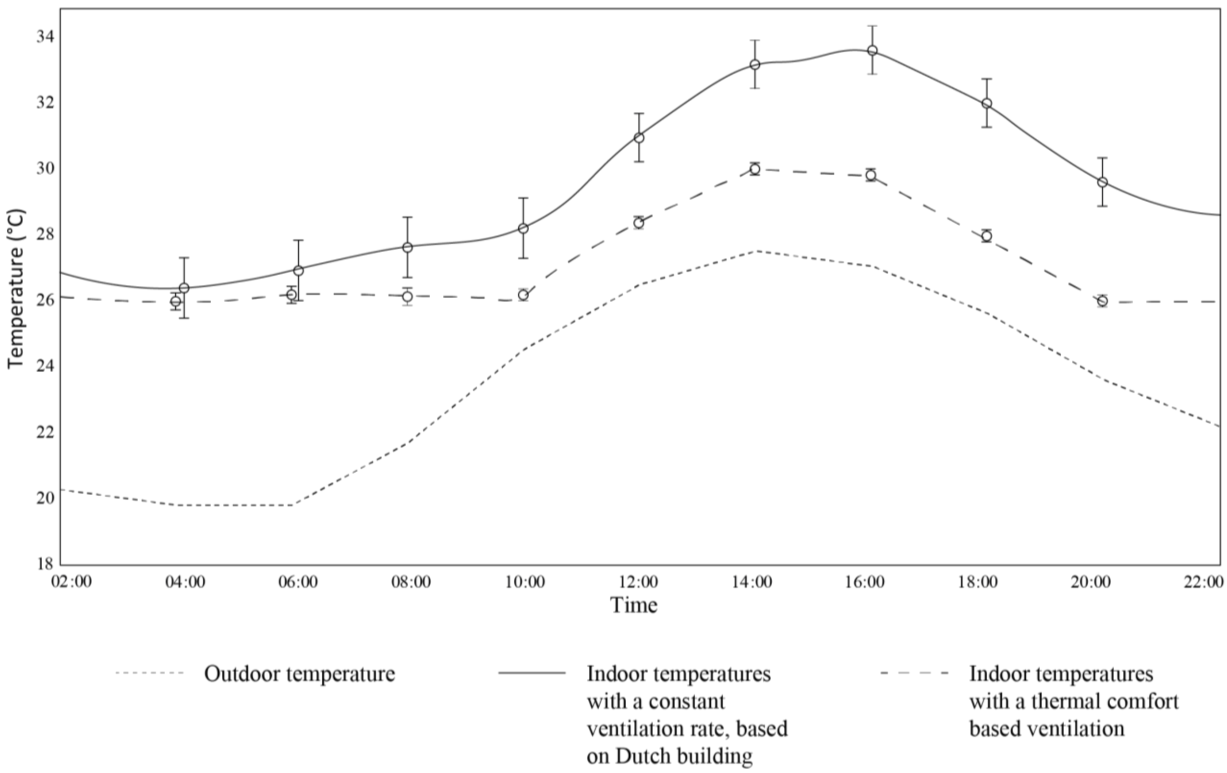


Figure 3-16 Indoor temperatures in the living room

An insulated building envelop result in a warmer indoor temperature for all ventilation strategies. The insulated building envelop has a higher resistance to heat flow, meaning a lower heat transfer through the building envelop. This is desirable during heating season, trapping the heat inside, but undesirable during a warm summer day when indoor temperatures exceed outdoor temperatures. A large deviation between indoor temperatures can be found between each building envelop type with the constant ventilation rate, which is based on Dutch building codes (Table 3-12). Especially during hottest time of the day, where the insulated building with improved infiltration rate can be almost 1,5°C warmer than the uninsulated building. The thermal comfort based ventilation shows a smaller deviation between each building envelop type.

	Constant ventilation	Thermal comfort based ventilation
Uninsulated and a poor infiltration rate	33,1 °C	30,0 °C
Uninsulated and an improved infiltration rate	33,4 °C	30,1 °C
Insulated and a poor infiltration rate	34,0 °C	30,1 °C
Insulated and an improved infiltration rate	34,5 °C	30,2 °C

Table 3-12 Maximum temperatures

Two large windows of 100cm x 70cm on each side of the living room and a windspeed of 4,5m/s will increase the air change rate to 20 ACH. This air change rate has the potential to lower indoor temperatures to 28,8°C for all building envelop types, with an outdoor temperature of 27,6°C. This shows that increasing the air change rate will lower indoor temperatures, but not significant due to the high outdoor temperature. The outdoor temperature is above a comfortable temperature of 26,2°C, therefore the ventilation strategy isn’t able to create a thermal comfort. The cooling potentials of this system is based on the outdoor temperature and windspeed, where indoor temperatures can’t reach temperatures lower than outdoor temperatures. Wind speed is defined as the change of position, which is expressed in meters per second (m/s). Air velocity can offset high temperature, creating comfort during summer. The ISO Standard 7730-2005 state that air velocity in a space influences the convective heat exchange between a person and the environment. For light primarily sedentary work, the max air velocity should be below 0,82 m/s, which results in a max temperature offset of 3 degrees (NEN-EN_ISO 7730, 2005). Different air velocities are tested on dry thermal heat loss on the head and covered body, by Simone and Olesen, in order to quantify the cooling potential of air velocity at three different room temperatures of 26 °C, 28 °C, and 30 °C. The air velocity was generated by a fan, placed 80cm perpendicular from the test manikin and 1,2m of the ground. These thermal manikins provided the local temperature on various body parts (Table 3-13).

Room temperature		26,0°C	28,0°C	30,0°C
Whole body	No fan	24,9°C	27,8°C	29,7°C
	0,6 m/s	24,7°C	27,5°C	29,2°C
	1 m/s	24,3°C	26,9°C	29,0°C
	1,5 m/s	-	26,5°C	28,8°C
Head	No fan	23,9°C	26,6°C	28,7°C
	0,6 m/s	21,4°C	24,5°C	26,7°C
	1 m/s	19,6°C	22,7°C	25,9°C
	1,5 m/s	-	21,6°C	25,1°C

Table 3-13 Local temperature of whole body and head (Angela & Bjarne, 2013)

An air change rate of 10ACH will result in a wind speed of around 0,05m/s in the narrowest point of the living room, calculated with equation 21. This air velocity will lower the temperature, but not significantly. Higher windspeeds will be felt near windows, due to the small cross section of the opening. Higher air change rates can be created with larger openings or higher wind speeds, but more than a large window of 70cm by 100cm on either side of the living room is not commonly present in existing buildings and therefore shows the limits and boundary conditions of this strategy.

$$\text{wind speed (m/s)} = \text{volume room x} \frac{\text{air change rate}}{\text{0,65 x cross section (of the room) x 3600}} \quad (21)$$

(ncbi, 2019)

The average indoor temperature in the bedroom of all the different building envelop types has been plotted in a graph (Figure 3-17). Also, similar to the living room, the adaptive thermal comfort algorithm tries to keep indoor temperatures below 26,2°C, which is based on a 90% acceptancy with the average outdoor temperature in July of 18,9°C (KNMI, 2019). The indoor temperature stays below 26,2°C for the thermal comfort based ventilation strategy until 09:00, after which solar load increases the indoor temperature 30°C. The thermal comfort based ventilation isn't able to keep the indoor temperature within comfortable limits from 10:00 until 19:00, due to the low air change rate. The ventilation rate based on the Dutch building codes can't create a comfortable indoor temperature during a warm summer day, with indoor temperatures reaching well above 33°C.

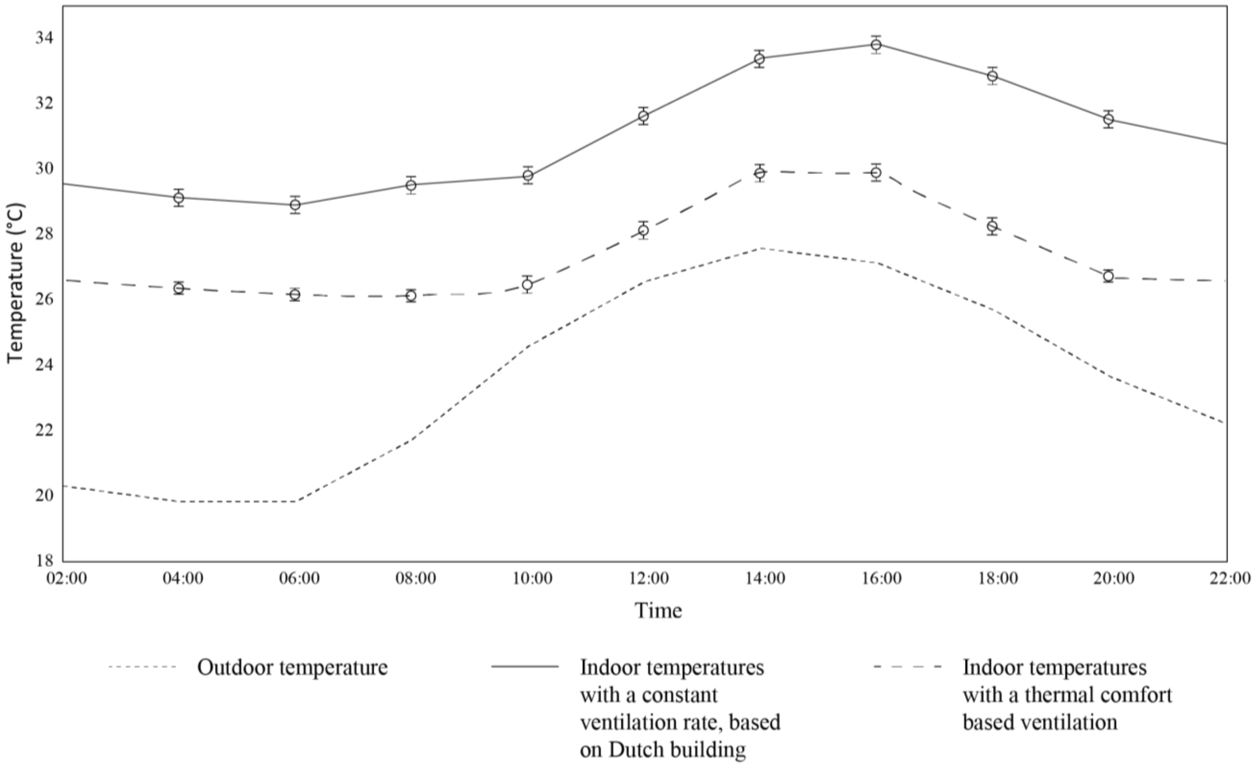


Figure 3-17 Indoor temperature in the bedroom

The thermal comfort based ventilation strategy can lower the indoor temperature by around 3°C during the entire day, compared to a constant ventilation rate which is based on the Dutch building codes. The deviation between each building envelop type is smaller, compared to the living room. The temperature difference between the uninsulated building envelop with a poor infiltrate rate is around 0,5°C lower compared to the insulated building envelop with and improved infiltration rate (Table 3-14). What is different from the living room, is that the insulated building type has a lower indoor temperature in the bedroom with the thermal comfort based ventilation strategy. During the simulations, it showed that the attic can get really warm, especially the uninsulated attic. This attic isn't outfitted with a thermal comfort based ventilation system, where indoor temperatures can reach 34°C. This will create a relative large heat transfer from the attic to the adjacent bedroom, which is larger for the uninsulated building envelop than for the insulated building envelop.

	Constant ventilation	Thermal comfort based ventilation
Uninsulated and a poor infiltration rate	33,5 °C	30,1 °C
Uninsulated and an improved infiltration rate	33,7 °C	30,2 °C
Insulated and a poor infiltration rate	33,7 °C	29,6 °C
Insulated and an improved infiltration rate	33,9 °C	29,6 °C

Table 3-14 Maximum temperature

Increasing the air change rate to 20 ACH will lower indoor temperatures to 27,7°C for all different building envelop types, with an outdoor temperature of 27,6°C. This air change rate creates an indoor temperature that is similar to outdoor temperatures, which is the maximum cooling potential of the ventilation strategy.

The adaptive thermal comfort based ventilation strategy can lower indoor temperatures in the living room and bedroom on a warm summer day in a rowhouse in Haarlem compared to a ventilation strategy that is based on the Dutch building code. This is not enough to keep indoor temperatures within comfortable limits during the entire day, due to high outdoor temperatures. High air change rates of around 20ACH are needed to lower indoor temperatures to match outdoor temperatures, which can only be created with relative large openings or high wind speeds.

3.6.5 Energy saving potential

The determined strategies are simulated for the building in the Ramplaankwartier. The ventilation strategies are only applied in de bedrooms and living room with kitchen. The strategy “bouwbesluit” will be used as a base line to compare and determine the energy saving potentials for the new designed strategies. Several simulations sets are made for each strategy, each with different building properties, as discussed in chapter 3.5.

The results of the simulations show a significant energy saving potential for the various strategies (Table 3-15). The effect of user behavior isn’t taken into account with strategy 1 and 2, therefor the energy consumption could be higher than this simulation shows.

Ramplaankwartier	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5
Building properties	Bouwbesluit (mWh/year)	Min. setting (mWh/year)	Same exposure (mWh/year)	Threshold (mWh/year)	Own (mWh/year)
0,8 ACH	19,8	15,9	15,4	15,7	14,2
0,4 ACH	16,9	13,8	13,2	14,4	12,9
0,8 ACH + small renovation	12,5	9,4	9,6	10,6	9,1
0,4 ACH + small renovation	10,5	7,5	7,9	9,1	7,7

Table 3-15 Energy consumption for the whole building

The current owners in this building consumed 2260m^3 of gas in 2016, which is for heating, hot domestic water and cooking. Energy consumption for heating will be estimated, because precise data for heating is not available. Around 80% of the total gas consumption is used for heating, meaning that approximately 1.800m^3 of gas is used for heating (Milieu Centraal, 2019). One cubic meter low calorific gas equals 9,77kWh on average (De energieconsultant, 2019), efficiency of the hr boiler will be set at 100%, meaning that the inhabitants consumed around 17.7mWh of energy from gas for heating in 2016. Simulation states an energy consumption for heating of 19.8mWh/year, which is a deviation of 10% compared to the actual consumption. As Design Builder will never be able to reproduce the exact same result due to differences in user behavior, weather and other parameters, a small deviation between the simulated and observed energy consumption is acceptable. The energy consumption can be reduced to 15.9mWh/year, by using the lowest setting on a mechanical ventilation system. This system is from an energy point of view interesting due to its energy savings of 20%, but creates an unsafe indoor environment.. The strategy called “same exposure” has the potential to lower the energy consumption for heating to 15,4mWh/year. Which is an energy consumption saving of around 22,5% compared to the current situation. Strategy “threshold” has the potential to lower the energy consumption for heating to 15,7mWh/year, which is an energy consumption savings of around 21% compared to the current situation. The final strategy “own” has the potential to lower the energy consumption for heating even further to 14,2mWh/year, which is an energy consumption savings of around 28% compared to the current situation. The strategies are only applied in the living room and bedrooms, other rooms are ventilated conform Dutch building codes and heating according to an pre-generated schedule, created by Design Builder. The energy saving potential of the strategies will increase when other rooms are also outfitted with the designed system.

The installment of new window frames will lower the approximated air change rate of 12 ACH at 50 pascal to an approximated air change rate of 7 ACH at 50 pascal. The current situation, with upgraded windows, will consume 16,9mWh/year of energy for heating, which is a decrease of energy consumption of 15%. The energy consumption will lower even further when using the lowest setting on a mechanical ventilation system to 13,8mWh/year, which is a decrease in energy consumption of 14% compared to the same strategy with an high air infiltration rate. The strategy called “same exposure” has the potential to lower the energy consumption for heating to 13,2mWh/year. This is a decrease in energy consumption of 14%, compared to the same strategy with an higher air infiltration rate. The impact of lowering the air infiltration rate has a small additional energy saving potential for the strategy called “threshold” of 8%, resulting in an estimated energy consumption for heating of 14,4mWh/year. The final strategy “own” has the potential to lower the energy consumption for heating to 12,9mWh/year, which is also a small decrease in energy consumption of 9%, compared to the same strategy with an higher air infiltration rate. Hand calculation showed that by lowering the infiltration rate, the air change rate through the windows had to be increased for the strategies that focusses on creating a better IAQ. The fourth and fifth strategies only ventilate when certain thresholds are met, uncontrolled air infiltration also contributes to the dilution of indoor air pollutants. By lowering the air infiltration rate, the air change rate through the windows had to be increased in order to meet the set pollution thresholds. This offsets the energy saving potential for the improved air tightness, which has a larger energy saving potential for a building without the designed ventilation.

The third set of simulations are done with a small renovation of the building envelope in combination with the poor air infiltration rate. The current situation with a renovated building envelope will consume 12,5mWh/year of energy for heating. This is a reduction of almost 37%, compared to the current situation. This renovation introduces insulation material, which the current building lacks, making the reduction in energy consumption quite large. The reduction in energy consumption is even larger when using the lowest setting of a mechanical ventilation system. It reduces the energy consumption for heating to 9,4mWh/year, which is a reduction of 41% compared to the same strategy in the current situation. The strategy “same exposure” with the improved building envelope has the potential to lower the energy consumption for heating to 9,6mWh/year. This is a decrease in energy consumption of 37%, compared to the same strategy without the improved building envelope. The impact of decreasing the u-values of the building envelope decreases the potential energy consumption to 10,6mWh/year for the strategy “threshold”. This is a decrease in energy consumption of 32%, compared to the same strategy without the improved building envelope. The final strategy “own” with the improved building envelope has the potential to lower the energy consumption for heating to 9,1mWh/year, which is also a decrease in energy consumption of 35%, compared to the same strategy without the renovation.

The final set of simulations have been done with a small renovation of the building envelope in combination with the improved air infiltration rate. The current situation with a renovated building envelope and upgraded windows will consume 10,5mWh/year of energy for heating. This is a reduction of almost 47%, compared to the current situation. By using the lowest setting of a mechanical ventilation system, energy consumption will lower to 7,5mWh/year, which is a reduction of 53%. The strategy “same exposure” has the potential to lower the energy consumption for heating to 7,9mWh/year. This is a decrease in energy consumption of 49%, compared to the same strategy without the improved building envelope. The impact of decreasing the u-values and improving the air infiltration rate of the building envelope decreases the potential energy consumption to 9,1mWh/year for the strategy “threshold”. This is a decrease in energy consumption of 42%, compared to the same strategy without the improved building envelope. The final strategy “own” with the improved building envelope has the potential to lower the energy consumption for heating to 7,6kWh/year, which is also a decrease in energy consumption of 46%, compared to the same strategy without the renovation.

3.7 Automated window mechanism

Multiple products from different manufactures are used to create a first system that can measure air quality and determine a corresponding action to it, which is to open or close a window. Companies that were interviewed and investigated during the literature study will be asked to sponsor parts in order to create a first prototype. This prototype will functions as a proof of concept and to determine if this system can be created with existing hardware and software. The sensors from Netatmo are well known and fit perfectly for this application, therefor the weather station sensor will be used to determine the IAQ. The window opener from AXA will be used to operate the window. These devices do not communicate with each other, therefor multiple communication actions are done in order to create the desired output. The entire process takes 3 steps, Figure 3-18.

Step 1

The Netatmo weather station is used to measure CO_2 concentrations and temperature. It uses WiFi to communicate with their own app or with third party apps.

Step 2

The Netatmo weather station sends the data to an applications called IFTTT, IfThisThanThat. IFTTT is a free web-based service to create chains of simple conditional statements, which are used to determine thresholds for IAQ and temperature. The parameters are monitored and checked if the pollution concentration and temperature does not exceed the preset thresholds. The threshold is set at 1200ppm for CO_2 and 25 degree for the tests. When IFTTT detects that thresholds are exceeded, it sends a signal to BLYNK.

Step 3

BLYNK is an Internet of Thing, IoT, platform which can be used to connect devices to the cloud, which is in this case the Arduino board. Virtual buttons are created in BLYNK that can control the Arduino board. The Arduino board consist out of an NodeMCU wifi module that includes firmware which runs on the ESP8266 Wi-Fi SoC from Espressif Systems. It’s a cheap wifi board that can be controlled and monitored from the internet. Two relays are connected to this board, which are used to control the remote controller from the AXA REMOTE 2.0. This remote controller uses infrared to send the signal, the duration of the infrared signal can be adjusted in order to open and close the window in multiple steps.

Code has been written, see Appendix H, which connects the device to the internet and determines the timing characteristics of relays. The characteristics of the relays can be adjusted in order to alter the increments of window opening.

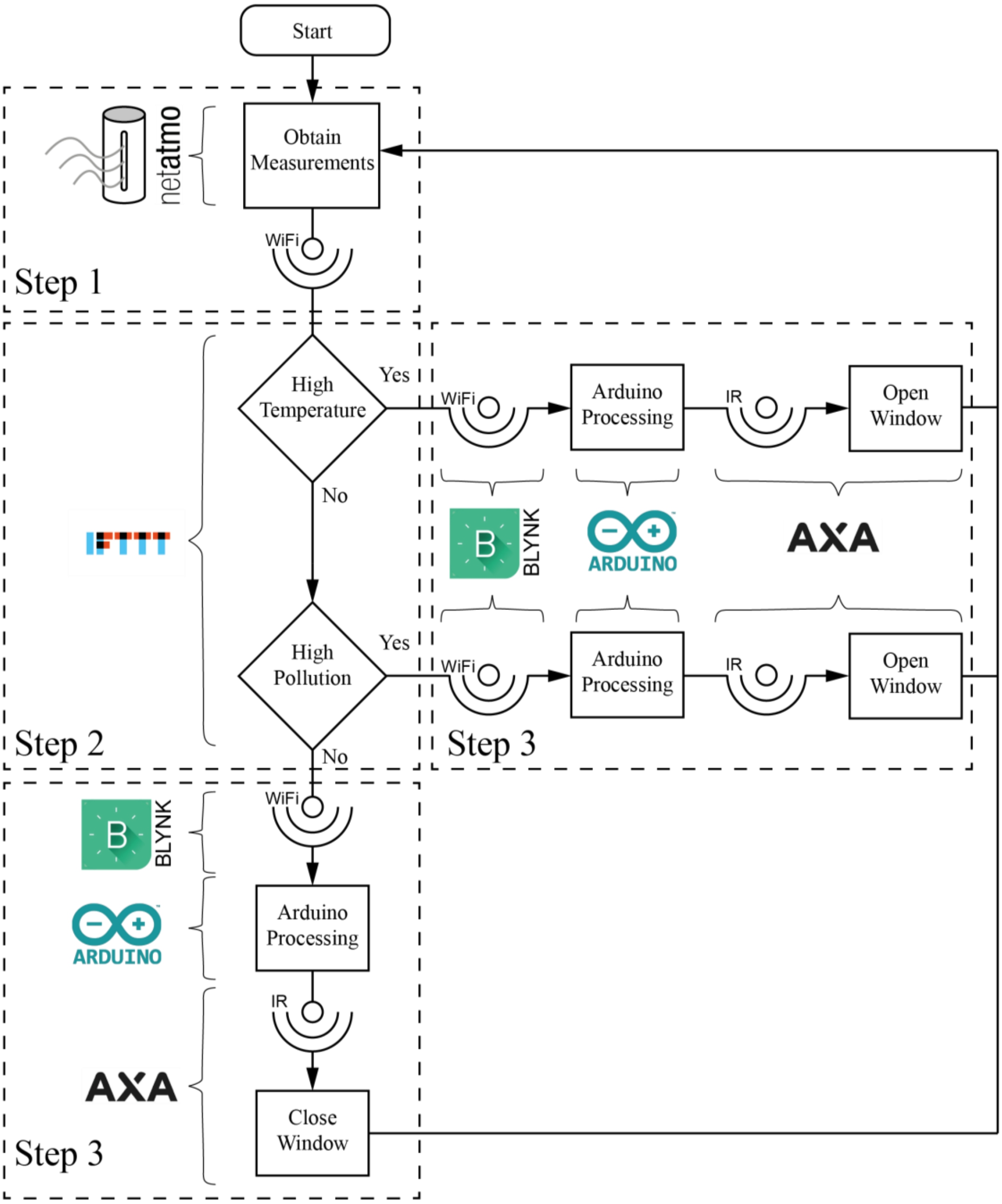


Figure 3-18 Flow chart mechanism

The system was able to open and close windows according to the measurements from the sensor. The reaction time between the sensor and the window actuator was slow, due to the way they communicate with each other. The biggest slowdown was at IFTTT, where the processing of the data could take up to an hour. The other steps, such and Blynk and Arduino, were almost instantaneously.

The optical sensor in the Netatmo weather station is, according to Arie den Hartog, quite accurate. It samples the CO_2 concentration every 5 minutes and sends the results, via Wi-Fi, to various applications. Connecting a system to the Wi-Fi creates opportunities, such as offsite monitoring and updating, but also vulnerabilities, such as the risk of hacking or data leaking. A Wi-Fi connection should be eliminated, due to potential data leaking and hacking. Unfortunately, this Netatmo weather station doesn't work without a Wi-Fi connection, which is one of the many problems of a pre-made smart product. The Netatmo weather station is hard to tinker with, adjusting different parameters of the sensor itself is almost impossible. The sample rate can't be adjusted, different sensors can't be added and communication between devices is slow and fails to keep up with IAQ development. The aesthetics of the sensors doesn't resemble a building product, it has the look and feel of a gadget. This means that when installed, it isn't an integrated part of the building, but the installment of an appliance which will be taken along when occupants move. This should be eliminated by changing the look and feel of the housing of the sensor.

The used actuator could be applied as a retrofit in smaller renovation projects, resulting in a finishing level that can be unwanted by an occupant. The motors create noise when operated, the actuator is quite bulky and it eliminates the operation of the window by hand. Also, the system doesn't know if the window is opened or closed, because there is no communication feedback from the actuator.

3.8 Conclusion

The calculated strategies are calculated and simulated in order quantify their energy saving potentials and contribution to thermal and IAQ comfort. Each strategy has its own potential benefit or expense, making them suitable for different applications. This research will focus further on strategy 4 and 5, because these strategies have the most potentials at saving energy, while creating comfort. Strategy 4 creates the safest indoor air quality, making it suitable for situations where reduced CO_2 or PM_{10} concentration could be beneficial, such as students housing. Strategy 5 creates the most energy saving potential, making it more suitable for the energy transition.

Strategy 1: Bouwbesluit

- energy saving	●●○○○	Constant ventilation creates high thermal loss even when the occupant is absent. This ventilation doesn't always contribute to comfort.
- IAQ	●●○○○	
- thermal comfort	●●○○○	

Strategy 2: Minimum setting

- energy saving	●●●○○	Lowering the ventilation rate decreases thermal loss at the expense of indoor air quality.
- IAQ	●○○○○	
- thermal comfort	●○○○○	

Strategy 3: Same exposure

- energy saving	●●●●○	Reducing the ventilation rate when the occupant is absent decreases the thermal loss significant, but doesn't contribute to a safer IAQ.
- IAQ	●●○○○	
- thermal comfort	●●●●○	

Strategy 4: Threshold

- energy saving	●●●○○	Increasing the ventilation rate at certain pollution thresholds creates a safe IAQ, but high air change rates of around 10ACH can create discomfort and a high thermal loss
- IAQ	●●●●●	
- thermal comfort	●●●●○	

Strategy 5: Own

- energy saving	●●●●○	Allowing higher pollution levels at certain moments decreases the air change rates, which can create lower thermal loss and more comfort.
- IAQ	●●●●○	
- thermal comfort	●●●●○	

Strategy 4 has the ability to lower energy consumption for heating from 19,8mWh/year to around 15,7mWh/year, while improving thermal and IAQ comfort. Strategy 5 can lower the energy consumption for heating even further to 14,2mWh/year, while creating a better IAQ than strategy 1 and 2. All strategies benefit from a high insulated and air tight building envelop, but strategy 1, 2 and 3 benefit more from an air tight building. By lowering the air infiltration rate, the air change rate through the windows had to be increased for strategy 4 and 5 in order to meet the set indoor air pollution thresholds. This offsets the energy saving potential of the improved air tightness. This means that this system is ideal for older buildings where air tightness is hard to achieve, such as buildings in the Ramplaankwartier in Haarlem.

An adaptive thermal comfort algorithm can operate the windows in a way that lowers indoor temperature by around 3 degrees on a warm summer day compared to a ventilation strategy that is conform to the Dutch building code, which can be reached with a similar air change rate (10ACH) that is necessary for the IAQ strategies. This depends on outdoor temperature and windspeed, as the system isn't able to lower the indoor temperature below the outdoor temperature. Thus if outdoor temperatures are above comfortable levels, the system isn't able to create thermal comfort. An air change rate of 20ACH in the living room and the bedroom show the limitations of the ventilation strategy, as indoor temperatures are similar to outdoor temperatures. Windspeed can also offset high temperature, creating comfort during summer, but this will only be noticeable when sitting next to the window. With an air change rate of 20ACH, the windspeed will be around 0,1m/s at the smallest part of the living room, which may lower thermal sensation by a little. An air change rate of 20ACH if hard to achieve with natural ventilation through tilted windows, as fenestration will most likely not create large enough openings to support this. For living room of the building in the Ramplaankwartier, this air change rate can be achieved with four tilted windows of 70cm by 100cm, two on either side of the room. This is currently not present in the existing building, therefore new fenestration is necessary in order to gain full cooling potential of the ventilation strategy.

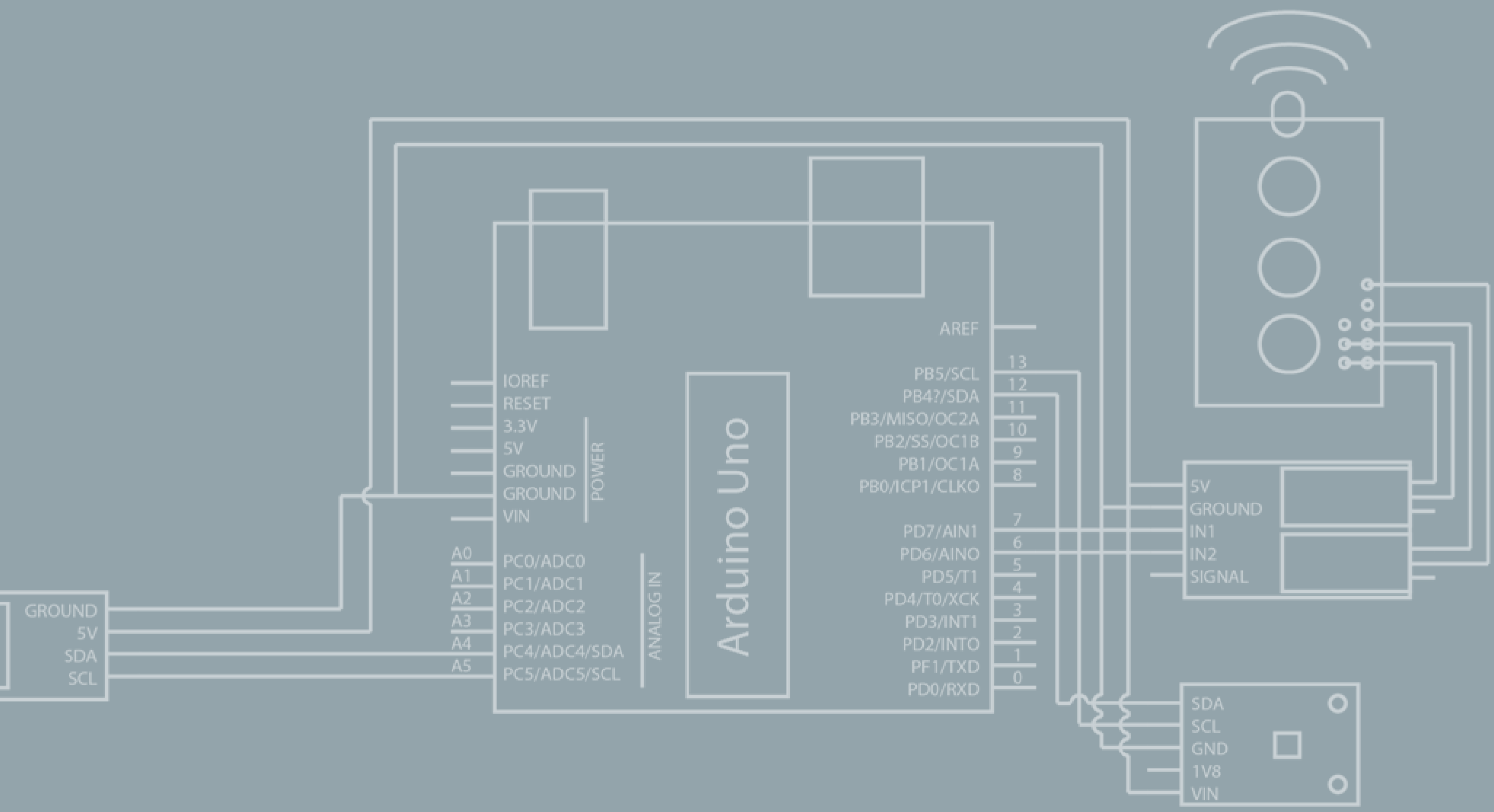
It is possible to create a system with existing products that operates windows based on various parameters. The optical sensor in the Netatmo weather station is, according to Arie den Hartog, quite accurate and can be used to communicate via various hardware and software to an AXA Remote 2.0. It is a consumer product that samples the CO_2 concentration and temperature at a fixed rate of 5 minutes. This sample rate can't be adjusted, reducing flexibility in adjusting sample rate. Also, this system communicates via Wi-Fi, which increases the difficulty to install this system and making it vulnerable for data leaking and hacking. The used actuator could be applied as a retrofit in smaller renovation projects, resulting in a finishing level that can be unwanted by an occupant. The motors create noise when operated and are quite bulky. The system doesn't know if the window is opened or closed, because there is no communication feedback from the actuator. Also, all windows that are outfitted with an AXA Remote 2.0 can't be operated by hand, limiting the user flexibility. This could be fixed when using a Schuco Tiptronic window frame.

The real downside of this system is the reaction time between the sensor and the actuator, which can take up to an hour, making this product unusable in a real world situation. Indoor pollutants can change drastically within an hour, making this product unable to control indoor conditions.

04

Design

A final prototype will be created and installed in the PDlab. Boundary conditions will be formed for this system and inside information will be gather in the creation of the set indoor climates.



4.1.1 Test setup

4.1.1.1 PDlab

The model will be installed and tested in the Product Development Lab, located in the west courtyard of the faculty of Architecture in Delft. The PDLab is a pavilion that is used as a platform for developing new building products and techniques. The pavilion is 3,2 meters in width, 5,8 meters in length and has a gabble roof with a ridge height of around 5,5 meters (Figure 4-1). It is fully insulated with glass wool, but Rc-value is unknow. The building has a fully glazed façade, facing southwest, and two aluminum turn-tilt windows, facing northwest and southeast.

Figure 4-1 PDlab (The New Makers, n.d.)

The test setup consist out of the prototype, heating system and a monitoring system (Figure 4-2).

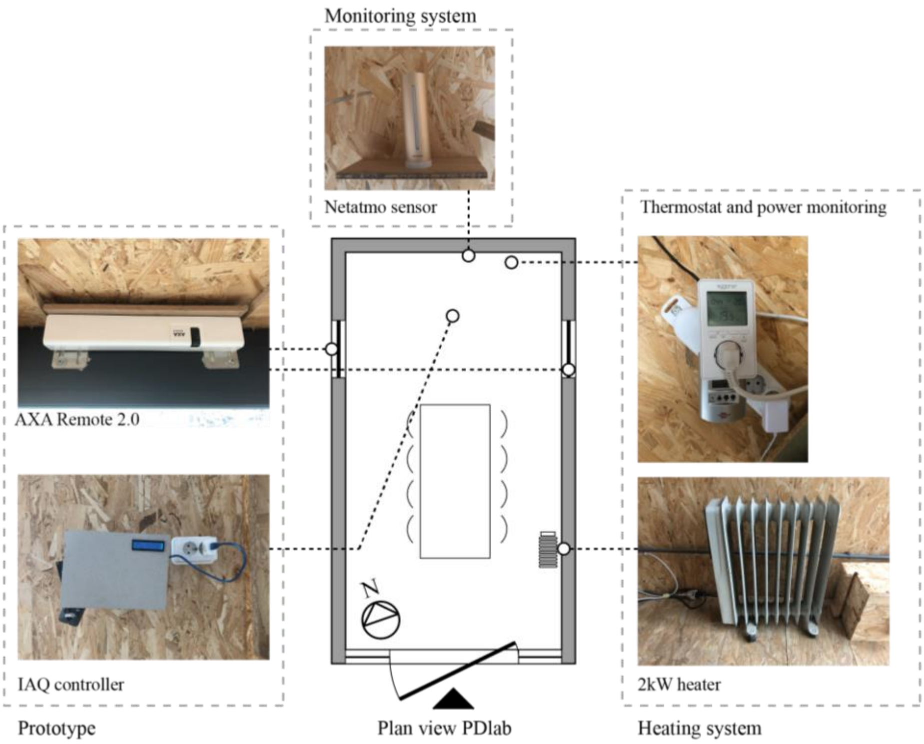
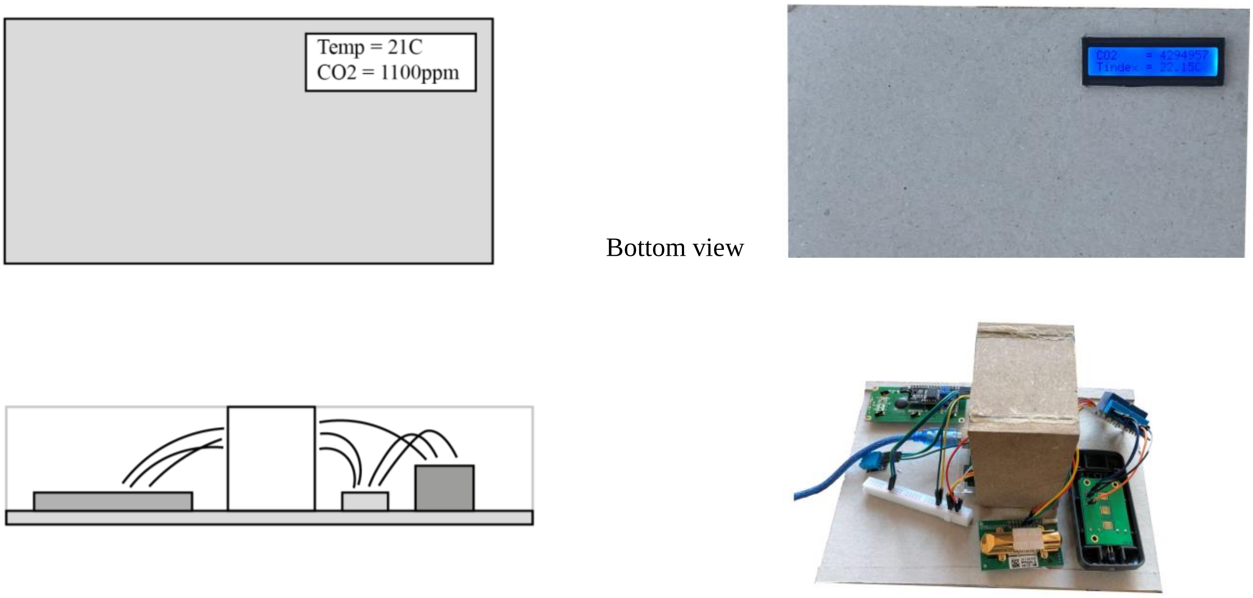


Figure 4-2 Plan view of the test setup

4.1.1.2 Prototype

A simple design has been made for the IAQ controller, making it a product that feels less like a gadget compared to a Netatmo sensor. It is a small rectangular plate with a display in the corner, showing different indoor parameters. It is similar to an open test bench during testing, making it easy to swap sensors and change wiring. This display shows temperature and CO_2 concentrations during part of the testing period, which is necessary to understand the actions that the controller performs.



Side view

Figure 4-3 IAQ controller

Both windows are outfitted with an AXA Remote 2.0, making them automated. The window opens in 4 steps, where position 1 is with the window just cracked open and position 4 is with the window fully opened. This way, the system can change the air change rate to fit the CO_2 production in the room.

Figure 4-4 Opening secuence of window

The windows need to meet certain boundary conditions in order to create the necessary air change rate. During construction and testing in the PDlab, it became clear that the space around the window frame effects the ease of installation and can affect the effectiveness of the system. When the window is fully opened, a gap of 20mm is between the wooden reveal and the tilted window frame (Figure 4-5), which creates a window opening of around 850cm^2. This gap can be increased to 40mm by removing part of the reveal (Figure 4-6), creating an opening of around 1000cm^2.

Figure 4-5 with reveal, 20 mm gap between window pane and reveal

Figure 4-6 without reveal, 40mm gap between window pane and reveal

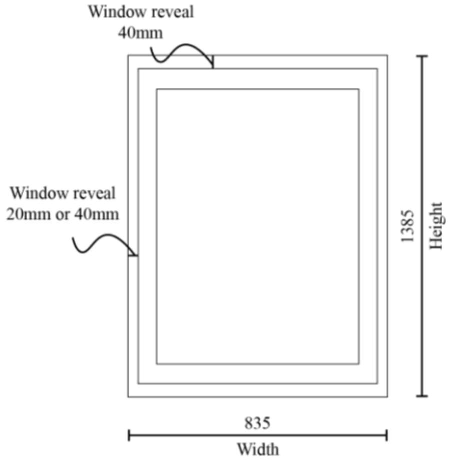


Figure 4-7 Dimensions window

A bottleneck for ventilation through the window seems to be the gap in between the reveal and the tilted window frame. The air change rate potentials that can be achieved in the PDlab with these windows is shown in Table 4-1, created with equation 9. For the test, the reveal will be removed, increasing the range of air change rates that the mechanism can create. The air change rate in the PDlab also depends on wind speed, which is difficult to determine due to the sheltered location of the building in the courtyard of the faculty of Architecture. Additional pressure from a mechanical source will only be used if the IAQ becomes unsafe due to insufficient pressure differential due to windspeeds.

PDlab	Wind speed							
Window opening	1 m/s	2 m/s	3 m/s	4 m/s	5 m/s	8 m/s	10 m/s	15 m/s
800 cm^2	1,6	3,2	4,7	6,3	7,9	12,6	15,8	23,7
1000 cm^2	2,0	3,9	5,9	7,9	9,9	15,8	19,7	29,6

Table 4-1 Air change rate potentials

4.1.1.3 Heating system

The heating system isn't part of the proposed system, but is needed to determine the energy saving potentials of the proposed system by heating the PDlab according to the adaptive thermal comfort algorithm. It consist out of a 2kW radiator that is control by a programable thermostat plug. A power monitoring plug displays the power consumption of the heating system.

4.1.1.4 Monitoring system

Arie den Hartog from Airteq uses Netatmo products to monitor several buildings, therefor the healthy home coach from Netatmo will be used to monitor indoor parameters in the PDlab. It measures decibels, CO_2 concentrations, humidity levels and temperature, which are all parameters that are interesting in order to determine if this product could create comfort.

4.1.2 Strategy

The designed system will have two strategies, a ventilation strategy and a thermal strategy. The ventilation strategy is based on research that is done in chapter 3.6 and the heating strategy is based on the adaptive thermal comfort algorithm. Heating will be done with a radiator, which will keep the indoor temperature to the minimum thermal comfort level (Tcomf). Tcomf is determined with the adaptive thermal comfort algorithm, with an outside temperature of the average temperature during that month, see chapter 2.3.1.2. The formula for the minimum Tcomf that corresponds with 90% satisfaction is given by;

$$T_{comf} = (T_{outside}\ x\ 0{,}255) + (18{,}9 - 2{,}5) \quad (22)$$

During testing, Touside will be set at 12,2 degrees Celsius, which is the average outdoor temperature during the testing period (KNMI, 2019). The mechanism will calculated and performs actions based on the heat index, as discussed in chapter 2.3.1, which provides a human-perceived equivalent temperature.

4.1.2.1 Ventilation strategy “Threshold”

Windows will be opened at 1200ppm of CO_2 and closed at 1100ppm. The gap in between these two thresholds will be adjusted during testing in order to stabilize the system.

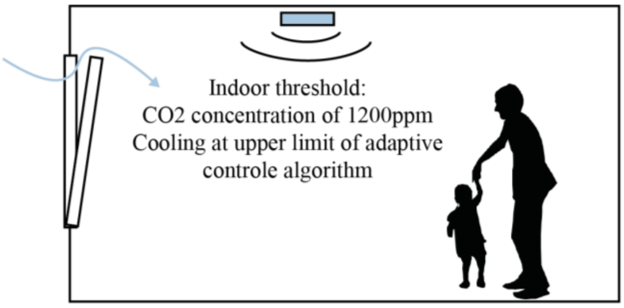


Figure 4-8 Threshold

A principle of the commands and statements is illustrated in a flowchart (Figure 4-9). The threshold for the temperature, shown in the flowchart, can be adjusted during testing, but will be based on preliminary research.

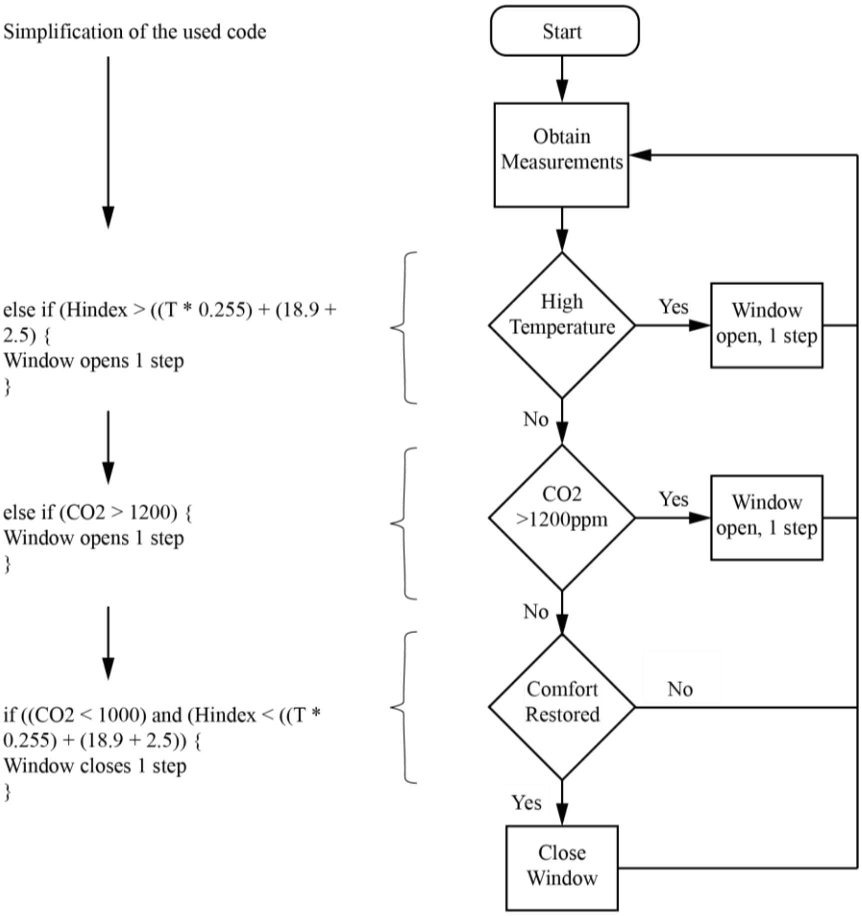


Figure 4-9 Flowchart threshold strategy

4.1.2.2 Ventilation strategy "Own"

Windows will be opened at 1600ppm of CO_2 and closed at 1200ppm. The gap in between these two thresholds will be adjusted during testing in order to stabilize the system. A principle of the commands is illustrated in a flowchart (Figure 4-11). The threshold for the temperature, shown in the flowchart, can be adjusted during testing.

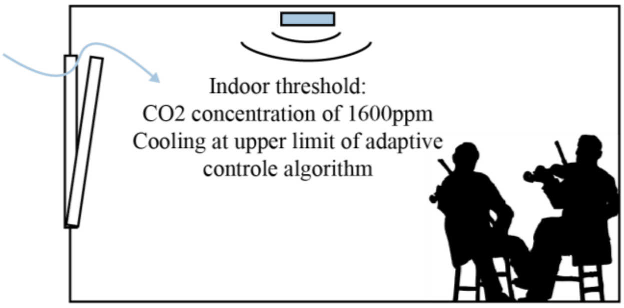


Figure 4-10 Own

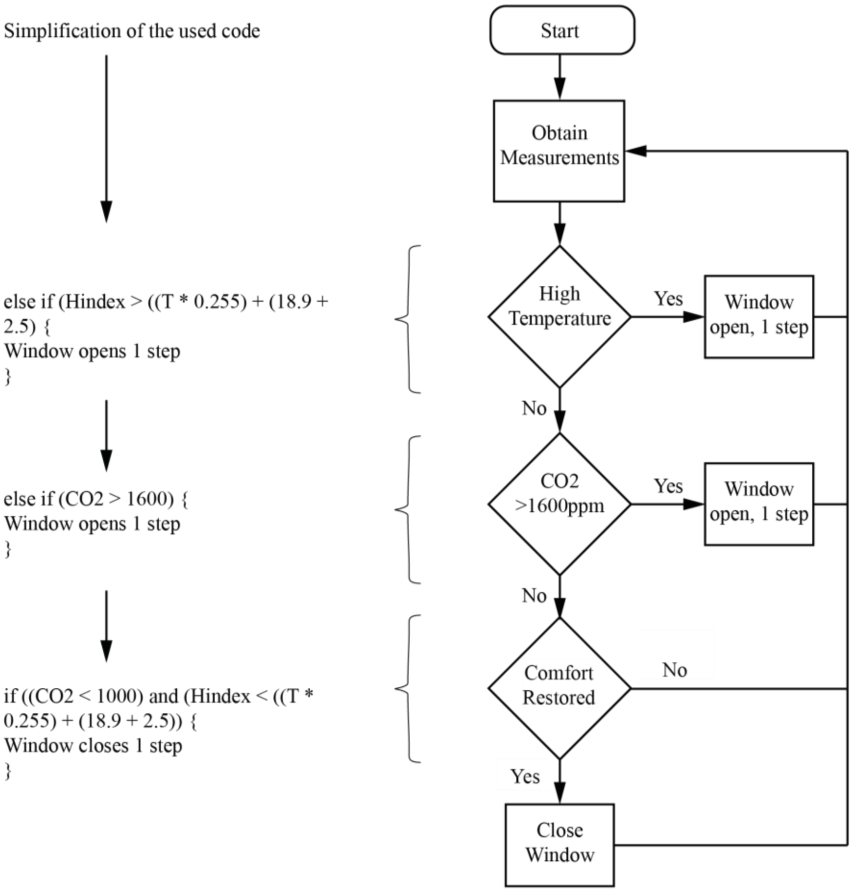


Figure 4-11 Flowchart Own strategy

4.1.2.3 Ventilation strategy "Combination"

A combination of both strategies is made in order to create a more balanced strategy that can improve the air quality and reduces the thermal loss. This strategy determines the pollution threshold based on the difference between the indoor temperature and the set temperature from the adaptive thermal comfort algorithm. The thresholds are derived from the results from the case study (chapter 3.6). The thermal loss difference between strategy 5 and the baseline (strategy 1) is around 10,0kWh/day during the winter, but only 2,0kWh/day during autumn and spring. The thermal loss difference between strategy 4 and the baseline is around

5,0kWh/day during winter and only 0,4kWh/day during autumn and spring, while providing a better IAQ. Meaning that most of the energy saving potentials are during winter. Therefore, focusing on energy savings in winter and IAQ in summer.

The adaptive thermal comfort determines the thermal comfort based on the season, which allows lower temperatures in winter and higher temperatures in summer (Figure 4-12). When indoor temperatures are low, the mechanism will run strategy 5, which focusses on lowering thermal loss, and when indoor temperatures are high, the mechanism will run strategy 4, which focusses on creating a better IAQ. By comparing the indoor temperature and the temperature calculated by the adaptive thermal comfort algorithm, the mechanism can improve the IAQ better within the thermal comfort limits of an occupant.

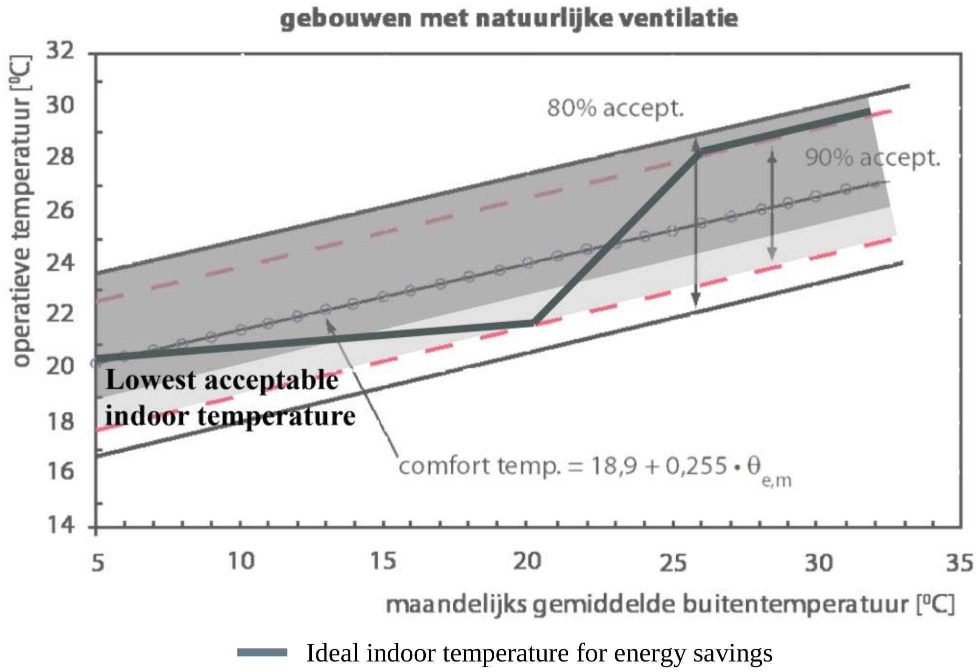


Figure 4-12 Adaptive thermal comfort algorithm, adapted from (NEN-EN 15251, 2007)

Solar load can increase the indoor temperature during winter, while the adaptive thermal comfort algorithm states that low temperatures are acceptable. The mechanism can use this additional thermal load to improve the IAQ even further by increasing the air change rate, while keeping indoor thermal comfort.

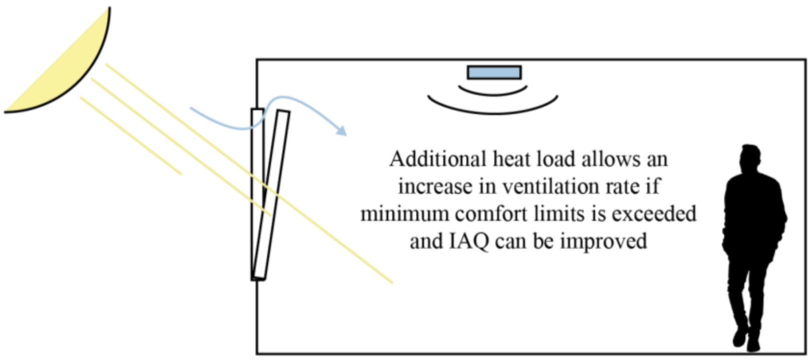


Figure 4-13 Combined strategy

A principle of the commands is illustrated in a flowchart. The threshold for each statement, shown in the flowchart, are based on preliminary research. The last statement, high pollution+, will open the windows twice as fast if high CO_2 pollutants levels are detected. This could simulate an activity such as cooking, where a large number of air pollutants are produced in a short amount of time.

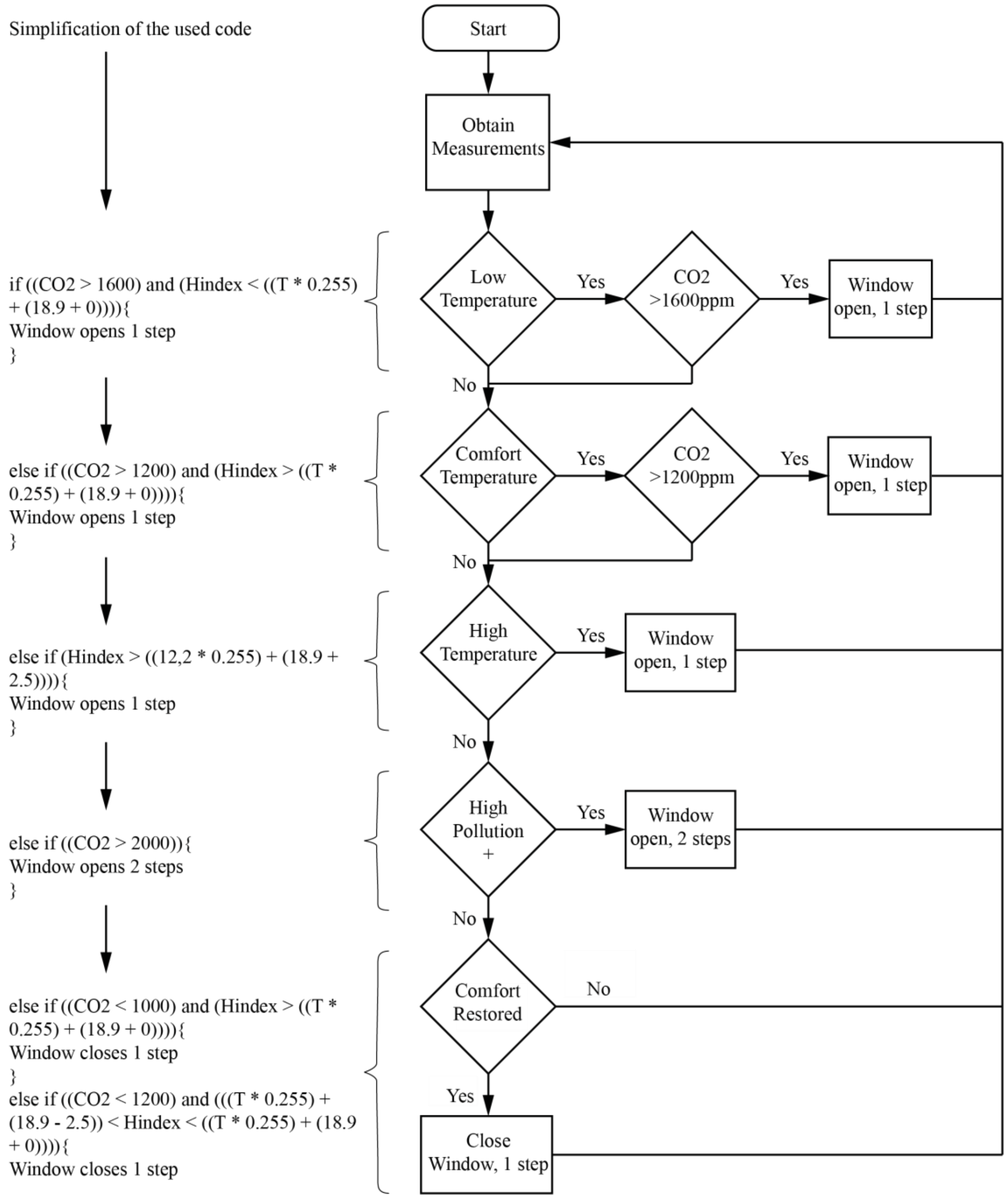


Figure 4-14 Flowchart combined strategy

4.1.3 Mechanism

A prototype is installed in de PDLab, where it will investigate various strategies and sensors. The prototype will only measure CO_2 concentrations, humidity levels and temperature. No particulate matter, because there are no cooking facilities or other PM sources in the PDlab.

The aim of the prototype is to create a device that can test the various strategies, while aiming to meet most of the criteria that was formed during the case and literature study. The main objective for the device is to read the data from the air quality sensor and thermometer, processing it into an action for the windows and testing its potentials on saving energy, IAQ and thermal comfort. Sensors and actuators from existing companies will be used to create the product that will be tested. Multiple different sensors, from different price categories and qualities, will be used to see their response time and accuracy.

Automation can be done with open-source electronic platforms, which becomes easier to use due to the large community sharing ideas and information. Especially Arduino, which is commonly used to build low cost scientific instruments and prototypes. Arduino will be used as a platform to read the air quality sensors, program the different strategies and control the actuators.

An Arduino board uses a variety of microprocessors and controllers. The boards are the brains of the operation with sets of digital and analog input/output (I/O) pins that may be interfaced to various expansion boards or sensors. The boards feature serial communications interfaces, which is used for loading programs with statements. The microcontrollers are typically programmed using a dialect of features from the programming languages C++. Arduino's own IDE, integrated development environment, version 1.8.8 is used to control the Arduino. The IDE is a source code editor, where statements can edited or created in order to communicate with the different components. It supports Java, C and C++, which are some of the most used programming languages, making it ideal for a novice due to the large active online community. This Arduino board communicates with the AXA Remote 2.0 window actuator with relays.

The build consist out of sensors, processing unit, relays, motors and a display. The measured values from the sensors need to be processed into an action. This will be done with an Arduino board and various materials. The materials that are used:

- Arduino Uno
- Liquid crystal display
- Double relay
- AXA Remote 2.0 controller

The *Arduino Uno* is a microcontroller board that is designed for 'first time experienced' tinkerers. Therefor it is the most used and documented board of the whole Arduino family. This board cost around 5,- euro's if ordered from China and around 24,- euro's if ordered in the Netherlands.

(Opencircuit OÜ, 2019)

The *liquid crystal display* show the output of the sensors. During prototyping, this display can be used to see if the device behaves correct. This display cost around 1,62 euro if ordered from China and around 9,- euro's if ordered in the Netherlands.

(Opencircuit OÜ, 2019)

The 5V 2-channel relay interface board can be used to control various appliances and other equipment's with large currents. For this application, it is used to short circuit contact points on the remote controller of the AXA Remote 2.0. On relay is connected op the contact points in order to open the window, the other is connected to contact points to close the window. This relay can be bought for around 7 euro's.

(Opencircuit OÜ, 2019)

An AXA remote will be highjacked, with the relays, in order to operate the AXA Remote 2.0. This remote comes with an AXA Remote 2.0.

(AXA home security, 2019)

Measuring these parameters can be done with various sensors, each sensor from a different price bracket and measuring technique will be considered. The different sensors that will be investigated are:

- MQ135
- SGP30
- CCS811
- SCD30
- MH-Z14a

The *MQ* series of gas sensors use a small heater inside with an electrochemical sensor, making it a semiconductor sensor. These sensors need a burn in time of around 48 hours before their first use and have a warm up time of around 2 to 3 minutes before their output becomes stable. Depending on voltage, some sensors use 1.4V and some 5V or 6V, the internal heater can get 50 or 60 degrees Celsius. These sensors cost around 1,- euro if ordered from China and around 12,- euro's if ordered in the Netherlands.

(Opencircuit OÜ, 2019)

The CCS811 air quality breakout is a digital metal oxide semiconductor gas sensor solution that senses a wide range of total volatile organic compounds (TVOCs), including equivalent carbon dioxide (eCO_2) and metal oxide (MOX) levels. This sensor is commonly used to measure pollutants and/or sensory irritants and can come from a variety of sources like construction materials (paint, carpet, etc.), machines (copiers, processors, etc.) and people (breathing, smoking, etc.). This sensor can be bought for around 25 euro's.

(Opencircuit OÜ, 2019)

The SGP30 is a fully integrated multi pixel semiconductor gas sensor, made by Sensirion, measuring volatile organic compounds and eCO_2. It is calibrated by the manufacturer, when setup correctly, Sensirion guarantees output signals with a typical accuracy of 15% within measured values. The SGP combines multiple metal-oxide sensing elements on one chip to provide more detailed air quality signals. This sensor cost around 25 euro's.

(Opencircuit OÜ, 2019)

Sensirion SCD30 sensor module uses NDIR CO_2 sensor technology to sense CO_2, meaning it uses infrared to count the CO_2 concentration. The SCD30 features dual-channel detection which increases stability and ±30ppm + 3% accuracy, making it one of the most accurate sensor for measuring CO_2 concentration. This sensor can be bought for around 70 euro's.

(Sensirion AG, 2019)

MH-Z14a NDIR Infrared gas module uses a non-dispersive infrared (NDIR) principle to detect CO_2 in the air. It has a built-in temperature compensation, resulting in an accuracy of ±50ppm and a detection range of 0-5000ppm, making it suitable for measuring CO_2 concentrations in residential buildings. This sensor can be bought for around 30 euro's.

(Opencircuit OÜ, 2019)

Not all sensors measure temperature and humidity, those sensors that don't will be outfitted with a DHT11 sensor. It reads humidity levels between 20-80% with an accuracy of 5% and temperatures between 0-50°C, making it ideal for monitoring indoor parameters. This sensor can be bought for around 1 euro.

(Opencircuit OÜ, 2019)

All sensors are verified in order to determine if they measure the given parameter correctly to be useable for this application. Research papers can be found using different sensor technologies, with mixed experiences. Loads of research, from different Universities, has been done with semiconductor, because it's a cheap sensor technology. Adrian Florea, computer scientist and electrical engineer at the University of Sibiu, created a low cost mobile embedded system for air quality monitoring in order to preserve citizens' health with semiconductors (Florea, Berntzen, & Johannessen, 2017). The same sensor technology was used by Umit Isikdag, researcher at the Mimar Sinan University in Istanbul, to predict the number of occupants in an indoor space (Isikdag, Sahin, & Cansiz, 2018). Therefore, this sensor will be tested first in order to determine if air quality can be monitored correctly. If not, a more expensive IR sensor will be used to monitor indoor air quality.

The building schemes and codes of all the systems can be found in Appendix I.

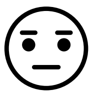
4.2 Results

4.2.1 User interaction

The AXA remote 2.0 makes it impossible to manually operate the window, reducing the user interaction with the mechanism. The strategy that has been programmed is written with interaction in mind. If the window could be manually opened, the code will determine if the indoor temperature falls within a certain threshold, which is based on the adaptive thermal comfort. This action is performed every 5 minutes. The manually opened windows will close automatically in various steps when indoor temperatures drops below a certain threshold where additional thermal heat is need and the IAQ is healthy. If the indoor temperature rises, the window will open even further automatically. This way, if a user really wants to open a window, it will stay open for at least 5 minutes. This idea is transferred from a heating system that was descripted by Regina Bokel (personal communication), which determines indoor temperatures conform an algorithm and could be temporarily increased by an occupant for a set amount of time, after which the heating system will turn back to the temperature conform the algorithm.

The interaction with the controller is also limited. Participants reacted positive on the display that showed the pollution levels (Figure 4-15). This gave a clear understand of the necessity of ventilation, therefor accepting the window operations. The layout of the displayed output could be improved, it shows CO_2 concentrations in parts per million, which can be an unknow unit for the user. This could be solved with pre-made emoticons, corresponding with different levels of pollutions (Figure 4-15).

CO_2 < 1000ppm



1000ppm < CO_2 < 1200ppm

CO_2 > 1200ppm

Figure 4-15 Emoticons for pollutants indications

4.2.2 Thermal comfort

The DHT11 sensor is compared with the sensor from the Netatmo and a temperature sensor from an unknown brand. All sensors were within a margin of 1 degree to each other, giving the system a class C (comfort) accuracy (NEN-EN-ISO 7726, 2001). Class C sensors for have an measuring range of 10°C to 40°C, making them suitable for these purposes.

The thermal strategies for the strategy 'threshold' and strategy 'own' are similar to each other, the windows open and close at the upper limit of the 90% acceptability of the adaptive thermal comfort algorithm. The indoor temperature in the PDlab is monitored for a week and plotted in a graph (Figure 4-16). The system is unable to cool this building to a comfortable level, which can be due to multiple factors. The indoor temperature increases far above the outdoor temperature, which indicates a high amount of additional thermal energy due to solar radiation. The natural ventilation through the small opening of the windows didn't create the air change rate that was needed to lower the indoor temperature to a comfortable temperature.

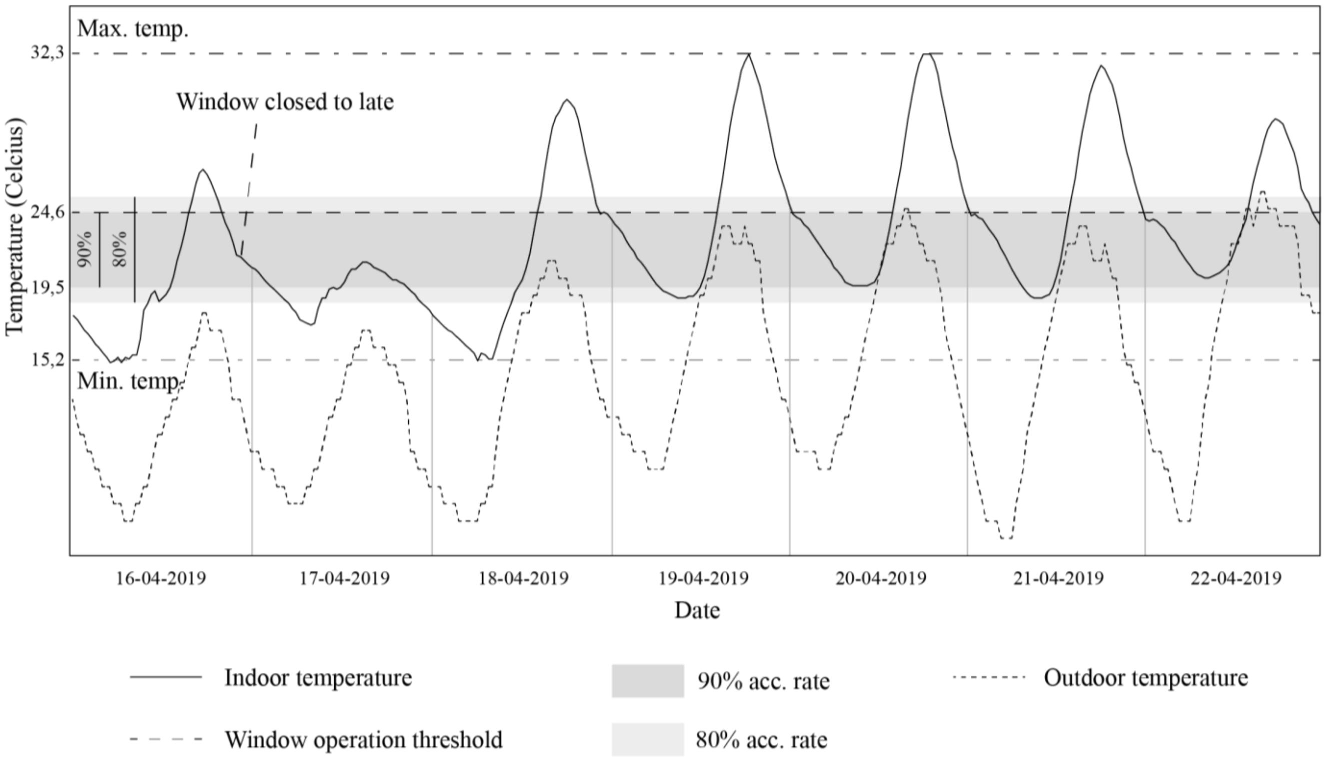


Figure 4-16 Indoor temperature in the PDlab for a week

The glass façade of 13m^2 on the southwest side of the PDlab is relatively large compared to the volume of the building. The building that was used for the case study has a living room with a volume of 106m^3 and 5m^2 of glass facing the South side, which is a more common ratio for residential buildings in the Netherlands. This means that the overheating that occurred in the PDlab will be less in a building with a lower 'glass volume' ratio (Table 4-2).

	Glass facing south side	Volume	'Glass volume' ratio
PDlab	13 m^2	75 m^3	0,17
Ramplaankwartier	5 m^2	106 m^3	0,05

Table 4-2 Glass-volume ratio

The system didn't made a noticeable contributes to thermal comfort by cooling, due to the limited air change rate that could be created to the relative small opening of the windows and the relative large additional solar load. The windows are recessed in the façade, creating a small gap between the windowpane and the reveal where air can passes through. During testing with fully opened windows, the indoor temperature was around 10 degrees higher than the outdoor temperature. Indicating that the airflow capacity through the windows was too low for the amount of solar load on the South facing façade. This could be solved by increasing the gap between the windowpane and reveal, but also by increasing the length of the chain on the window actuator which could open the window even further.

Figure 4-17 shows day 19-04-2019 and 20-04-2019 in more detail with the desired indoor temperatures as $T_{comfort}$ and $T_{setback}$. At around 14:00, the window opens for cooling, which has no visible effect in the data. At around 00:00, the windows close because the indoor temperature threshold is met, lowering the air change rate. The indoor temperature decreases less quickly and stays within a 90% acceptability of the adaptive thermal comfort for the entire night and morning. This means that the heating didn't need to be switched on to create a comfortable indoor temperature. A line is added in the graph, showing the theoretical indoor temperature if the air change rate stayed constant, indicating an open window or ventilation grill. This would lower the indoor temperature by around 2 degrees, which creates an uncomfortable indoor climate in the morning that can only be restored by switching on the heating system. This means that the system can successfully operate the windows in order to store thermal energy, which can lower the energy demand for heating.

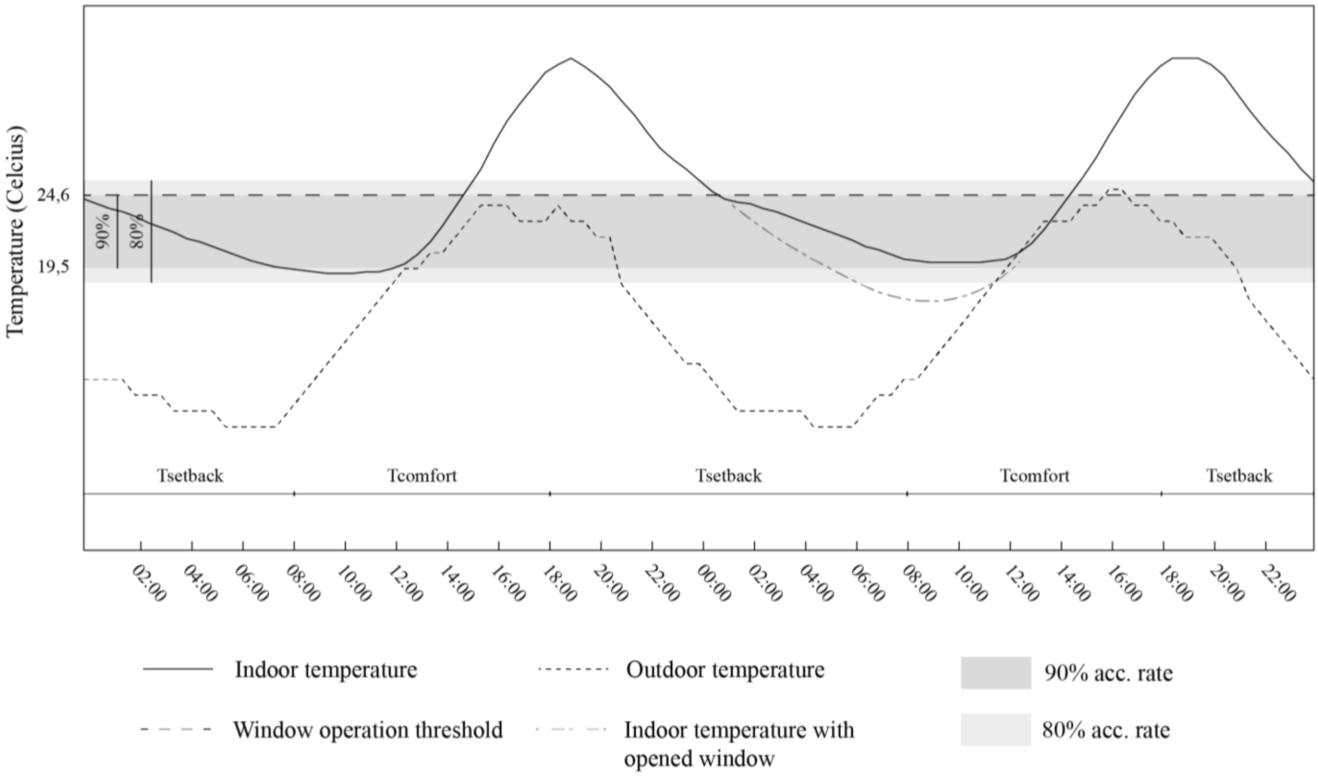


Figure 4-17 Indoor temperature in the PDlab at 19-04 and 20-04

4.2.3 Indoor air quality

The MQ sensor is semiconductor, measuring differences in voltage, which is read by the Arduino board. These voltages can be converted to a value that is more common for measuring air quality, like ppm or $\mu g/m^3$. Interference from other components in the loop can change the reading from the sensor. Arie den Hartog, owner of AirTeq B.V., considers semiconductors inaccurate due to this phenomenon. Therefore, this sensor will not be used for the final design.

The CCS811 sensor measures total volatile organic compounds, including equivalent carbon dioxide. This sensor is commonly used in small devices, such as wearables, to monitor IAQ. The sensor output is different from the output from the Netatmo healthy home coach, which has a calibrated CO_2 sensor. The CO_2 measurement from the CCS811 sensor is an equivalent, which is a measurement for describing how much of a given type of gas contributes to global warming, where CO_2 is used as the reference. This sensor measures more than just CO_2, it also senses methane (CH4) and nitrous oxide (N2O). This sensor gives different readings within same situations. It has been tested in a small airtight box, food container, where it measures different CO_2e concentrations throughout the day, which should be impossible (Figure 4-18). Therefore, making this sensor unusable for this application.

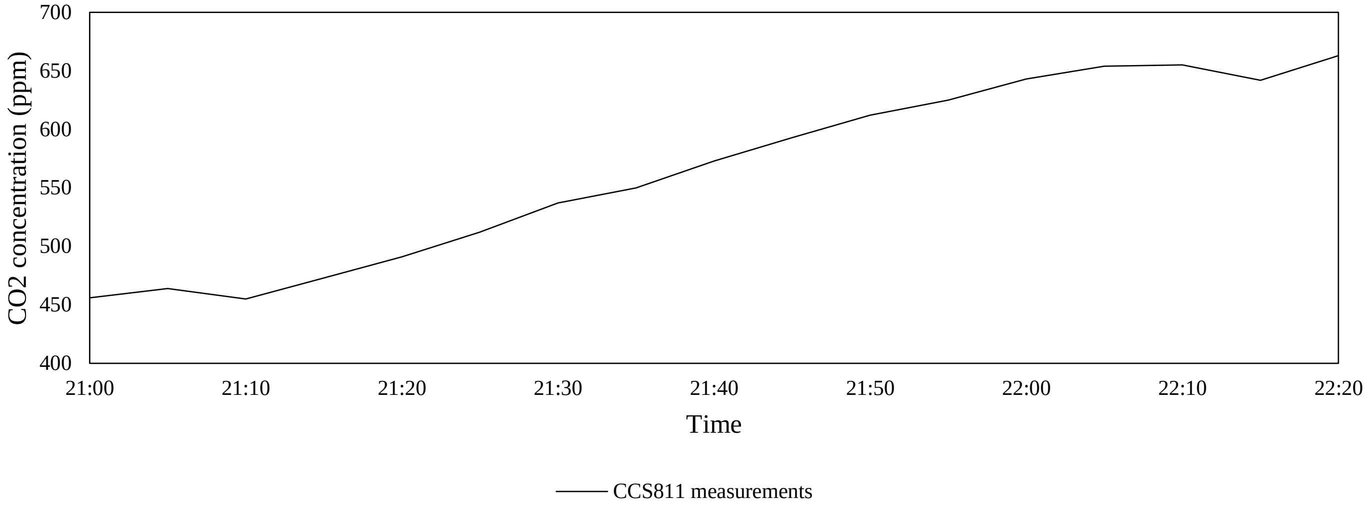


Figure 4-18 CO_2 measurements from CCS811 in airtight container

The SGP30 sensor measures the same gasses as the CCS811, but is calibrated and stable. This sensor should be within a 15% margin of the calibrated sensor in normal indoor conditions, thus the first test will include this sensor.

A test was conducted on 16-04-2019, 6 people occupied the room from 09:00 till 11:00, where CO_2 concentration exceeded the preset threshold of 1200ppm that was programmed (Figure 4-19). The maximum CO_2 concentration that was monitored by the Netatmo station is around 2000ppm, which is 800ppm higher than the threshold stated by the script. Despite the high CO_2 concentrations, the occupants thought that the IAQ was good, confirming that it is hard to detect an unhealthy IAQ by our self. The SGP30 detected a CO_2 concentration of around 700ppm.

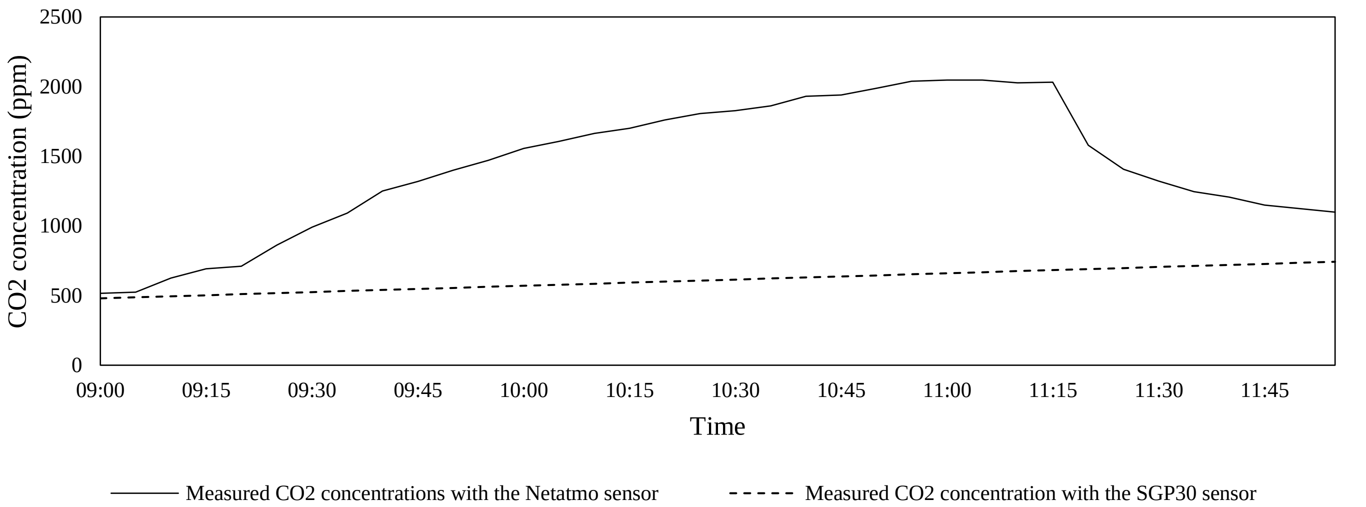


Figure 4-19 CO_2 measurements from the Netatmo sensor and the SPG30 sensor

The sensor was unable to detect the high CO_2 concentration, even though it was calibrated by the factory and compensated with humidity and temperature according to the datasheet from Sensirion. The humidity and temperature used for the compensation was provided with a dht11 sensor. Thus making this sensor unusable for this application.

The SCD30 sensor is a new sensor which has a high accuracy for measuring CO_2 concentrations and reacts within 5 seconds. This high quality sensor worked properly, until multiple scripts were uploaded. The communication bus (I2C) with the Arduino board can get stuck when tinkering and uploading different scripts in a short amount of time. Due to price and the lack of knowledge on these types of sensors, tinkering with this sensor had to be discontinued. It created great results when it works, matching the CO_2 concentrations from the Netatmo sensor, but it was unreliable.

The MH-Z14a works with the same technology as the SCD30, only is it an older sensor and a lot slower. It uses a different way of communicating with the Arduino board (PWM). There is limited documentation about this sensor, but it matches the output from the Netatmo sensor after multiple calibrations. The MH-Z14a has been included and installed in the final prototype (Figure 4-20).

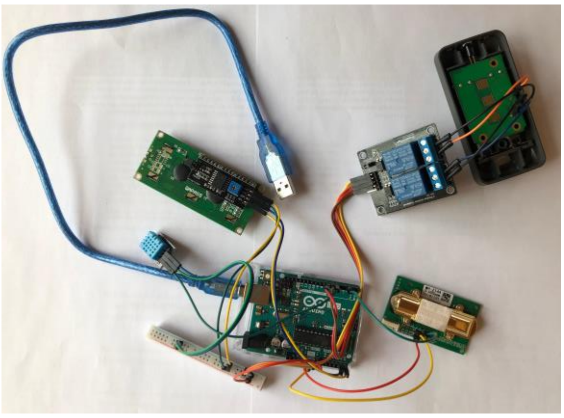


Figure 4-20 Controller and sensor built

Figure 4-21 Controller mounted on the ceiling of the PDlab

Calibration is done in the PDlab, with the test setup described in chapter 4.1.1 (Figure 4-21). After calibration, a test was conducted to determine if the system works according to the algorithm. One participant in the PDlab creates a max CO_2 concentration of around 920ppm, which is within the save thresholds stated by the World Health Organization. Thus, additional CO_2 production of six candles was needed to simulate an additional two or three participants. This seemed sufficient and increased the CO_2 concentration well above 1200ppm in the PDlab.

Figure 4-22 additional CO_2 production setup

The windows behaved according to the programmed algorithm and the MH-Z14a measured similar concentrations as the Netatmo sensor. A CO_2 concentration between 1000ppm and 1200ppm was set as a bandwidth for the ideal indoor CO_2

concentrations (Figure 4-23). The system was able to create a safe IAQ, with a CO_2 concentration that never went above 1300ppm. Window operation occurred around every 90 minutes and it took around three and a half hours, from the first window operation, to find the ideal window position for the indoor CO_2 production.

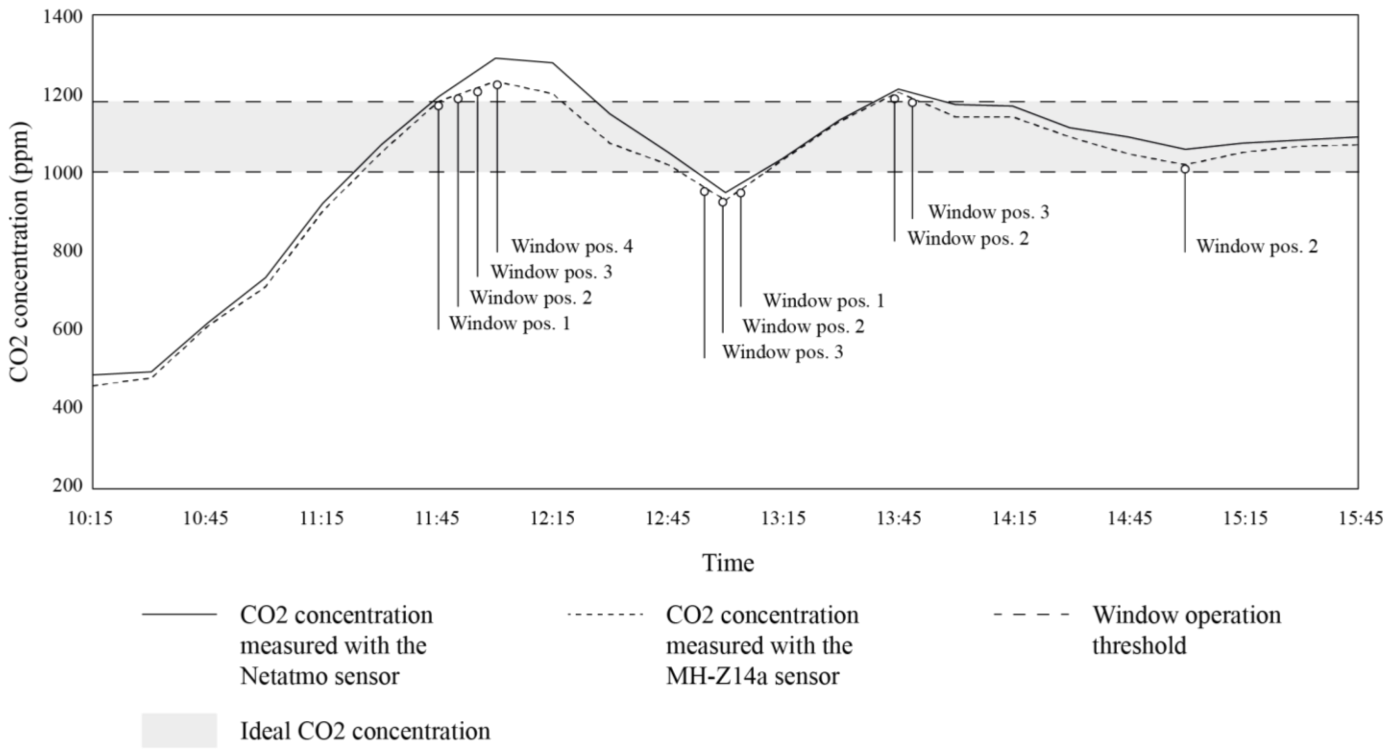


Figure 4-23 CO_2 concentrations in PDlab at 02-05-2019

This CO_2 concentration bandwidth can be made narrower to 1100ppm - 1200ppm in order to speed up the process of finding the ideal window position (Figure 4-24). The system was able to keep the CO_2 concentration below 1250ppm during the entire test period, contributing to a healthy IAQ. The system found the ideal window position within 2 and a half hours from the first window operation, with window operation that occurred around every 45 minutes.

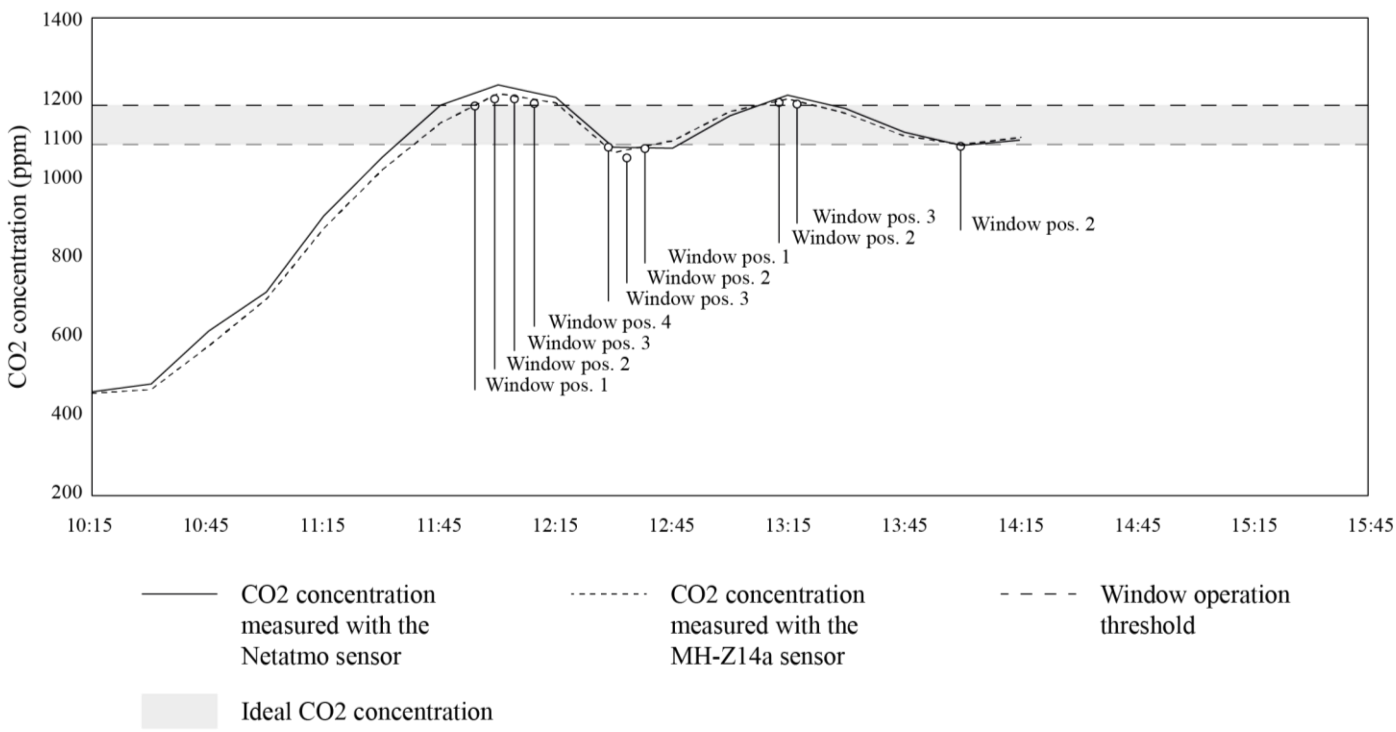


Figure 4-24 CO_2 concentration in the PDlab at 14-05-2019

During testing, it seemed difficult to keep the CO_2 concentration at a constant level. This is mainly due to variation in air change rate, caused by different wind speeds. It is important to keep the amount of window operations to a comfortable number, because it is annoying when the window finds a new position due to the noisy actuators. With the AXA Remote 2.0, a comfortable bandwidth for CO_2 concentration in the PDlab is around 200ppm. Depending on the CO_2 production, fenestration and wind speeds, this causes a window operation that takes place every 60 to 75 minutes. By narrowing this bandwidth, thermal loss can be reduced, but window operations will increase. These noisy window operations can cause discomfort due to the used actuators from AXA. Schuco actuators are a lot quitter and faster, which allows for more window operations before it becomes annoying and thus a narrower CO_2 concentration band width.

4.3 Conclusion

A prototype is built that is successful in measuring indoor parameters and communicates with the window actuators. It has been installed in the PDlab, where is was open for people to use and experience. The prototype is based on an Arduino Uno platform, which is a commonly used platform to build low cost scientific instruments. The CO_2 sensor is a MH-Z14a which has a detection range of 0-5000ppm, making it ideal for measuring CO_2 concentrations in residential buildings. A DHT11 sensor is used to measure humidity levels and temperatures, with an detection range between 0-50°C. The windows were outfitted with AXA Remote 2.0's. The Arduino Uno operates the AXA Remote with relays.

The proposed system is able to find the right the air change rate to guarantee safe indoor CO_2 concentrations. Thermal loss due excessive air change rates is minimized and a unsafe IAQ due to inadequate air change rates is diminished. Accurate sensor technologies, window actuators and algorithms can create a safe indoor air quality, while reducing thermal loss. Depending on wind speeds, fenestration and CO_2 production, it takes around three and a half hour to find the ideal window position to keep CO_2 concentration to a comfortable level. This can be shortened to two and a half hour by making the acceptable CO_2 concentration bandwidth narrower, which will decrease the window operation intervals. This will lower thermal loss even further at the cost of potential acoustical discomfort from the noisy actuators.

The contribution to indoor thermal comfort was hard to determine during the test, the results didn't show a decrease in indoor temperatures. This is due to the limited air change rate that could be created to the relative small opening of the windows. The windows are recessed in the façade, creating a small gap between the windowpane and the reveal where air can passes through. During testing with fully opened windows, the indoor temperature was around 10 degrees higher than the outdoor temperature. Indicating that the airflow capacity through the windows was too low for the amount of solar load on the South facing façade. This could be solved by increasing the gap between the windowpane and reveal, but also by increasing the length of the chain on the window actuator which could open the window even further. The mechanism was able to store thermal energy during the night, which created indoor comfort during the next morning without using an additional heating source. No real answer can be given on which strategy performs the best due to variations in outdoor conditions.

The user interaction with the prototype is limited, due to the used actuators. The windows that are outfitted with a window actuator can't be opened, so the mechanism can't react to that behavior. This limits the interaction and acceptability of this system. Also, the cooling thresholds can't be manually set, this is controlled by an algorithm, which could be difficult to understand for a user. Understandable symbols should be presented to the user in order to explain certain action the mechanism performs. Emoticons could be used as indicators for indoor pollutants and thermometer symbol for uncomfortable thermal conditions. Actions will be understood by the use and therefore more likely to be accepted.

4.3.1 Boundary conditions

Boundary conditions were formed during installation and testing of the system.

- System is only effective in rooms with operable façade elements
- The windows needs to have a tilt function
- Preferable fenestration of automated operable elements in the façade are windows that are opposite to each other
- Space of 60mm above window frame is necessary for installing the actuators
- The gap in between the reveal and the windowpane can influence the effectiveness of the system, a gap of at least 40mm is recommended in order for the system to improve IAQ and large than 40mm is recommended for cooling

05

Feasibility

Feasibility check is an assessment of the practicality of a proposed system and to objectively and rationally uncover its strengths and weakness. The product line-up of the proposed system will be explained. Each product will be financially evaluated and compared in order to understand the potentials for success.

5.1 System

The system consist of IAQ controllers and actuators. Each room will be outfitted with an IAQ controller and all operable façade elements will be outfitted with an actuator. This way, decentralized climatization is possible per room. The actuators from Schuco and AXA will be used to automate the windows, each offering a different finishing level. A design should be made for the IAQ controller that resemble a building product, unlike the sensors from Netatmo. The sensors from Netatmo are designed as a consumer product. This stylish gadget will not be part of a home renovation, as it will be removed from the building when occupants move out to a new building. The proposed IAQ controller should be part of a home renovation, thus it should be designed for this purpose.

The indoor air quality controller will be mounted to the ceiling, similar to a smoke detector. This is not the most ideal location for the sensor, according to EN ISO 7726:2001 that recommend to place these sensors at a height of 1,1m above the ground, but tests in the PDlab showed no visible difference in the CO_2 concentration on 1,1 meter height (location of the Netatmo sensor) and the ceiling (location of the IAQ controller). Placing sensors on the wall positions them too much in sight and placing these sensors on tables of closets is also unwanted, as they should be fixed to a part of the building in order to prevent occupants moving the sensors. Placing them on the ceiling is already familiar to an occupant, due to the smoke detector or doorbell.

The overall shape and size of the IAQ should accommodate multiple sensors that could be placed or replaced in the future. A square shape is more effective compared to a circular shape, due to the square shape of the sensors (Figure 5-1). More sensors can be placed in a smaller box, thus a square shape will be used for the IAQ controller.

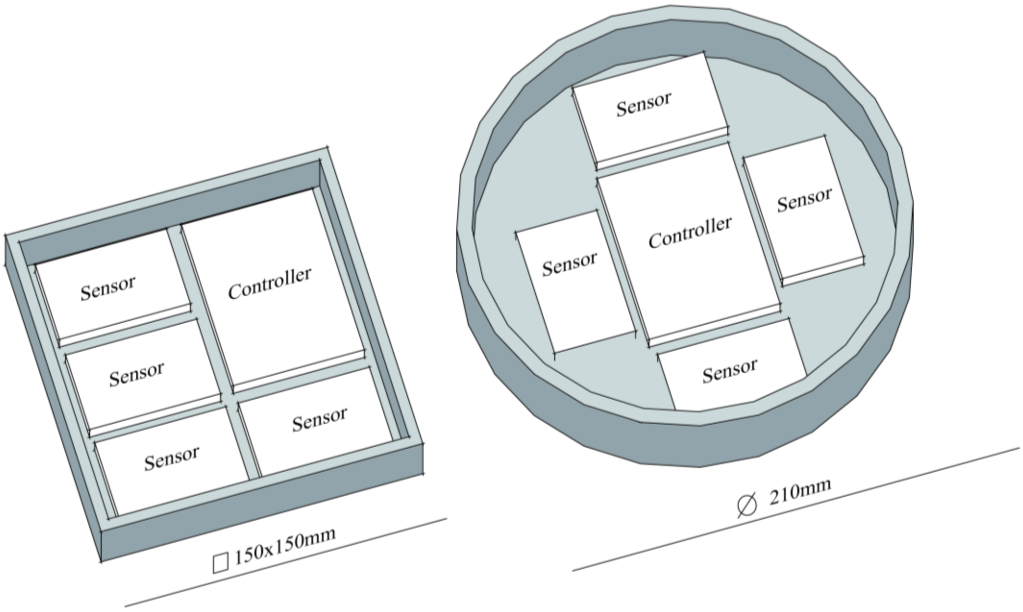


Figure 5-1 Square vs. circular shape

The sides of the IAQ controller should be perforated so indoor air can enter the box. The Netatmo sensor housing has a single slot with an opening of around 2mm, indication that a small opening is sufficient for measuring CO_2 concentrations, humidity, temperature and air pressure. Future expandability with new types of sensor may need a high air change rate within the box, thus a larger opening should be created in the sides of the IAQ controller. These openings can’t be big enough, the sensor used in the PDlab weren’t covered and still gave reliable results.

The IAQ controller should be relatively open and cover the electronics completely. Different designs can be created, from slots to holes. The most ideal design is using angled slats, which creates large openings but keeps the electronics out of sight due to the angle of the slats (Figure 5-2). Thus, angled slots will be used to cover the electronics while covering the electronics.

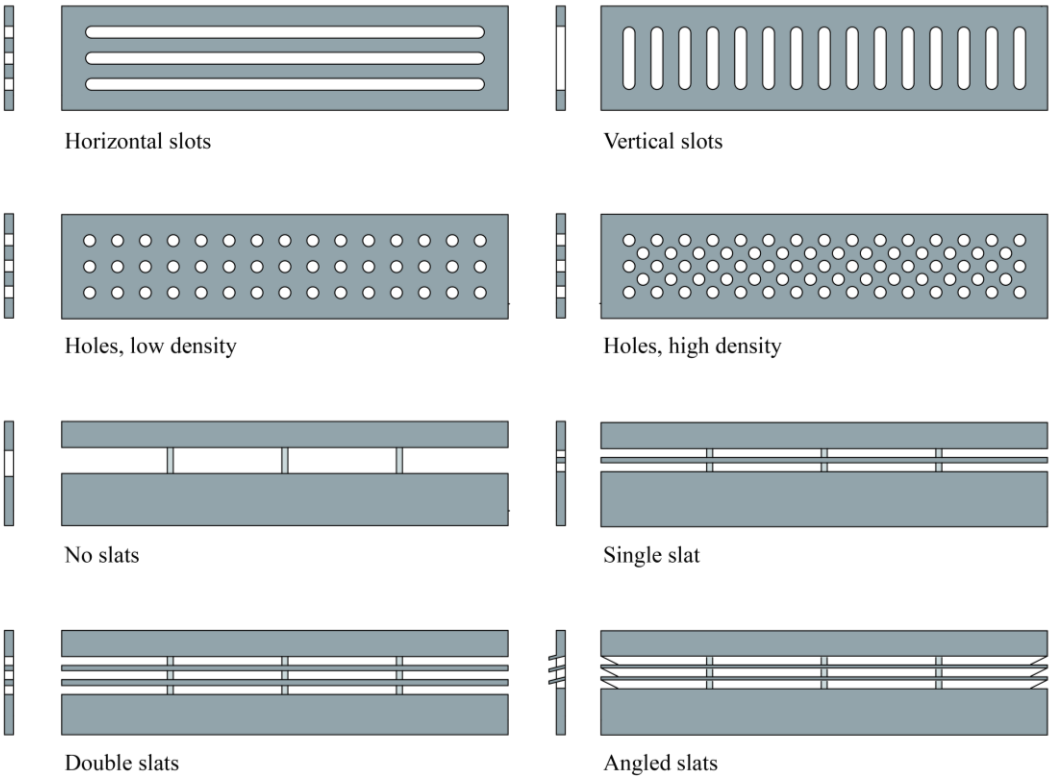


Figure 5-2 Multiple designs

Mounting the module to the ceiling will be done with a bracket, similar to the installment of a smoke detector. The bracket will be fixed to the ceiling with screws and plugs, after which the module can be attached to the bracket with the clips (Figure 5-3).

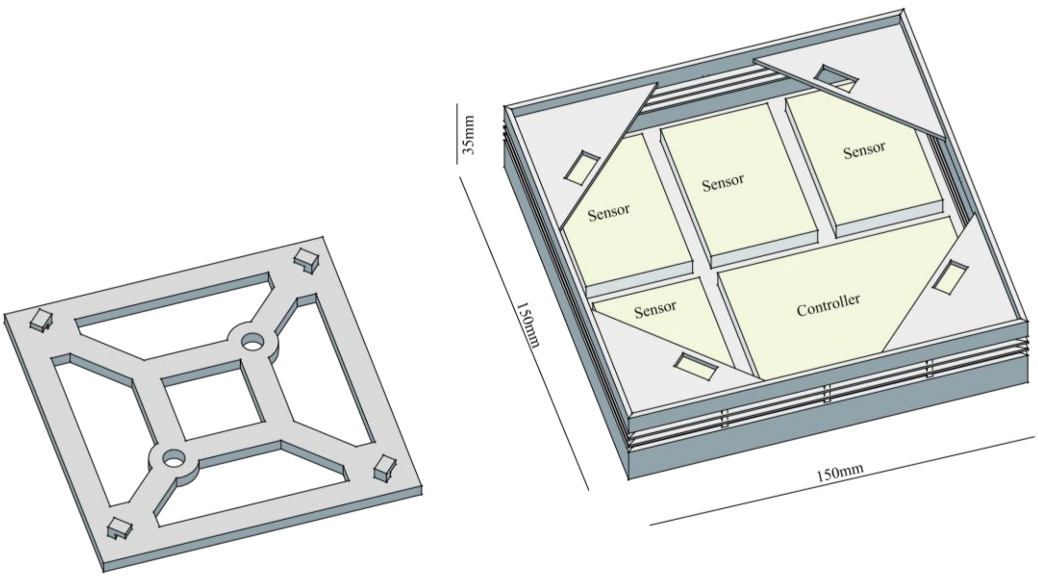


Figure 5-3 3D view

A small display will show the air quality in the room in order to explain certain window operation decision to an occupant (Figure 5-4). This display can also display if windows need to be operated manually, when maintenance is necessary or if the system isn’t able to create a safe or comfortable indoor climate.

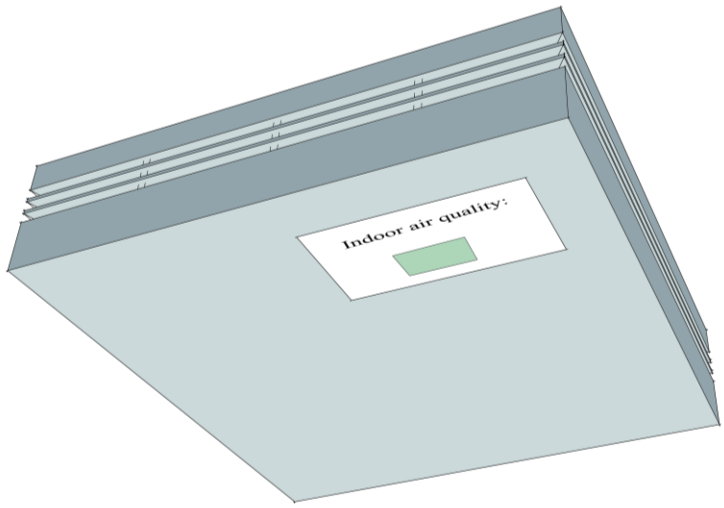


Figure 5-4 Final IAQ controller

In order to increase the feasibility of this system, multiple finishing levels at different price brackets will be offered for different costumers. The provision of choice can increase the individual’s sense of personal control and satisfaction in the desired outcome (Leotti, Iyengar, & Ochsner, 2010).

A ‘step up’ model of the system, called ‘building mentor’, will be created, which consist out of the sensors and a controller. The mechanism sends an indicator, with emoticons or a blinking led, to the occupant that should spur the active participant to carry out an operation. Initial investment cost will be lower than the other options, but the energy saving potentials will depend on the cooperation of the occupant. This will introduce an occupant to the importance of indoor climate by showing the potential energy savings and additional comfort it could create. This mechanism can easily be upgrade to a finishing level 2 or 3 by adding actuators to the system, where it becomes an fully automated system. No financial incentives are offered for this system, which lowers the financial resistance to upgrade to a fully automated system.

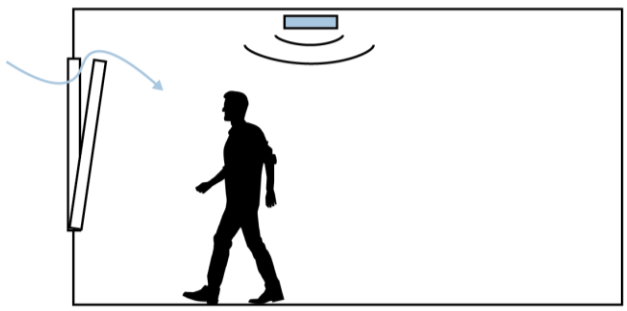


Figure 5-5 The building mentor

Finishing level 2, residence assist, consist out of the sensors, the controller and multiple AXA Remote 2.0 modules. This is the most basic fully automated option where the existing windows can be maintained. Operation freedom for the occupant is hindered in this solution due to the limitations of the AXA Remote 2.0. When installed, no operation by hand is possible anymore. Later updates for this unit may solve this. The benefit of this system is that it has a low initial investment.

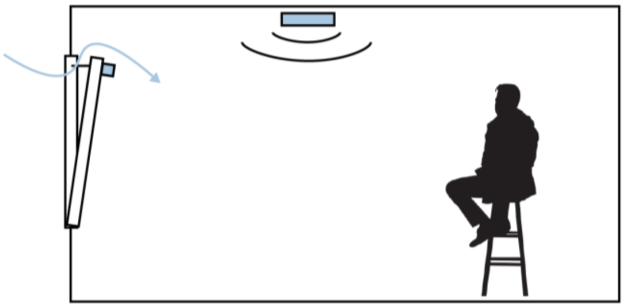


Figure 5-6 Residence assist

Finishing level 3, residence assist deluxe, is the most luxuriance system with integrated window actuators from Schuco, as discussed in chapter 0. These windows can be operated by an actuator and by hand, therefor not hindering operation freedom for the occupant. These motors are fully concealed and integrated in the window frame, thus installing new window frames is mandatory for this solution. This makes it the most expensive and time consuming variant of these systems, because it is part of a larger renovation.

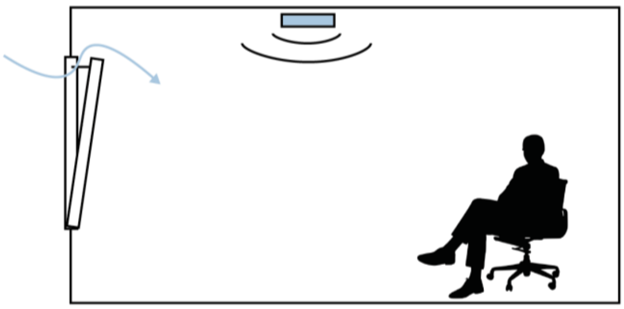


Figure 5-7 Residence assist deluxe

5.2 Financial evaluation

The financial evaluation of the mechanism will be done by calculation the payback period. The payback period for the mechanism will be determined similar to how the payback period for pv panels is calculated. This process has the following steps:

- Investment cost
- Financial incentives
- Energy savings
- Maintenance
- Running cost

(Aggarwal, 2018)

5.2.1 Investment cost

These three different mechanisms have different initial investment costs for the actuators, the rest of the system will be identical. The cost of the sensors differs from the location in the building and the pollutants it needs to detect. The sensor in the bedroom only measures CO_2, temperature and humidity. The sensor in the living room/kitchen also measures particulate matter, because the kitchen can be a source of particulate matter. The total cost of the sensor for in the bedroom is 70 euro/unit and the sensor for in the living room cost around 110 euro/unit, which falls within the same price range of the sensors from Netatmo. The cost for manufacturing can be lowered by the economy of scale, buying these sensors in bulk will reduce the price by around 2 or 3 times. The controller is the brain of the operation, it only needs to receive all the data, compute it and send it to the necessary window actuators. This can be done with an Arduino “like” board and a simple housing. The cost of this controller is around 30 euro/unit.

The investment cost for the actuators is the only part that will be different for the various finishing levels. Finishing level 1 doesn't have any actuators, finishing level 2 uses AXA Remote 2.0 motors that cost around 75 euro's each. Finishing level 3 uses Schuco Tiptronic actuators that cost 600 euro's on top of the price of the Schuco window frame. For these calculation, the price for the Schuco window frame will not be included in the calculations.

The final investment cost for finishing level 1, for a building with similar dimensions as the case study, is around 1.365 euro's. Finishing level 2 cost around 2.658 euro's and finishing level 3 cost around 6.550 euro's. Comprehensive structure of the price can be found in Appendix J.

5.2.2 Financial incentives

The Dutch government provides financial benefits to consumers, employees and organizations to encourage behavior to invest in a CO_2 controlled ventilation system. A subsidy of 800 euro is offered when installing this type of system for people in an owners association before the end of 2019. This system could also be an addition to a bigger 'nul-op-de-meter-concept' renovation where a heat recovery ventilation system or CO_2 controlled ventilation system is mandatory, giving investors an alternative solution to get a bonus subsidy of 4000 euro (RVO, 2019). This most likely refers to an expensive mechanical decentralized CO_2 ventilation system from ITHO, but could be applied to this proposed system.

5.2.3 Energy savings

Different indoor and outdoor conditions will affect the energy saving potentials of this system drastically, because reactions are formed based on these conditions and not on the input of the user. Except for finishing level 1, user error has limited effect on the results of this system, thus making the energy saving potentials more reliable than the energy saving potentials of a system that needs to be programmed or operated by the occupant. The results, presented in chapter 3.6, represent a potentials, not a certainties. These values will be used for the financial evaluation (Table 5-1).

	Existing situation	Threshold		Own	
Thermal energy	19,9mWh	15,7	mWh	14,2	mWh
Thermal energy savings		4,2	mWh	5,6	mWh
Energy from gas (incl. efficiency boiler)		9,77	kWh/m^3	9,77	kWh/m^3
Gas price (2019)		0,76	$euro/m^3$	0,76	$euro/m^3$
Financial savings		325	euro/year	439	euro/year

Table 5-1 Energy saving potentials

5.2.4 Maintenance

This mechanism only needs additional grease in the chain actuator, which cost nearly nothing. Some parts have a certain lifespan before replacement is advised by the manufacturer. The MH-Z14a has a lifespan of around 5 years and the sensor from Sensirion has a lifespan of 8 years, readings become inaccurate after this time period. The manufacturer for the actuators do not specify a lifespan, for educational purposes, replacement will be set at 10 years for the AXA Remote and 20 years for the Schuco Tiptronic.

	Part	Lifespan	Price
Sensor	MH-Z14a	5 years	20 euro

	Sensirion Sps30	8 years	40 euro
Actuators	AXA Remote 2.0	10 years	75 euro
	Schuco Tiptronic	20 years	200 euro

Table 5-2 Maintenance

A maintenance contract could offer the best solution to ensure a correctly function system for years. The monthly payment depends on the amount of sensor and actuators that are installed. For a building with 5 rooms, the contract could cost 7 euro's a month for finishing level 1, 11,25 euro's a month for finishing level 2 and 12,70 euro's a month for finishing level 3.

5.2.5 Running cost

The running cost of the sensor and controller of the prototype is around 1Wh, tested with an energy meter, thus 24Wh per day. The running cost of the window actuators depend on the amount of operations that it performs. When not in use, it doesn't consume any power. Calculations and simulations showed that in the most unideal situation, windows needed to open and close 3 times a day, once in the morning, once during the warmest part of the day and once during cooking. The AXA remote consumes around 4 AA batteries per 1000 operations, thus every 166 days the batteries should be changed. Four AA batteries produce around 12,96 Wh, meaning an actuator consumes around 0,08W per day.

The Schuco Tiptronic consumes around 2,1W in stand-by, which rises to 8,5W when opening and 10,2W when closing. The operation takes around 4 second, making the energy consumption due to operation minute compared to the stand-by energy consumption. Therefore, the energy consumption of the Schuco Tiptronic will be set at 2,1Wh.

	Energy consumption/year	Amount of units	Price/year
Sensor and controller	8,76 kWh	1 x	1,84 euro
AXA remote 2.0	0,08 kWh	7 x	0,12 euro
Schuco Tiptronic	18,40 kWh	7 x	27,05 euro

Table 5-3 Running cost

5.2.6 Investment payback period

The payback time is different for every finishing level, due to different purchase values, financial incentives, energy saving potentials, maintenance and running cost. The payback time is an indication, because it is based on various parameters that are hard to determine and vary from year to year. The energy savings only represent potentials, no certainties. This certainly applies for finishing level 1, where energy saving potentials are purely based on how cooperative a user is with the commands. Payback time for the active participant is around 3 years, but will differ when commands are ignored (Figure 5-8). Finishing level 2 has a payback time of around 6 years, which is due to the higher investment and maintenance cost. Finishing level 3 has a payback time of around 22 years.

These calculations are done without inflation and with a fixed gas price of 0,76 euro/m^3 and a fixed energy conversion efficiency of 9,77kWh/m^3. This may all change within the calculated timeframe, but will not be taken into consideration because this will only provoke speculations.

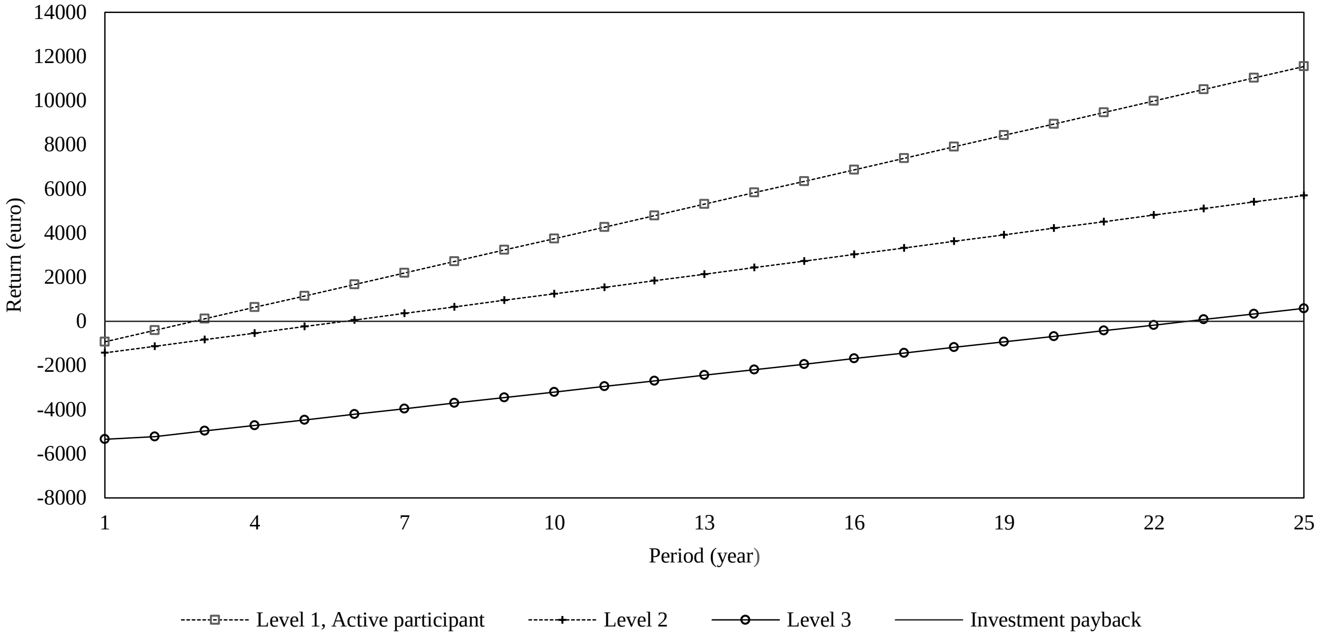


Figure 5-8 Financial potentials

5.3 Comparison

The proposed product will be compared with various renovation concepts made by ir. L. L. Franx the Ramplaankwartier and a demand driven mechanical ventilation system. This will determine how it should be positioned in the market.

5.3.1 Renovation

The results from the simulations will be compared to renovation concepts made for the post-war era residential building in the Ramplaankwartier. Three different strategies were designed by ir. L.L.Franx, each with their own set of boundary conditions. The first strategy is called “Basic insulation”, which is best suited for homeowners with a small budget whom only wish to improve the insulation level of their house. This second strategy, called EPC 0,4, is suited for homeowners who aim for a good insulation level of their homes and want to use renewable sources for part of their energy consumption. The last strategy is aimed at homeowners who are willing to make a large investment in order to drastically lower their energy consumption and live gas-free (Table 5-4).

Renovation strategies		
Basic insulation	EPC 0,4	Net Zero
- Simple insulation techniques	- Maximum EPC of 0,4	- A (nearly) NZEB
- Payback time: 10 years	- Use of renewable energy sources	- Gas-free
- Minimal disturbance level	- Payback time: 10-25 years	- Use of renewable energy sources
- Rc-values:	- Medium disturbance level	- No budget limits
Wall > 2,0 (m^2K)/W	- Rc-values:	- Rc-values:
Floor > 3,5 (m^2K)/W	Wall > 2,0 (m^2K)/W	Wall > 4,5 (m^2K)/W
Roof > 4,0 (m^2K)/W	Floor > 5,0 (m^2K)/W	Floor > 5,0 (m^2K)/W
Dormers > 2,5 (m^2K)/W	Roof > 6,0 (m^2K)/W	Roof > 6,0 (m^2K)/W
- Windows: HR++	Dormer > 4,5 (m^2K)/W	Dormer > 4,5 (m^2K)/W
- Frames: U-value < 1,4 W/(m^2K)	- Windows: HR+++	- Windows: HR+++
- Hot water installation < 15 years old	- Frames: U-value < 1,4 W/ (m^2K)	- Frames: U-value < 1,4 W/ (m^2K)

- LED lighting	- LED lighting	- LED lighting - Efficient electric appliances

Table 5-4 Renovation strategies (Franx, 2018)

Installations and building materials that don’t contribute in reducing the energy demand for heating will be removed from the cost. These are;

- pv panels
- induction stove
- efficient electric appliances

The potentials for each renovation strategy are plotted in Table 5-5 and Table 5-6. The energy consumption for heating is reduced significantly more with the renovation strategies proposed by L.L. Franx, compared to proposed ventilation system. Simple insulation techniques reduces the energy consumption by almost 50%, which is almost double the energy saving potentials for the proposed ventilation system.

	Current situation	Basic insulation	EPC 4,0	Net Zero
Energy consumption for heating	18,2 mWh	9,5 mWh	7,7 mWh	1,5 mWh
Energy consumption reduction	-	48 %	57 %	92 %
Cost	-	9.480 euro	20.180 euro	33.020 euro
	-	20.360 euro	41.590 euro	69.090 euro
Payback	-	13 – 29 years	24 - 49 years	29 - 60 years

Table 5-5 Potentials of the proposed renovation strategies (Franx, 2018)

The investment cost for the renovation proposals are a lot higher and the payback time is longer than the proposed ventilation system. Thus making it a viable alternative for a more extensive renovation.

	Current situation	Level 1	Level 2	Level 3
Energy consumption for heating	18,1 mWh	14,2 mWh	14,2 mWh	14,2 mWh
Energy consumption reduction	-	29 %	29 %	29 %
Cost		1.365 euro	1.858 euro	5.750 euro
Payback	-	± ≥ 3 years	6 years	22 years

Table 5-6 Potentials of the proposed products

A financial comparison between these renovation concepts doesn’t decide which approach is the most effective. Other incentives could stimulate an occupant to desire to renovate and should be taken into consideration. These side effects are;

- contribute to a better indoor comfort
- hinderance during construction
- difficulty during operation
- maintenance
- additional acoustical benefits
- added value to the building
- aesthetics or socially desirable

These incentives can be subjective or hard to determine, making them hard to quantify. Therefore, no further research is done in these incentives.

5.3.2 Ventilation system

This comparison will be done to evaluate the potentials of the proposed system to a CO_2 demand controlled mechanical ventilation system, which is the main competitive product for the designed system. This system uses a mechanical element to create pressure difference in order to ventilate a room or an area that is hard to reach with natural ventilation and a mechanical element to extract indoor air. A CO_2 sensor is used to determine the necessary airflow, similar to the proposed system.

Mechanical ventilation is commonly used in residential buildings. The mechanical inlet could filter or humidify incoming air in order to improve indoor conditions faster or to levels that can't be met with outdoor air. The mechanical outlet is redirected to a centralized location within the building where additional mechanisms could be used to recovery heat. In practice, it shows that occupants do not always understand the need and function of a ventilation system. User error or ignorance can work against the system, which leads to frustration, bad indoor air quality and it has an unknown effect on the final energy consumption. Common user error include blocking the in-or outlets of the ventilation system with furniture or a painting. These user errors could be prevented with clear instructions on the system and its necessity (Dijken & Boerstra, 2010).

Table 5-7 Painting covering inlet (Dijken & Boerstra, 2010)

Also, centralized ventilation systems depend on overflow from one room to another. Normally, this happens through the gap underneath the door. This gap can be blocked with a renewed floor finish or dust.

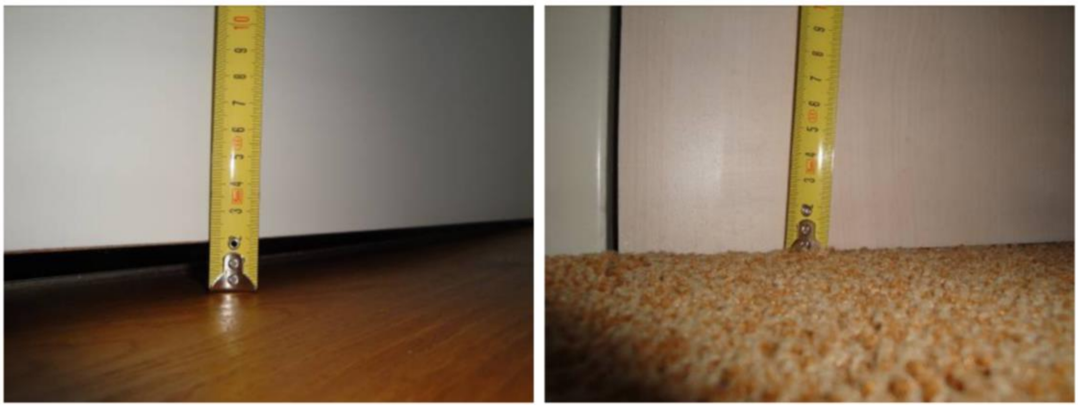


Table 5-8 Carpet blocking overflow (Dijken & Boerstra, 2010)

Cleaning a mechanical ventilation is needed on a regular basis, especially if there is a mechanical inlet. Fungi, dust mites and other forms of pollution can accumulate and grown in mechanical ventilation systems. This harms the quality and quantity of incoming air, creating an unhealthy indoor environment.

Table 5-9 Fungi and mold growth in ventilation system (Dijken & Boerstra, 2010)

A CO_2 driven mechanical ventilation doesn’t guarantee a safe and comfortable IAQ. In 2014, a new building for the Goese Lyceum in Goes was completed (Figure 5-9), which has a CO_2 driven mechanical ventilation system. Every room of the building is outfitted with CO_2 sensors, light intensity sensors and movement detectors, which all communicate to the HVAC and lighting system. This should create a safer and more comfortable indoor climate.

Figure 5-9 Goese Lyceum

PREMIUM

Mieke van Herwijnen (achter de balie) kreeg de afgelopen dagen meer dan 400 ziekmeldingen te verwerken op het Goese Lyceum. © Marcelle Davidse

Kwart van alle leerlingen Goese school ziek thuis

Een enorme griepgolf teistert het Goese Lyceum. Inmiddels heeft een kwart van alle leerlingen zich ziek gemeld. Dat zijn er meer dan 400. „Dit aantal is bizar",

Figure 5-10 News article on February the 13th 2019

The school has around 1600 student, at different educational levels. At 13 February 2019, more than 400 student and around 13 teachers have reported to be sick from an influenza epidemic (Figure 5-10). This is far higher than the average amount of sick leave during an influenza epidemic. It is possible to link this to the buildings ventilation system. Maybe CO_2 isn’t a sufficient indicator for ventilation need, malfunction of the HVAC system or lack of maintenance caused an unhealthy IAQ. This can’t be confirmed, more research has to be done.

The cost of a demand driven mechanical ventilation system is around 12.875 euro, but may vary based on the needed capacity and amount of rooms that need ventilation (Bouwkosten online, 2019). Financial incentives can lower this to 12.075 euro, which is still high enough to be a financial barrier for occupants. Initial investment can persuade a user to choose a certain product, but this is only if the benefits can justify the investment. A SWOT analysis will be used to compare these system without taking cost into consideration.

Strength	Weakness
- active ventilation, doesn’t depend on pressure difference due to wind - can ventilate rooms that are not adjacent to windows - can be combined with a heat recovery system - no acoustical pollution from outdoor source through ventilation	- prone to user error - loss of indoor space - accumulation of pollutants in the system, which needs maintenance - electricity usage during operation
Opportunities	**Threat**
- filtered inlets can achieve lower levels of pollutants than outside air, which can be mandatory for location specific regulations	- less radical interventions are available

The proposed system is a decentralized demand driven natural ventilation system, which controls indoor parameters per room, making it a unique product that doesn’t exist yet. This system has a relative low initial investment cost and no loss of indoor space. No permits are needed for the construction of this system for buildings that are constructed before 1975, because no regulations existed during that period of construction.

The effectiveness depends on the fenestration of the building, because it relies on wind pressure through the windows to ventilate. This can make the product unreliable, therefore boundary conditions for this system needs to be followed for the desired end result. This natural ventilation can stimulate cold draft in winter and noise pollution. Home automation is still unknown territory in normal households, making acceptability and added value to a residential building questionable.

Strength	Weakness
- low electricity usage during operation - no loss of indoor space - not prone to user error - decentralized ventilation	- fenestration determines effectiveness of the system - difference in wind pressure makes this product unreliable - cold draft in winter can occur - noise pollution can occur when in operation - acoustical pollutants from an outdoor source
Opportunities	**Threat**
- only product of this kind on the market - market increase results in home owners to invest in sustainable interventions - expandable and upgradeable with new sensor technologies	- regulatory limitations for newer building - home automation is still unknown territory in the normal household, acceptability is questionable - added value to the home depends on the acceptance of the product

5.4 Conclusion

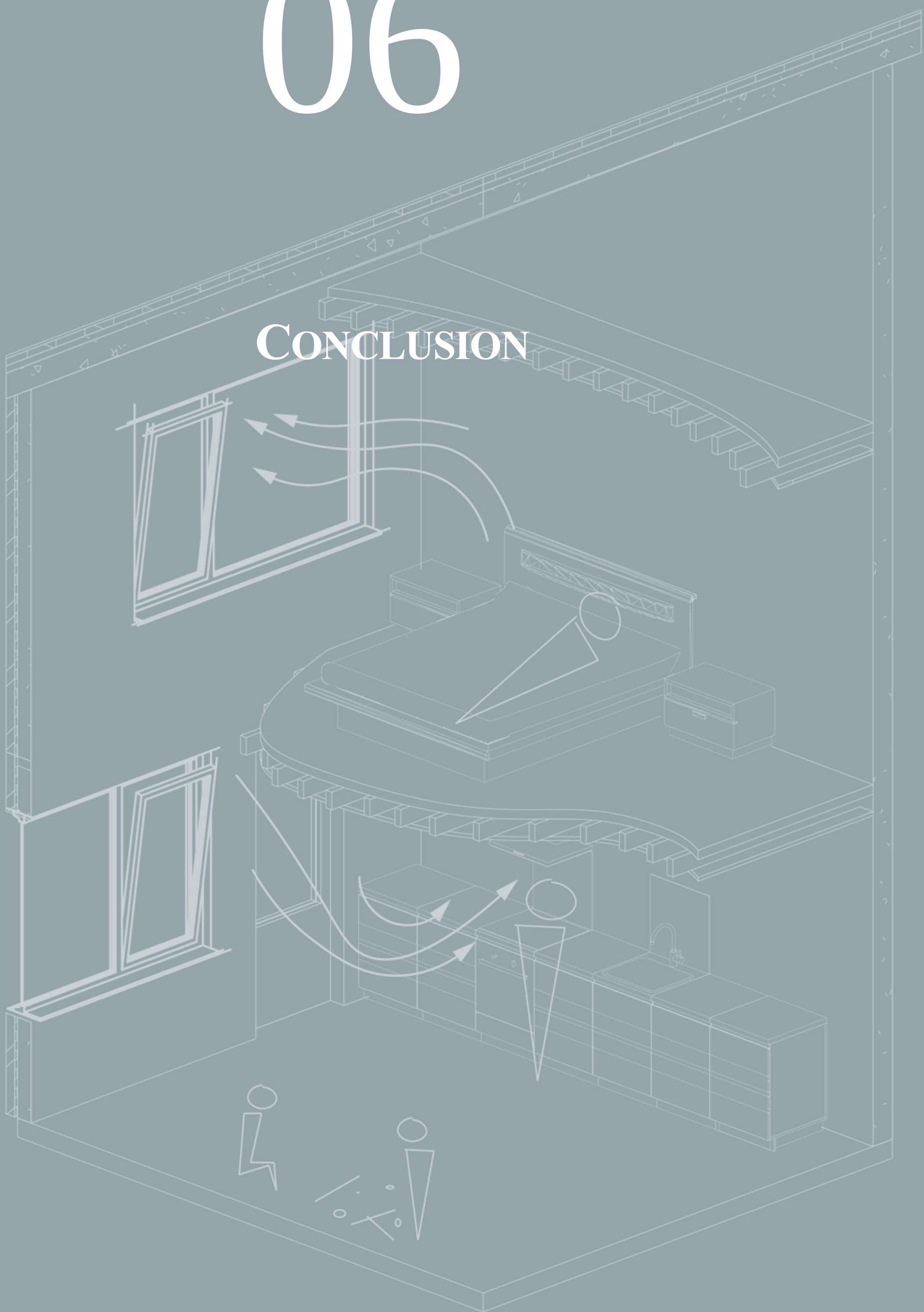
The final product consist out of two components, an IAQ controller and actuators. The IAQ controller has a simple design, trying to resemble a building product as opposed to a gadget such as the sensors from Netatmo. Multiple actuators can be used, with different finishing levels. Offering multiple finishing levels at different price points makes the product interesting for a wider range of people. The first model is a 'step up' model, which consist out of the controller and sensors in order to coach the occupant in sustainable behavior. The initial investment is around 1.365 euro for a single family home and has the potential to have a payback period of 3 years. Due to financial incentives, the cost to upgrade this 'step up' model to an automated system can be relatively low. The cheapest automated system is the 'residence assist', that includes automating operable windows with AXA Remote 2.0's, is a 500 euro upgrade from the 'step up' model. The most luxuries automated system includes Schuco Tiptronic actuators, which is an integrated actuator, thus installing new Schuco windows is mandatory. Investment cost for the system is around 5.750, excluding the additional cost for the window frames.

The energy saving potentials are relatively low, compared to a more conventual renovation with insulation of the building envelope. But the energy saving potentials and financial benefits are not the only reason why a building should be renovated. Additional comfort during construction and operation are real advantages compared to a more conventual renovation.

The proposed system has similarities with a demand driven mechanical ventilation system, where the air change rate is based on CO_2 concentration, but at a much lower cost. A mechanical ventilation system can sometimes be difficult to understand for an occupant, making them disconnect fans, block inlets or block overflow gaps underneath the doors. The proposed system is self-explanatory, ventilation through the opening of windows is easy to understand for an occupant. It has no ventilation grills that can be blocked or noise from a fan. The effectiveness of natural ventilation depends on the outside windspeeds and the fenestration of the building. Therefore, boundary conditions need to be met in order to guarantee a safe and comfortable ventilation system.

06

Conclusion



6.1 Conclusion

This concept focuses on reducing the thermal loss due to the increase of the air change rate resulting from window operation. The additional energy consumption due to window operation during heating season is difficult to quantify. It varies based on climate related parameters and building related parameters. While saving energy is the reason of development of this concept, it is not the main priority during the decision making of the system. The system only operates within the comfort limits of an occupant, which will increase the acceptability for the designed system. Thermal comfort will be determined with the adaptive thermal comfort and IAQ will be determined with pollutants threshold from the World Health Organization. These pollutants are CO_2 and PM pollutants, because they are produced in unsafe quantities by normal indoor user behavior, such as cooking, cleaning and breathing.

Different ventilation strategies are created, resulting in different energy saving potentials, thermal comfort and IAQ. A balanced strategy is created that focusses on creating a comfortable IAQ when additional heat sources increase the indoor temperature above the minimum comfort levels. When the indoor temperature is near the minimum thermal comfort level, the strategy will focus on reducing thermal loss due to ventilation. This system has the potential to decrease the energy consumption by around 29% for a uninsulated row house with a poor airtightness, where most of the energy saving potentials are during winter. An airtight building envelope isn't mandatory for this strategy. By lowering the air infiltration rate through the building envelope, the air change rate through the windows had to be increased in order to meet the set pollution thresholds. This offsets the energy saving potential for the improved air tightness, making it an ideal solution for buildings that are harder to make airtight.

With similar air change rate that are necessary to create a comfortable IAQ (maximum of 10ACH), indoor temperatures can be reduced by 3 degrees on a warm summer day in a rowhouse in Haarlem compared to a ventilation strategy that is based on the Dutch building code. This adaptive thermal comfort based ventilation strategy can't lower indoor temperatures below outdoor temperatures, meaning that if outdoor temperatures are above comfortable levels, the system isn't able to create thermal comfort. Windspeed can offset higher temperatures, but this high windspeed can only be noticed near the window.

The designed and created system measures indoor parameters with sensors, determines the ideal ventilation rate and operates windows with actuators. A human-perceived equivalent temperature, heat index, is measured with an DHT11 sensor and indoor air quality is measured with an MH-Z14a NDIR sensor. Data from these sensors is fed to a Arduino based controller, which generates an output via an algorithm. This algorithm determines the ideal air change rate based on the measured parameters. This air change rate is created with automated windows that open and close. During the test, an AXA Remote 2.0 is used to operate the windows, which is a motor that can be fitted to a window as a retrofit. The entire system is installed and tested in the PDlab, which is a small pavilion located in the courtyard of the faculty of architecture. The mechanism could create a healthy indoor air quality and lower the thermal loss due to ventilation. CO_2 concentrations stayed within comfort limits, contributing to multiple health benefits. Depending on wind speeds, fenestration and CO_2 production, it takes around three and a half hour to find the ideal window position to keep CO_2 concentration to a comfortable level. This can be shortened to two and a half hour by making the acceptable CO_2 concentration bandwidth narrower, which will decrease the window operation intervals. This will lower thermal loss even further at the cost of potential acoustical discomfort from the noisy actuators. The system didn't made a noticeable contributes to thermal comfort by cooling, due to the limited air change rate that could be created to the relative small opening of the windows. The windows are recessed in the façade, creating a small gap between the windowpane and the reveal where air can passes through. During testing with fully opened windows, the indoor temperature was around 10 degrees higher than the outdoor temperature. Indicating that the airflow capacity through the windows was too low for the amount of solar load on the South facing façade. This could be solved by increasing the gap between the windowpane and reveal, but also by increasing the length of the chain on the window actuator which could open the window even further.

The proposed system doesn't only contribute to lower thermal loss due to ventilation, but can increase indoor thermal comfort and lower indoor pollutants. Therefore, this system can be interesting for people that want to lower their energy consumption, but also for people that want to increase comfort. Unfortunately, the AXA remote 2.0 that were used during the test, made it impossible to manually operate the window, reducing the user interaction with the mechanism. There are multiple reasons why an occupant wants to open a window, but are not always related to ventilation need. Window operation by the user should still be possible, in order to fur fill window opening needs that are not ventilation related. More research and development in creating a actuator that doesn't limit operation by hand should be done. If operation by hand is possible, the controller determines if window operations from the occupant contributes in saving energy, indoor air quality or thermal comfort. If not, the window will stay open for 5 minutes and will close automatically, preventing unnecessary thermal losses.

Home owners in residential buildings that were constructed before 1975 are the target audience for this system. Older buildings have a high level of gas consumption for heating, due to the low amount of energy awareness during this time. This system has a low initial investment cost and could be implemented in these buildings without building permits, making it a feasible renovation alternative. Older buildings are harder to make air tight, the designed ventilation strategy performs better in less air tight building envelope than a conventional ventilation system. The system will be come in different finishing levels. The most basic version in this product line up is called the building mentor and only consist out of the IAQ controller, which cost around 1.365 euro to install in a standard rowhouse. It will notify the occupant when a window should be opened or closed, thus it will need an active participant in order to reduce thermal loss and improve comfort. The most basic fully automated system includes AXA remote 2.0 window actuators, which cost around 2.670 euro to install in a standard rowhouse. This system can be installed as a retrofit, making it ideal as a low cost investment. The most extensive version includes the Tiptronic system from Schuco, meaning that all automated windows need to be replaced with Schuco window frames. These actuators are fully integrated in the window frame, can be operated by hand and are verily quite. The additional cost of the actuators and the IAQ controller is around 6.550 euro, making it the most expensive version. Financial incentives can be used to lower the initial investment cost by 800 euro and can be increased if it is part of a renovation project that creates a 'nul-op-de-meter' building.

Calculations showed that a payback period of around 6 years can be achieved with the most basic fully automated window system for a uninsulated rowhouse and around 22 years for the most extensive version. This may vary based on the desired finishing level, user activities, building related parameters and climate related parameters. These energy saving potentials are most likely to be met if the building fits the following boundary conditions;

- System is only effective in rooms with operable façade elements
- The windows need to have a tilt function
- Preferable fenestration of automated operable elements in the façade are windows that are opposite to each other
- Space of 60mm above window frame is necessary for installing the actuators
- The gap in between the reveal and the windowpane can influence the effectiveness of the system, a gap of at least 40mm is recommended in order for the system to improve IAQ and large than 40mm is recommended for cooling

6.2 Future work

This work was focused on the automation of user behavior in residential buildings. Throughout the development of this study, multiple potential research topics have been emerged. Some could be explored in future research;

- During coding of the algorithm, I discussed the thinking process of the controller with an Artificial Intelligent student and Econometrics student. They both mentioned that algorithms with statements are becoming old for these kinds of applications. Artificial neural networks or supervised learning can be a better option in predicting actions in order to create comfort or save energy. The downside of this method is that the system needs to make a lot of mistakes before it determines an ideal window operation sequence. Mistakes that are made by the proposed system can lead to frustration from an occupant, lowering its acceptability. But it has the potential to create an even smarter system, that doesn't follow scripted statements and thresholds, but learns when the occupant feels comfort.
- Long running test of the system in multiple buildings in order to quantify the energy saving potentials.
- The actuator that automates a turn tilt window, while being operable by an occupant, should be developed. Schuco creates a system that is automated and still operable by hand, but only for the tilt function.
- This proposed system is developed for oceanic climates (the Netherlands), potentials in other climates could be interesting.
- More parameters should be added to the final product, such as VOC. There are a lot more pollutants in the air than only CO_2 and PM.
- Measuring local outdoor pollutants in order to optimize the system

07

References

Aggarwal, V. (2018, 10 29). *Understand solar financial benefits: Payback period.* Retrieved 04 14, 2019, from news.energysage: https://news.energysage.com/understanding-your-solar-panel-payback-period/

Akerkar, R., Andersson, K., & Castra, P. P. (2015). *International Sustainable Ecological Engineering Design for Society (SEEDS) Conference 2015.* Leeds: Leeds Beckett University.

Aleixandre, M., & Gerboles, M. (2012). Review of Small Commercial Sensors for Indicative Monitoring of Ambient Gas. *CHEMIICAL ENGIINEERIING TRANSACTIIONS VOL. 30*, 169 - 174.

Alifrio. (n.d.). *Like*. Retrieved January 3, 2019, from the noun project: https://thenounproject.com/search/?q=thumb%20up&i=2069163

American Industrial Hygiene Association. (2013). *Odor Thresholds for Chemicals with Established Health Standards, 2nd Edition.* Falls Church: American Industrial Hygiene Association.

Anderson, G. B., Bell, M. L., & Peng, R. D. (2013). Methods to Calculate the Heat Index as an Exposure Metric in Environmental Health Research. *Environmental Health Perspectives, volume 121 | number 10*, 1111-1119.

Angela, S., & Bjarne, O. W. (2013). Preferred Air Velocity and Local Cooling Effect of desk fans in warm environments. *PREFERRED AIR VELOCITY AND LOCAL COOLING* (p. 11). Denmark: International Center for Indoor Environment and Energy.

AXA home security. (2019). *Raamopener met afstandsbediening AXA Remote valraam*. Retrieved 05 05, 2019, from AXA security: https://www.axasecurity.com/home-security/nl-nl/producten/uitzetters/11/29022096/raamopener-met-afstandsbediening-axa-remote-valraam

Bader, S., & Blaauboer, R. O. (2009). *Mechanische ventilatie in nieuwbouwwoningen: gebruik, geluidsniveau en beleving.* Bilthoven: RIVM.

Barrett, K. E., Boitano, S., Barman, S. M., & Brooks, H. L. (2010). *Ganong's review of Medical Physiology.* New York: McGraw Hill. Retrieved from https://emergencypedia.files.wordpress.com/2013/04/ganong-pdf.pdf

Blanchard, B. S. (2016). *Systems Engineering and Analysis.* Virginia: Wiley.

Blauw Research bv. (2018, February 7). *Concentraties fijnstof in Nederlandse huizen te hoog*. Retrieved January 5, 2019, from Blauw: https://www.blauw.com/nl/news/concentraties-fijnstof-in-nederlandse-huizen-te-hoog

Bluyssen, P. M. (2009). *The indoor environment handbook.* London: Earthscan.

BomSymbols. (n.d.). *Finger pointing*. Retrieved January 3, 2019, from the noun project: https://thenounproject.com/search/?q=finger%20pointing&i=1240316

Bouwkosten online. (2019, 05 01). *Bouwkosten*. Retrieved from Bouwkosten online: https://bouwkosten.bouwformatie.nl/

Castell, N., Dauge, F. R., Schneider, P., Vogt, M., Lerner, U., Fishbain, B., . . . Bartonova, A. (2016). *Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates?* Kjeller: Environment International.

Commission on Economic Justice. (2017). *Managing Automation, Employment, inequality and ethics in the digital age.* London: IPPR.

Corredor, J. M. (n.d.). *Automation*. Retrieved January 3, 2019, from the noun project: https://thenounproject.com/juan_corredor/uploads/?i=2098222

Curto, A., Donaire-Gonzaleza, D., Barrera-Gómeza, J., Marshalld, J. D., Nieuwenhuijsena, M. J., Welleniuse, G. A., & Tonnea, C. (2018). *Performance of low-cost monitors to assess household air pollution.* Barcelona: Environmental Research.

de Dear, J. R., & Brager, S. G. (2002). *Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55.* Sydney: Energy and Buildings.

De energieconsultant. (2019). *Omrekening van m3 (n) naar kWh*. Retrieved 02 10, 2019, from De energieconsultant: https://www.energieconsultant.nl/energiemarkt/energie-berekeningen-uit-de-praktijk/omrekening-van-m3-n-naar-kwh/

De Gids, W. F. (2015). *Ventilatie, achtergrond van de eisen.* Delft: TNO.

Delzendeh, E., Wu, S., Lee, A., & Zhou, Y. (2017). The impact of occupants' behaviours on building energy analysis: A research review. *Renewable and Sustainable Energy Reviews 80*, 1061-1071.

Dijken, F. v., & Boerstra, C. A. (2010). *BBA Binnenmilieu, onderzoek naar de kwaliteit van ventilatiesystemen in nieuwbouw eengezinswoningen.* Rotterdam: Ministerie van VROM.

D'Oca, S., Corgnati, P. S., Fabi, V., & Andersen, R. K. (2014). *Effect of thermostat and window opening occupant behavior models on energy use in homes.* Torino: Journal of Building Performance Simulation.

Engineering Toolbox. (2019). *Carbon Dioxide Concentrations in Rooms with People*. Retrieved 01 14, 2019, from Engineering toolbox: https://www.engineeringtoolbox.com/pollution-concentration-rooms-d_692.html

Eragon. (n.d.). *Bulb*. Retrieved January 3, 2019, from the noun project: https://thenounproject.com/search/?q=light%20bulb&i=1601282

European Commission. (2018). *Buildings*. Retrieved January 3, 2019, from ec.europa: https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings

European Environment Agency. (2014). *Air pollution fact sheet 2014, The Netherlands.* Denmark: European Environment Agency.

Florea, A., Berntzen, L., & Johannessen, M. R. (2017). Low Cost Mobile Embedded System for Air Quality Monitoring Air quality realtime monitoring in order to preserve citizens' health. *SMART 2017, International Conference on Smart Systems, Devices and Technologies* (p. 9). Italy: IARIA.

Fountain, M., & Edward, A. A. (1993). *Indoor environmental quality.* California: ASHRAE Journal.

Francesca, S., Naspi, F., Ulpiani, G., & Di Perna, C. (2017). *Indoor air quality and thermal comfort optimization in classrooms developing an automatic system for windows opening and closing.* Ancona: Energy and Buildings.

Franx, L. L. (2018). *Post-War refurbishment.* Delft: Delft University of Technology.

Gas-sensor. (n.d.). *MH-440D infrared gas sensor.* Retrieved January 5, 2019, from gas-sensor: http://gas-sensor.ru/pdf/ndir-gas-sensor.pdf

Gezondheidsraad. (2018). *Gezondheidswinst door schonere lucht.* Den Haag: Gezondheidsraad.

Google. (2019, 6 15). *google maps*. Retrieved from google maps: https://www.google.nl/maps

Gutierrez, D. (2019, 3 27). *Doug Cutting, Chief Architect of Cloudera*. Retrieved from insideBIGDATA: https://insidebigdata.com/2016/02/17/14486/

HANWEI ELECTRONICS. (n.d.). *Technical Data MQ5 gas sensor.* Retrieved January 5, 2019, from hwsensor: https://www.parallax.com/sites/default/files/downloads/605-00009-MQ-5-Datasheet.pdf

HBopeners. (n.d.). *SW-200 Automatische deurdranger*. Retrieved January 5, 2019, from HBopeners: https://www.hbopeners.nl/a-50731308/deuropener/sw-200-automatische-deurdranger/#description

Honeywell. (n.d.). *Round T87F (1960-2002).* Retrieved January 5, 2019, from kijkvoelbeleef: https://www.kijkvoelbeleef.nl/HoneywellHome/Producten/Product/Round-T87F-1960-2002/

Hong, T., Yan, D., D'Oca, S., & Chen, C.-f. (2016). *Ten questions concerning occupant behavior in buildings: The bigpicture.* Berkeley: Building and Environment.

Huiskamp, A. (2019, 4 10). *KNMI*. Retrieved from KNMI: https://www.knmi.nl/nederland-nu/klimatologie/maand-en-seizoensoverzichten/2018/april

Isikdag, U., Sahin, K., & Cansiz, S. (2018). a machine learning approach on occupant number prediction for indoor spaces. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-4, 2018* (pp. 275-281). Delft: ISPRS.

Itho Daalderop. (2017, 12 19). Installatie en gebruik. *Itho Daalderop CVE-S ECO*. Schiedam: Itho Daalderop.

Jack, R., Loveday, D., Allinson, D., & Lomas, K. (2015). *Quantifying the Effect of Window Opening on the Measured Heat Loss of a Test House.* Leicestershire: Leeds Beckett.

Jacobs, P. (2017). Fijnstof bronnen in en rondom woningen. *TVVL Magazine*, 18 - 20.

Jacobs, P., Cornelissen, E., & Borsboom, W. (2017). Energy efficient measures to reduce PM 2,5 emissions due to cooking. *Indoor air conference.* Gent: Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek.

KNMI. (2019). *Zomer 2018*. Retrieved 6 3, 2019, from KNMI: https://www.knmi.nl/nederland-nu/klimatologie/maand-en-seizoensoverzichten/2018/zomer

Leotti, L. A., Iyengar, S. S., & Ochsner, K. N. (2010). Born to Choose: The Origins and Value of the Need for Control. *Trends Cogn Sci.*, 457-463.

Liddament, M. W. (2001). *Occupant impact on ventilation.* Air Infiltration and Ventilation Center.

Lidman, K., & Restrom, S. (2011). *How to design for sustainable behaviour.* Goteborg: Chalmers.

Lilley, D. (2009). Design for sustainable behaviour: strategies and perceptions. *Design Studies, volume 30, issue 6*, 704-720.

Lopes, J. S., & Agnew, P. (2010). *FPL Residential Thermostat Load Control Pilot Project Evaluation.* Washington D.C.: ACEEE.

Majava, J., Haapasalo, H., & Harkonen, J. (2015). The relations between stakeholders and product development drivers: Practitioners' perspectives. *International Journal of Innovation and Learning*, unknown.

Majcen, D., & Itard, L. (2014). *Relatie tussen energielabel, werkelijk energiegebruik en CO2-uitstoot van Amsterdamse corporatiewoningen.* Delft: Rekenkamer Metropool Amsterdam.

McCoy, A. G. (2012). *"Smart" Residential Thermostats: Capabilities, Operability and Potential Energy Savings.* Washington: Washington State University.

Meer Met Minder. (2019). *energielabelatlas*. Retrieved January 9, 2019, from energielabelatlas: http://energielabelatlas.nl/#Haarlem/Haarlem/16/52.3823/4.6081

Meteoblue. (2019). *Klimaat Haarlem*. Retrieved 6 2, 2019, from Meteoblue: https://www.meteoblue.com/nl/weer/voorspelling/modelclimate/haarlem_nederland_2755003

Milieu Centraal. (2019). *Gemiddeld energieverbruik*. Retrieved January 9, 2019, from milieucentraal: https://www.milieucentraal.nl/energie-besparen/snel-besparen/grip-op-je-energierekening/gemiddeld-energieverbruik/

Milner, J., Armstrong, B., Davies, M., Ridley, I., Chalabi, Z., Shrubsole, C., . . . Wilkinson, P. (2017). *An Exposure-Mortality Relationship for Residential.* Bazel: MDPI.

Ministerie van Binnenlandse Zaken en Koninkrijksrelaties. (2016). *Cijfers over bouwen en wonen 2016.* Den Haag: Rijksoverheid.

Moghadam, T. S., Soncini, F., Fabi, V., & Corgnati, S. P. (2015). *Appraising the effects of window opening behaviour in an office building.* Bozen-Bolzano: International Building Performance Simulation Association.

Moon, J. W., & Han, S. H. (2010). Thermostat strategies impact on energy consumption in residential buildings. *Energy and Buildings*, 338-346.

National Oceanic & Atmospheric Administration. (2019, 04 19). *Up-to-date weekly average CO2 at Mauna Loa.* Retrieved 04 19, 2019, from Earth System Research Laboratory Global Monitoring Division: https://www.esrl.noaa.gov/gmd/ccgg/trends/weekly.html

ncbi. (2019). *Understanding natural ventilation*. Retrieved 6 14, 2019, from ncbi: https://www.ncbi.nlm.nih.gov/books/NBK143285/

Normcommissie 302 005 "Ergonomie van de fysische werkomgeving". (2001). *NEN-EN-ISO 7726.* Delft: NEN.

Normcommissie 302 005 "Ergonomie van de fysische werkomgeving". (2005). *NEN-EN_ISO 7730.* Delft: Nederlands Normalisatie-instituut.

Normcommissie 351 074 "klimaatbeheersing in gebouwen". (2007). *NEN-EN 15251 Binnenmilieu gerelateerde input parameters voor ontwerp en beoordeling van energieprestatie van gebouwen voor de kwaliteit van binnenlucht, het thermisch comfort, de verlichting en akoestiek.* Delft: Nederlands normalisatie-instituut.

O'Carroll, E. (2009, 3 27). *Does lighting candles for Earth Hour defeat the purpose?* Retrieved 2 21, 2019, from csmonitor: https://www.csmonitor.com/Environment/Bright-Green/2009/0327/does-lighting-candles-for-earth-hour-defeat-the-purpose

Opencircuit OÜ. (2019). *Open circuit*. Retrieved 02 10, 2019, from OpenCircuit: https://opencircuit.nl/

Prado, L. (n.d.). *Carrot and Stick*. Retrieved January 3, 2019, from The noun project: https://thenounproject.com/search/?q=carrot%20stick&i=84055

Psomasa, T., Fiorentini, M., Kokogiannakis, G., & Heiselberg, P. (2017). *Ventilative cooling through automated window opening controlsystems to address thermal discomfort risk during the summerperiod: Framework, simulation and parametric analysis.* Aalborg: Energy and Buildings.

Qian, J., Ferro, A. R., & Fowler, K. R. (2012). Estimating the Resuspension Rate and Residence. *Journal of the Air & Waste Management Association*, 502-516.

Rijksinstituut voor Volksgezondheid. (2019, 04 19). *Stations.* Retrieved 04 19, 2019, from Luchtmeetnet: https://www.luchtmeetnet.nl/

Rijksoverheid. (2018, November 3). *Afdeling 3.6. Luchtverversing*. Retrieved January 4, 2019, from Bouwbesluit 2012: https://rijksoverheid.bouwbesluit.com/Inhoud/docs/wet/bb2012/hfd3/afd3-6

Rijsoverheid. (2009). *Nationaal Samenwerkingprogramma Luchtkwaliteit.* Den Haag: Rijksoverheid.

RVO. (2019, 04 20). *Aanvullende maatregelen Vereniging van Eigenaren - SEEH*. Retrieved from Rijksdienst voor ondernemend Nederland: https://www.rvo.nl/subsidies-regelingen/subsidie-energiebesparing-eigen-huis/wat-kunt-u-aanvragen/aanvullende-maatregelen-vereniging-van-eigenaren

Schellevis, J. (2019, 2 21). *Honderden slimme gebouwen te kraken: 'Installateurs moeten bijleren'*. Retrieved from NOS: https://nos.nl/artikel/2272844-honderden-slimme-gebouwen-te-kraken-installateurs-moeten-bijleren.html

Schueco. (2019). *Schüco TipTronic*. Retrieved 03 10, 2019, from Schueco: https://www.schueco.com/web2/nl/architecten/producten/automatisering/schueco_tiptronic

Sensirion AG. (2019). *CO2 and RH/T Sensor Module*. Retrieved 02 10, 2019, from Sensirion: https://www.sensirion.com/en/environmental-sensors/carbon-dioxide-sensors-co2/

Sociaal-Economische Raad. (2013). *Energieakkoord voor duurzame groei.* Den haag: Sdu Uitgevers.

Strøm-Tejsen, P., Zukowska, D., Wargocki, P., & Wyon, D. P. (2015). *The effects of bedroom air quality on sleep and next-day performance.* Lyngby: John Wiley & Sons Ltd.

The Engineering Toolbox. (n.d.). *Psychrometric Chart - Barometric Pressure 29.921 inches of Mercury*. Retrieved 02 10, 2019, from The Engineering Toolbox: https://www.engineeringtoolbox.com/psychrometric-chart-d_816.html

The New Makers. (n.d.). *PDLab*. Retrieved 03 10, 2019, from https://www.thenewmakers.com/2017/12/15/lego-for-buildings-in-practice/: https://www.thenewmakers.com/2017/12/15/lego-for-buildings-in-practice/

Toon. (n.d.). *Met toon ben je baas over je huis*. Retrieved January 5, 2019, from Toon: https://www.toon.nl/

van Gorp, A. (2005). *Ethical issues in engineering design, safety and sustainability.* Delft: Simon Stevin Series in the Philosophy of Technology.

van Holsteijn, R., & Li, W. (2015). Monitoring the energy- & IAQ performance of residential ventilation systems. *REHVA Journal*, 6 - 10.

Vektiva. (n.d.). *Smarwi - smart window opener*. Retrieved January 5, 2019, from Vektiva: https://vektiva.com/en/shop/smarwi

Vroon, P. A. (1990). *Psychologische aspecten van ziekmakende.* Utrecht: ISOR.

Winsen. (n.d.). *Infrared Gas Sensor MH-440D/ Methane Gas Sensor/ CH4 Detection*. Retrieved January 5, 2019, from winsen-sensor: https://www.winsen-sensor.com/products/ndir-ch4-sensor/mh-440d.html

Winsen. (n.d.). *MQ-5 LPG Detection Sensor*. Retrieved January 5, 2019, from Winsen-sensor: https://www.winsen-sensor.com/products/semiconductor-gas-sensor/mq-5.html

Wookey, R., Bone, A., Carmichael, C., & Crossley, A. (2014). *Minimum home temperature thresholds for health in winter.* London: Public health England.

World Health Organization. (2009). *WHO guidelines for indoor air quality, dampness and mould.* Denmark: World Health Organization.

World Health Organization. (2010). *WHO guidelines for indoor air quality, selected pollutants.* Denmark: World Health Organization.

World Health Organization. (2013). *Health effects of particulate matter.* Denmark: World Health Organization.

Xella. (2019). *Luchtdichtheid*. Retrieved 02 10, 2019, from Xella: https://www.xella.be/nl/luchtdichtheid_3894.php

Yang, Y., Wu, H., & Li, Y. (2018). Hacking Intelligent Building. (p. 74). Amsterdam: HITBSecConf. Retrieved from https://conference.hitb.org/hitbsecconf2018ams/materials/D1T2%20-%20YuXiang%20Li,%20HuiYu%20Wu%20&%20Yong%20Yang%20-%20Hacking%20Intelligent%20Buildings%20-%20Pwning%20KNX%20&%20ZigBee%20Networks.pdf

APPENDIX A

The test building, from the department of Civil and Building engineering at Leeds Beckett University in Loughborough, is used to investigate the effect of window opening behaviors on heating demand with different insulation values and ventilation systems. Uniec 2 is used for these calculations, which is a tool to calculated energy usage and energy labels. The results of the test building showed a linear relationship between the additional infiltration and the openings, therefor different window opening behaviors can be calculated by changing the infiltration in the Uniec. The test house provides multiple data which is needed for this calculation.

Only the dimensions and the infiltration rates due to window opening behavior will be used for these calculations due to unknown parameters. The results will only be used to get a further understanding on the effect on window opening behavior on energy demand, not to verify the results made by the researchers at the department of Civil and Building engineering at Leeds Beckett.

Data:

Volume	=	$150m^3$		
Floor area	=	$60m^2$		
Add. infiltration due to opening	=	3,8 times/hour/m^2 opening		
	=	3,8 x 150	=	$570m^3/h$
	=	570 / 60 =	$9,5m^3/h/m^2$	
	=	$2,6l/s/m^2$		

Three different ventilation systems will be compared, a natural ventilation system, a natural inlet with mechanical exhaust and a mechanical ventilation system with heat recovery. These three systems are common ventilation system in the current residential built environment, representing a poor and high performing buildings. Also, three different levels of finishing will be compared, a poor performing building, a high performing building and a building conform Bouwbesluit 2012.

Infiltration (Dutch standards)

= Poor performing	=	0,90 $l/s/m^2$
= Bouwbesluit cf.	=	0,60 $l/s/m^2$
= High performing	=	0,15 $l/s/m^2$

Rc values

= Poor performing	=	avg.	= $0,9m^2K/W$
= Bouwbesluit cf.	=	floor	= $3,5\ m^2K/W$
	=	roof	= $6,0\ m^2K/W$
	=	wall	= $4,5m^2K/W$
=High performing	=	avg.	= $8,0m^2K/W$

The infiltration rate of the test building is $4,2l/s/m^2$, measured with a pressure difference of 50Pa. This data will not be used for these calculation, because Dutch measuring method state that infiltration needs to be measured at a pressure difference of 10Pa.

Four different window opening behaviors will be investigated (Table 0-1). These range from no window opening (0,0m^2 opening) till “unrealistic” high window opening (1,0m^2 opening) behavior.

Building type	0,0m^2 opening (l/s/m^2)	0,1m^2 opening (l/s/m^2)	0,5m^2 opening (l/s/m^2)	1,0m^2 opening (l/s/m^2)
Poor performing	0,9	0,9 + 0,26 = 1,16	0,9 + 1,3 = 2,2	0,9 + 2,6 = 3,5
Buwbesluit cf.	0,6	0,6 + 0,26 = 0,86	0,6 + 1,3 = 1,9	0,6 + 2,6 = 3,2
High performing	0,15	0,15 + 0,26 = 0,41	0,15 + 1,3 = 1,45	0,15 + 2,6 = 2,75

Table 0-1 Ventilation rate

The following graph shows the increase in heating demand for the different building types with different window opening behavior.

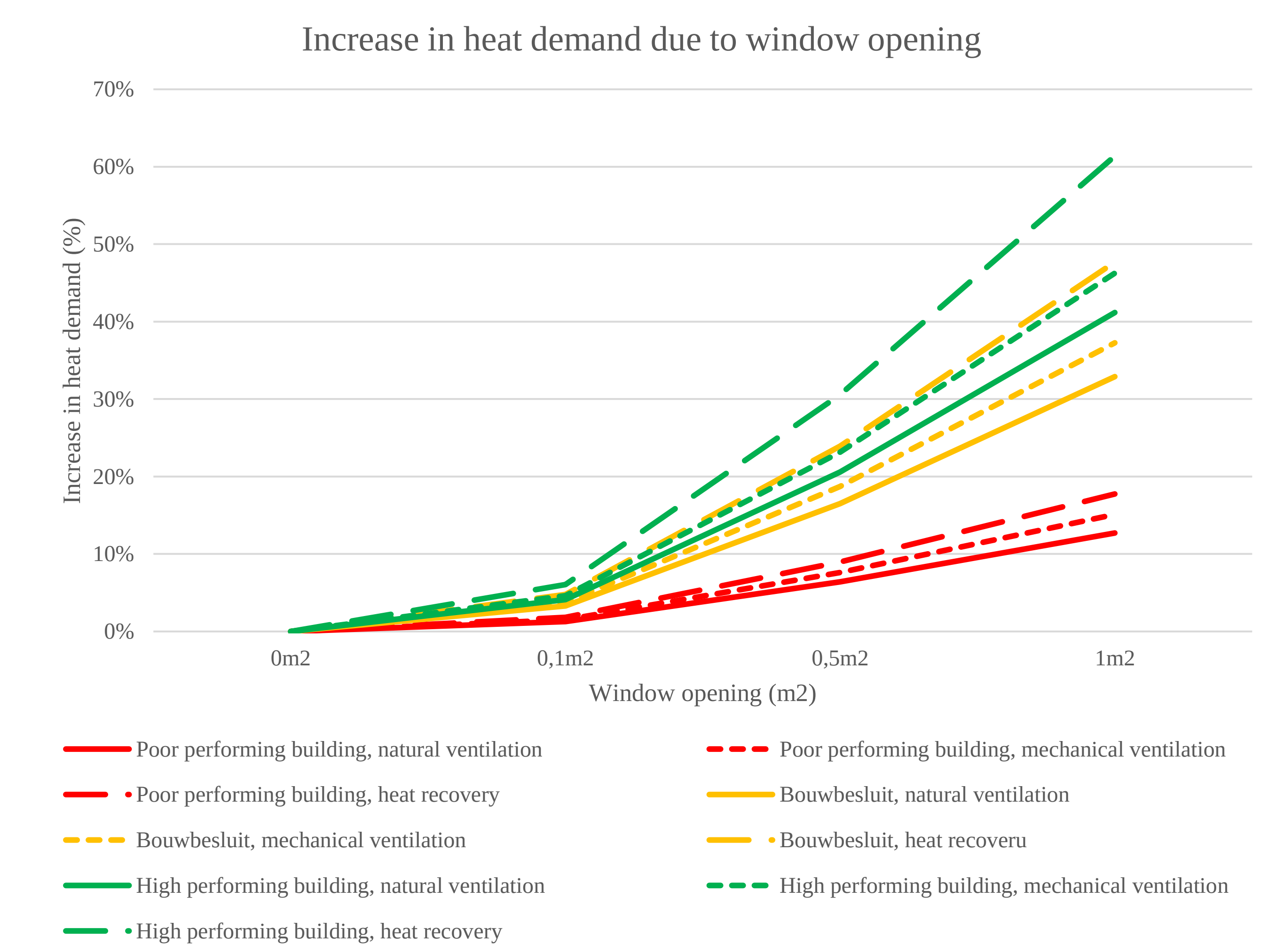


Figure 0-1 Heating demand increase

User behavior effect all building types, but especially high performing buildings and buildings with a heat recovery system. Therefore, this system will be designed for these types of buildings.

The internal doors could also be operated by a user and can have an effect on the heating demand. The effect on operation of the internal doors will be tested on the same test building, from the department of Civil and Building engineering at Leeds Beckett University in Loughborough. The building will be made conform the Dutch building code, to get a representative of the buildings in the Netherlands. The building will be outfitted with a natural ventilation system. Design builder will be used for these calculations in order to understand the internal doors operation on energy demand. Operation schedules can be seen in the following table, which represent a common operation schedule for a dwelling according to Design Builder.

Weekdays		Weekends	
Until 7:00	0%	Until 9:00	0%
Until 8:00	50%	Until 21:00	100%
Until 9:00	0%	Until 24:00	0%
Until 10:00	25%		
Until 17:00	50%		
Until 18:00	75%		
Until 22:00	100%		
Until 23:00	75%		
Until 24:00	25%		

Table 0-2 Window operation schedule

The standard value for door opening is set at 5% per percentage of operation by Design Builder. This opening time is increased by 20% in order to see the effect of door opening behavior.

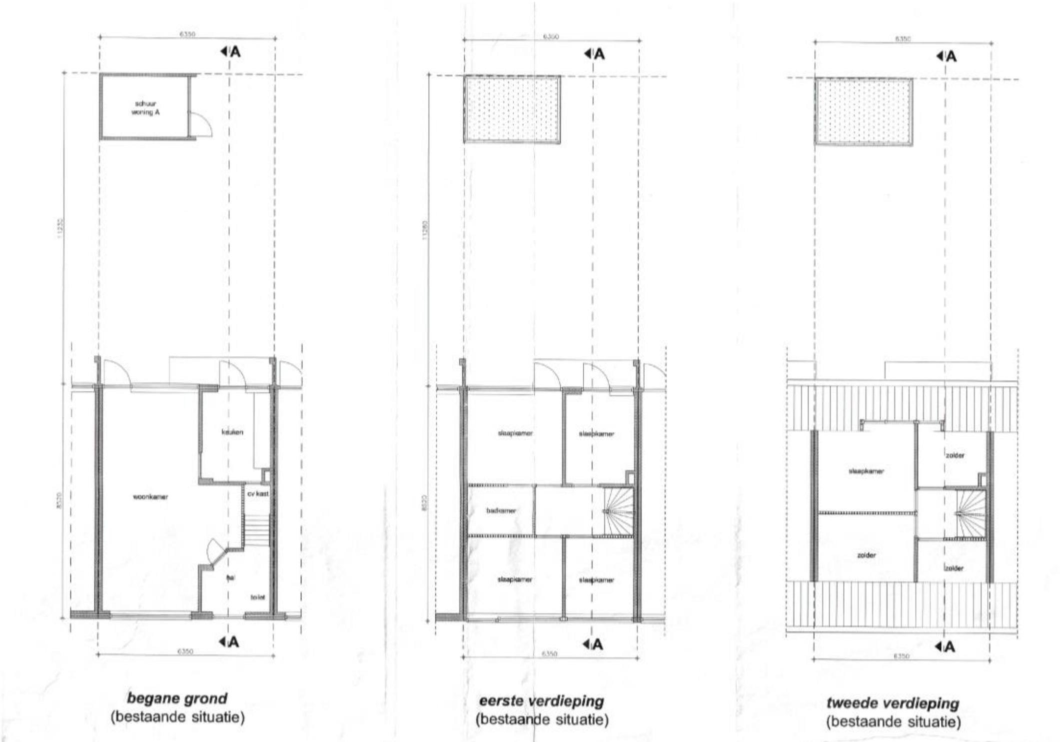
Door opening	Heating demand		Increase
5% door	2.932	kWh	
25% door	2.984	kWh	2%
45% door	3.012	kWh	1%
65% door	3.034	kWh	1%
85% door	3.053	kWh	1%

Table 0-3 Effect of door opening

The impact of door opening behavior has little impact on the total heat demand of a building.

APPENDIX B

The façade is made out of an uninsulated cavity brick wall and large windows, which are characteristic for that era. The facades are not load bearing, the main structure are the walls that separate the buildings. These loadbearing walls are made out of sand-lime bricks, other non-loadbearing walls are made out of aerated concrete. The ground floor has two different constructions, a wooden construction at the living room and a concrete element construction in the hallway and kitchen. The second floor is made out of cast-in-situ concrete. Throughout the passing years, large portions of the windows have been replaced with some form of double glazing, like HR++ glass. But there are still some windows with single glazing. The current owners in this building consume 4000kWh of electricity and 2260m^3 of gas in 2016. Electricity is used for the main appliances, like lighting, washing machine, fridge etc. Gas is used for heating, hot domestic water and cooking. Heating is provided by high temperature radiators in each room. A compact HR combi boiler provides hot domestic water and heating. Hot water in the kitchen is provided by a small electric boiler.



APPENDIX C

Living room

Mid-week	Occupant in room	Weekend	Occupant in room
00:00	0	00:00	0
01:00	0	01:00	0
02:00	0	02:00	0
03:00	0	03:00	0
04:00	0	04:00	0
05:00	0	05:00	0
06:00	0	06:00	0
07:00	3	07:00	0
08:00	3	08:00	3
09:00	0	09:00	3
10:00	0	10:00	3
11:00	0	11:00	3
12:00	0	12:00	3
13:00	0	13:00	3
14:00	0	14:00	3
15:00	0	15:00	3
16:00	0	16:00	3
17:00	2	17:00	3
18:00	2	18:00	3
19:00	3	19:00	3
20:00	3	20:00	3
21:00	3	21:00	3
22:00	3	22:00	3
23:00	0	23:00	0

Bedroom

Mid-week	Occupant in room	Weekend	Occupant in room
00:00	2	00:00	2
01:00	2	01:00	2
02:00	2	02:00	2
03:00	2	03:00	2
04:00	2	04:00	2
05:00	2	05:00	2
06:00	2	06:00	2
07:00	0	07:00	0
08:00	0	08:00	0
09:00	0	09:00	0

10:00	0	10:00	0
11:00	0	11:00	0
12:00	0	12:00	0
13:00	0	13:00	0
14:00	0	14:00	0
15:00	0	15:00	0
16:00	0	16:00	0
17:00	0	17:00	0
18:00	0	18:00	0
19:00	0	19:00	0
20:00	0	20:00	0
21:00	0	21:00	0
22:00	0	22:00	0
23:00	2	23:00	2

APPENDIX D

The same five strategies create different air change rates during the weekend in the living room with open kitchen with an air infiltration rate of 0,8ACH. These strategies are plotted in a graph (Figure 0-1), with corresponding CO_2(Figure 0-2) concentration and PM_{10}(Figure 0-3) concentration.

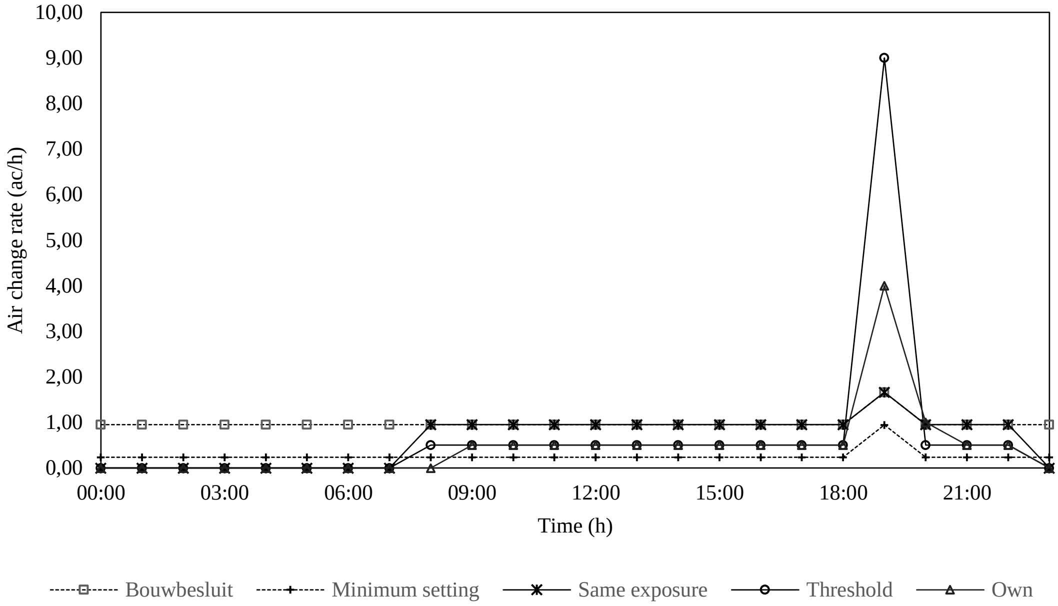


Figure 0-1: Air change rate with an infiltration of 0,8ACH (weekend)

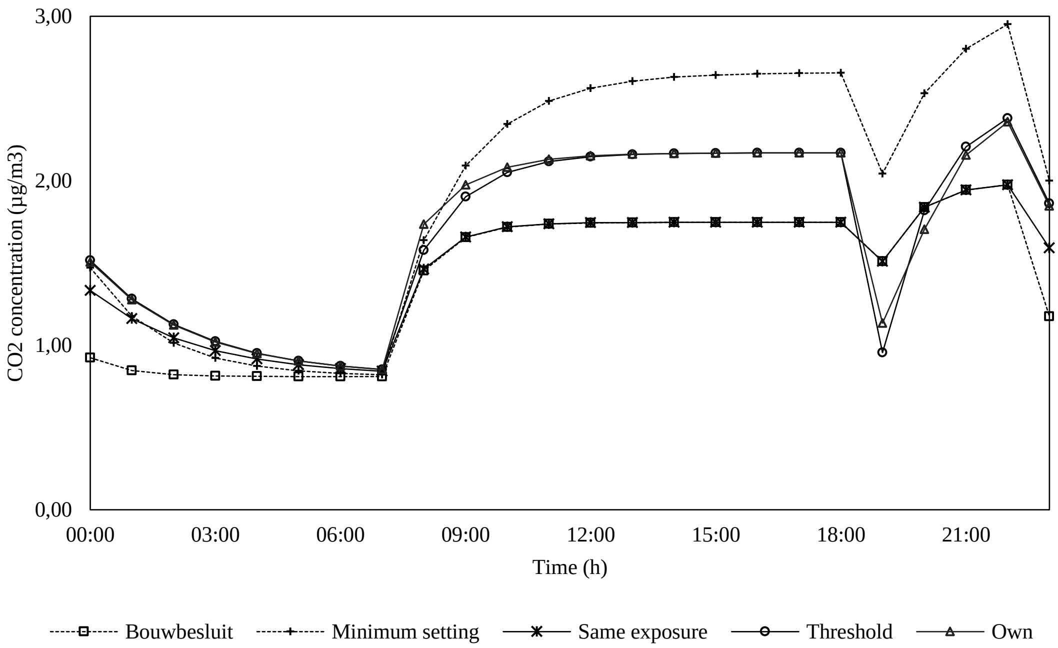


Figure 0-2 CO_2 concentrations with an infiltration of 0,8ACH(weekend)

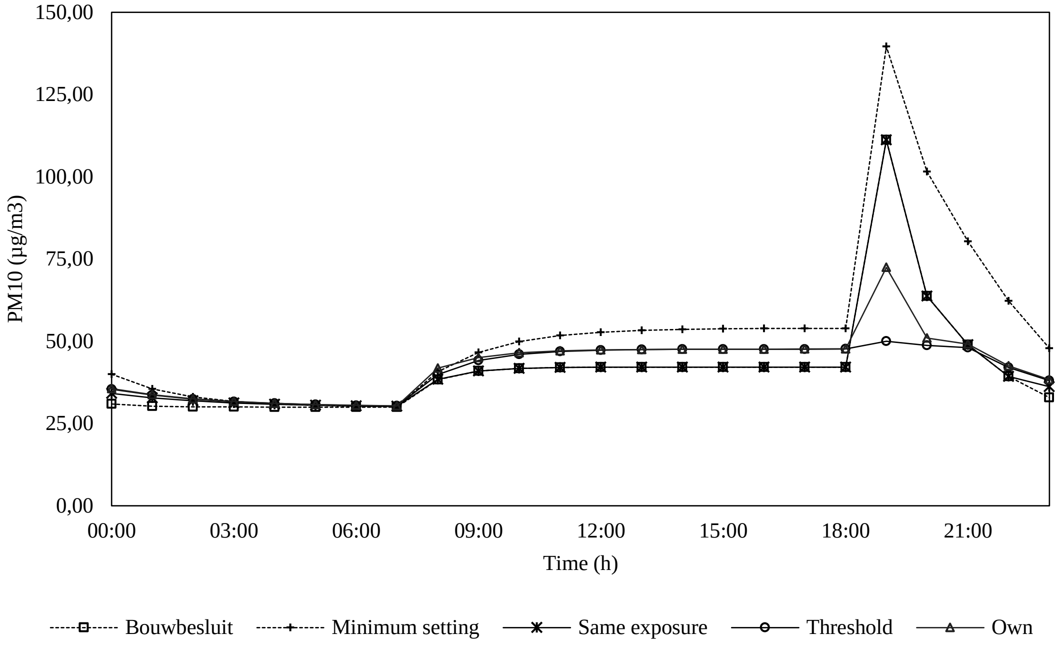


Figure 0-3 PM_{10} concentrations with an infiltration rate of 0,8ACH(weekend)

The same strategies are made for the building with a lower air infiltration rate. The same criteria has been used for each strategy, meaning that the ventilation strategies "Bouwbesluit", 'Minimum setting' and 'Same exposure' are unchanged. They ventilate at a constant rate conform the Dutch building codes or the lowest setting of a manually adjustable ventilation system. The strategies 'Threshold' and 'Own' are changed in order to meet the set thresholds of indoor air pollutants. These strategies are plotted in a graph for a midweek day (Figure 0-4) with corresponding CO_2 concentration (Figure 0-5) and PM_{10} concentration (Figure 0-6).

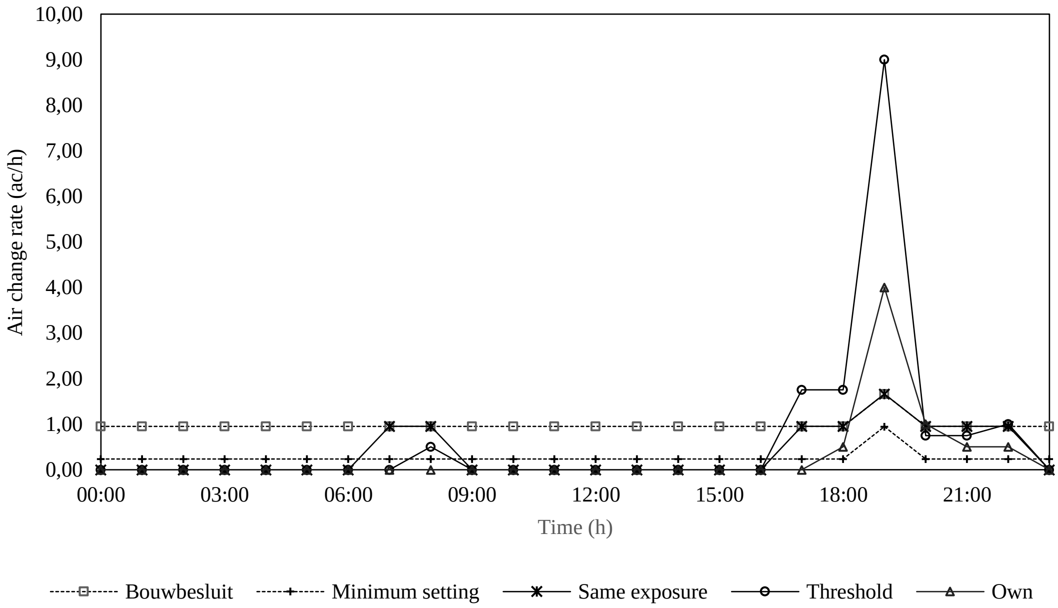


Figure 0-4: Air change rate with an infiltration of 0,4ACH (midweek)

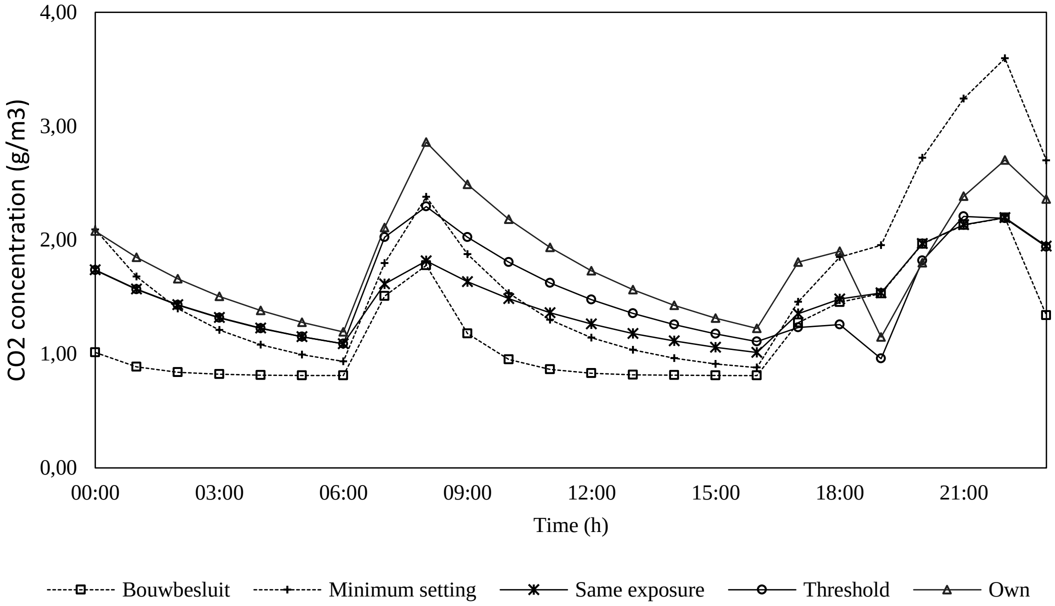


Figure 0-5 CO_2 concentrations with an infiltration rate of 0,4ACH (midweek)

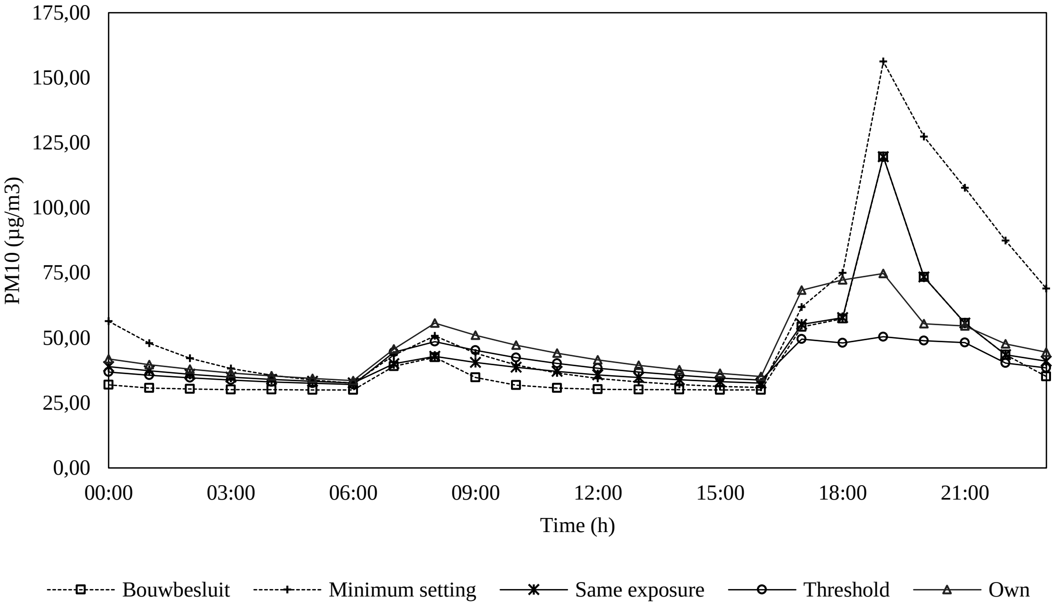


Figure 0-6 PM_{10} concentrations with an infiltration rate of 0,4ACH (midweek)

The same five strategies change their air change rates during the weekend in the living room with open kitchen with an air infiltration rate of 0,4ACH. These strategies are plotted in a graph (Figure 0-7), with corresponding CO_2(Figure 0-8) concentration and PM_{10}(Figure 0-9) concentration.

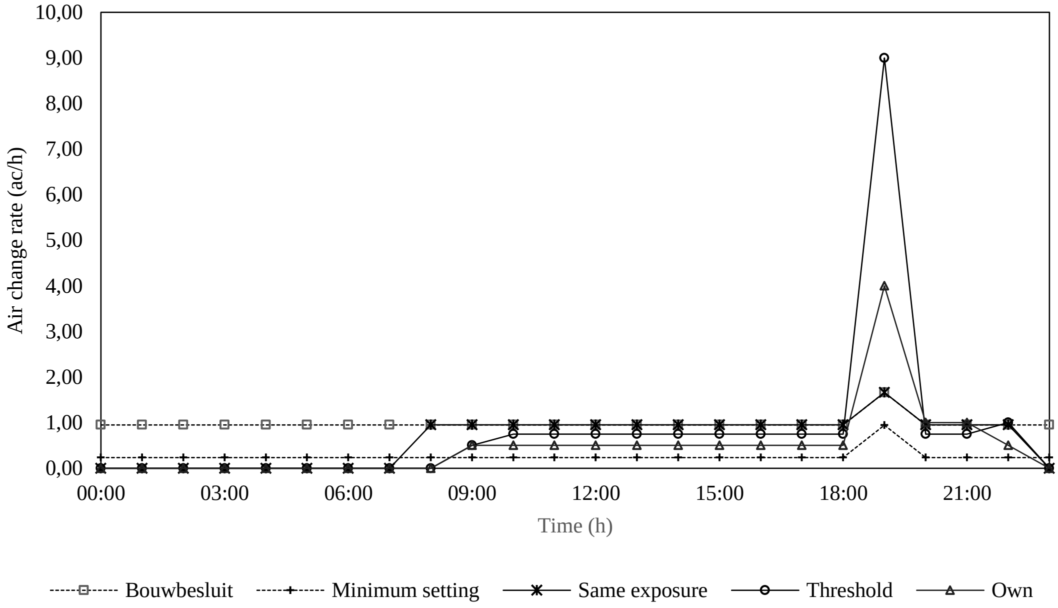


Figure 0-7Air change rate with an infiltration of 0,4 ACH (weekend)

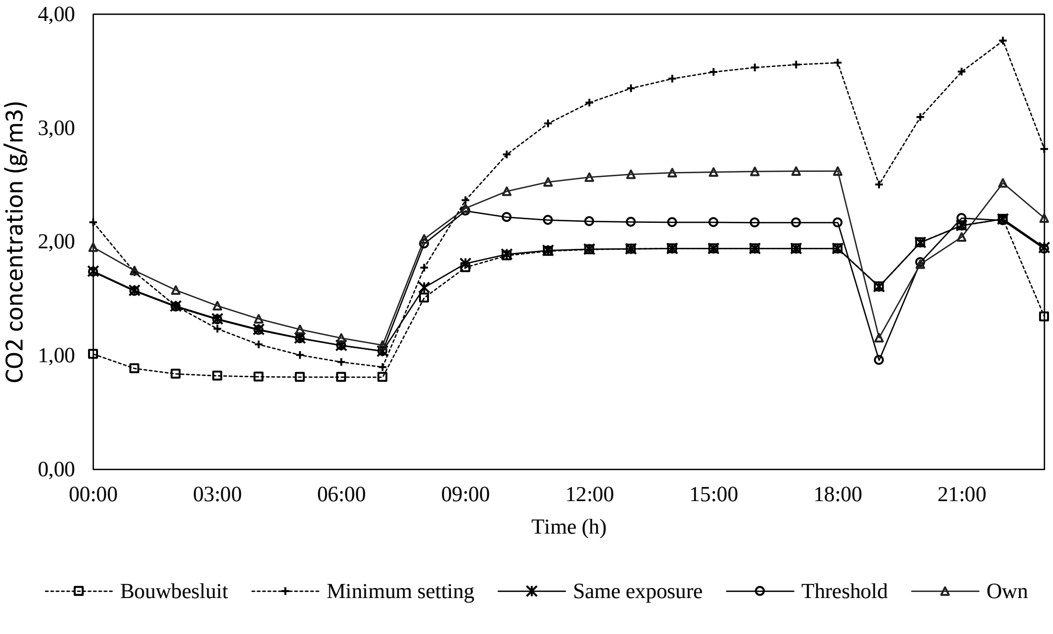


Figure 0-8 CO_2 concentrations with an infiltration of 0,4ACH (weekend)

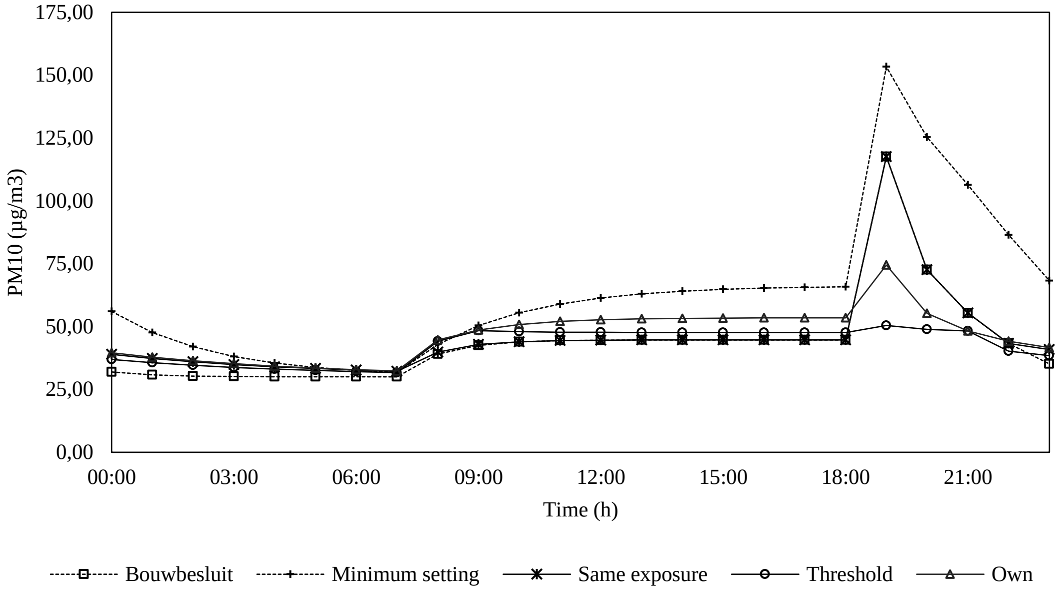


Figure 0-9 PM_{10} concentrations with an infiltration of 0,4ACH (weekend)

The same ventilation strategies are created for a building with an air infiltration rate of 0,4ACH. These lines represent the air change rate due to window opening without air infiltration. Also here, these strategies purely focusses on the removal of CO_2, not particulate matter, because no particulate matter sources are located in the bedroom.

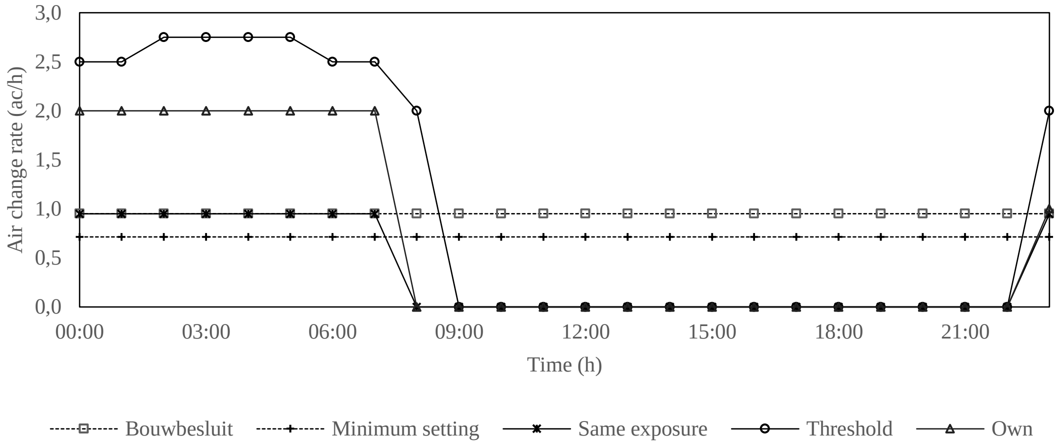


Figure 0-10 Air change rate with an infiltration of 0,4ACH

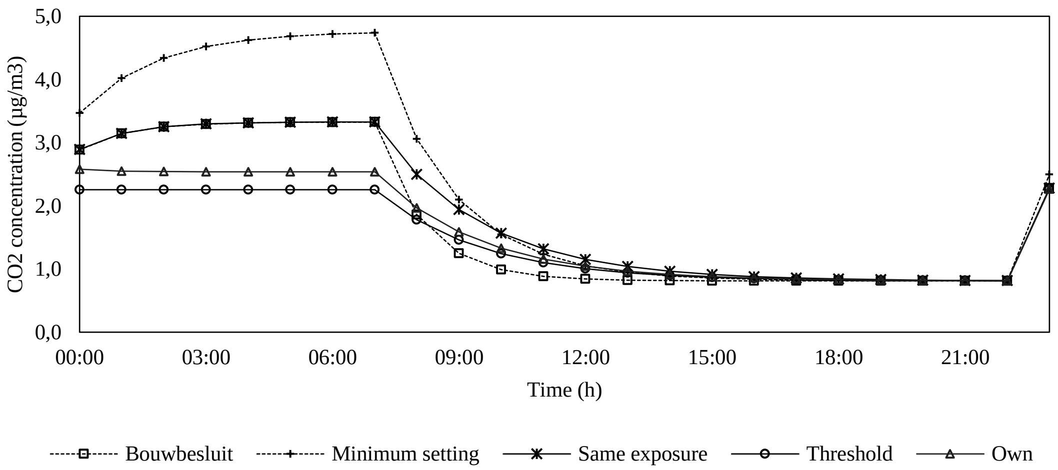


Figure 0-11 CO_2 concentrations with an infilatrion rate of 0,4ACH

Appendix E

Mid-week days

Living room	Activity	CO_2 production		PM production	
00:00	sleep	0	g/m^3	0	$\mu g/m^3$
01:00	sleep	0	g/m^3	0	$\mu g/m^3$
02:00	sleep	0	g/m^3	0	$\mu g/m^3$
03:00	sleep	0	g/m^3	0	$\mu g/m^3$
04:00	sleep	0	g/m^3	0	$\mu g/m^3$
05:00	sleep	0	g/m^3	0	$\mu g/m^3$
06:00	sleep	0	g/m^3	0	$\mu g/m^3$
07:00	waking up	115,668	g/m^3	1500	$\mu g/m^3$
08:00	eating	115,668	g/m^3	1500	$\mu g/m^3$
09:00	work	0	g/m^3	0	$\mu g/m^3$
10:00	work	0	g/m^3	0	$\mu g/m^3$
11:00	work	0	g/m^3	0	$\mu g/m^3$
12:00	work	0	g/m^3	0	$\mu g/m^3$
13:00	work	0	g/m^3	0	$\mu g/m^3$
14:00	work	0	g/m^3	0	$\mu g/m^3$
15:00	work	0	g/m^3	0	$\mu g/m^3$
16:00	work	0	g/m^3	0	$\mu g/m^3$
17:00	normal activity	77,112	g/m^3	4000	$\mu g/m^3$
18:00	normal activity	77,112	g/m^3	3000	$\mu g/m^3$
19:00	cooking	145,668	g/m^3	20000	$\mu g/m^3$
20:00	normal activity	145,668	g/m^3	1500	$\mu g/m^3$
21:00	normal activity	145,668	g/m^3	1500	$\mu g/m^3$
22:00	normal activity	145,668	g/m^3	600	$\mu g/m^3$
23:00	sleep	0	g/m^3	0	$\mu g/m^3$

Weekend

Living room	Activity	CO_2 production		PM production	
00:00	sleep	0	g/m^3	0	$\mu g/m^3$
01:00	sleep	0	g/m^3	0	$\mu g/m^3$
02:00	sleep	0	g/m^3	0	$\mu g/m^3$
03:00	sleep	0	g/m^3	0	$\mu g/m^3$
04:00	sleep	0	g/m^3	0	$\mu g/m^3$
05:00	sleep	0	g/m^3	0	$\mu g/m^3$
06:00	sleep	0	g/m^3	0	$\mu g/m^3$
07:00	waking up	115,668	g/m^3	1500	$\mu g/m^3$
08:00	eating	115,668	g/m^3	1500	$\mu g/m^3$
09:00	work	115,668	g/m^3	1500	$\mu g/m^3$
10:00	work	115,668	g/m^3	1500	$\mu g/m^3$

11:00	work	115,668	g/m^3	1500	µg/m^3
12:00	work	115,668	g/m^3	1500	µg/m^3
13:00	work	115,668	g/m^3	1500	µg/m^3
14:00	work	115,668	g/m^3	1500	µg/m^3
15:00	work	115,668	g/m^3	1500	µg/m^3
16:00	work	115,668	g/m^3	1500	µg/m^3
17:00	normal activity	115,668	g/m^3	4000	µg/m^3
18:00	normal activity	115,668	g/m^3	3000	µg/m^3
19:00	cooking	145,668	g/m^3	20000	µg/m^3
20:00	normal activity	145,668	g/m^3	1500	µg/m^3
21:00	normal activity	145,668	g/m^3	1500	µg/m^3
22:00	normal activity	145,668	g/m^3	600	µg/m^3
23:00	sleep	0	g/m^3	0	µg/m^3

Bedroom	Activity	CO_2 production		PM production	
00:00	sleep	0	g/m^3	0	µg/m^3
01:00	sleep	0	g/m^3	0	µg/m^3
02:00	sleep	0	g/m^3	0	µg/m^3
03:00	sleep	0	g/m^3	0	µg/m^3
04:00	sleep	0	g/m^3	0	µg/m^3
05:00	sleep	0	g/m^3	0	µg/m^3
06:00	sleep	0	g/m^3	0	µg/m^3
07:00	sleep	0	g/m^3	0	µg/m^3
08:00	waking up	115,67	g/m^3	1500	µg/m^3
09:00	eating	115,67	g/m^3	1500	µg/m^3
10:00	normal activity	115,67	g/m^3	1500	µg/m^3
11:00	normal activity	115,67	g/m^3	1500	µg/m^3
12:00	normal activity	115,67	g/m^3	1500	µg/m^3
13:00	normal activity	115,67	g/m^3	1500	µg/m^3
14:00	normal activity	115,67	g/m^3	1500	µg/m^3
15:00	normal activity	115,67	g/m^3	1500	µg/m^3
16:00	normal activity	115,67	g/m^3	1500	µg/m^3
17:00	normal activity	115,67	g/m^3	1500	µg/m^3
18:00	normal activity	115,67	g/m^3	1500	µg/m^3
19:00	cooking	145,67	g/m^3	20000	µg/m^3
20:00	normal activity	145,67	g/m^3	1500	µg/m^3
21:00	normal activity	145,67	g/m^3	1500	µg/m^3
22:00	normal activity	145,67	g/m^3	600	µg/m^3
23:00	sleep	0	g/m^3	0	µg/m^3

Appendix F

Living room

Thermal loss due to ventilation and air infiltration in the living room with an air infiltration rate of 0,8ACH during winter.

Winter	Strategy 1 (Wh)	Strategy 2 (Wh)	Strategy 3 (Wh)	Strategy 4 (Wh)	Strategy 5 (Wh)
00:00	782	462	357	357	357
01:00	782	462	357	357	357
02:00	782	462	357	357	357
03:00	968	572	442	442	442
04:00	968	572	442	442	442
05:00	968	572	442	442	442
06:00	968	572	442	442	442
07:00	1173	693	1173	536	536
08:00	1173	693	1173	871	536
09:00	906	536	414	414	414
10:00	906	536	414	414	414
11:00	906	536	414	414	414
12:00	782	462	357	357	357
13:00	782	462	357	357	357
14:00	782	462	357	357	357
15:00	782	462	357	357	357
16:00	782	462	357	357	357
17:00	1034	611	1034	1063	473
18:00	988	584	988	1016	451
19:00	1389	985	1389	5530	2709
20:00	988	584	988	1016	1016
21:00	1034	611	1034	916	473
22:00	1034	611	1034	768	473
23:00	782	462	357	357	357

Thermal loss due to ventilation and air infiltration in the living room with an air infiltration rate of 0,4ACH during winter.

Winter	Strategy 1 (Wh)	Strategy 2 (Wh)	Strategy 3 (Wh)	Strategy 4 (Wh)	Strategy 5 (Wh)
00:00	603	284	179	179	179
01:00	603	284	179	179	179
02:00	603	284	179	179	179
03:00	747	351	221	221	221
04:00	747	351	221	221	221
05:00	747	351	221	221	221
06:00	747	351	221	221	221
07:00	905	425	905	268	268
08:00	905	425	905	603	268
09:00	699	329	207	207	207
10:00	699	329	207	207	207
11:00	699	329	207	207	207
12:00	603	284	179	179	179
13:00	603	284	179	179	179
14:00	603	284	179	179	179
15:00	603	284	179	179	179
16:00	603	284	179	179	179
17:00	798	375	798	1270	236
18:00	762	358	762	1213	508
19:00	1163	760	1163	5304	2483
20:00	762	358	762	649	790
21:00	798	375	798	679	532
22:00	798	375	798	827	532
23:00	603	284	179	179	179

Thermal loss due to ventilation and air infiltration in the living room with an air infiltration rate of 0,8ACH during autumn and spring.

Autumn/spring	Strategy 1 (Wh)	Strategy 2 (Wh)	Strategy 3 (Wh)	Strategy 4 (Wh)	Strategy 5 (Wh)
00:00	223	132	102	102	102
01:00	223	132	102	102	102
02:00	223	132	102	102	102
03:00	223	132	102	102	102
04:00	223	132	102	102	102
05:00	223	132	102	102	102
06:00	248	147	113	113	113
07:00	526	311	526	240	240
08:00	479	283	479	356	219
09:00	37	22	17	17	17
10:00	37	22	17	17	17
11:00	223	132	102	102	102
12:00	0	0	0	0	0
13:00	0	0	0	0	0
14:00	0	0	0	0	0
15:00	37	22	17	17	17
16:00	37	22	17	17	17
17:00	479	283	479	493	219
18:00	479	283	479	493	219
19:00	804	570	804	3201	1568
20:00	572	338	572	588	588
21:00	572	338	572	506	425
22:00	618	365	618	459	282
23:00	223	132	102	102	102

Thermal loss due to ventilation and air infiltration in the living room with an air infiltration rate of 0,4ACH during autumn and spring.

Autumn/spring	Strategy 1 (Wh)	Strategy 2 (Wh)	Strategy 3 (Wh)	Strategy 4 (Wh)	Strategy 5 (Wh)
00:00	172	81	51	51	51
01:00	172	81	51	51	51
02:00	172	81	51	51	51
03:00	172	81	51	51	51
04:00	172	81	51	51	51
05:00	172	81	51	51	51
06:00	192	90	57	57	57
07:00	406	191	406	120	120
08:00	370	174	370	246	110
09:00	29	14	9	9	9
10:00	29	14	9	9	9
11:00	172	81	51	51	51
12:00	0	0	0	0	0
13:00	0	0	0	0	0
14:00	0	0	0	0	0
15:00	29	14	9	9	9
16:00	29	14	9	9	9
17:00	370	174	370	589	110
18:00	370	174	370	589	246
19:00	673	440	673	3070	1437
20:00	441	207	441	376	457
21:00	441	207	441	376	294
22:00	477	224	477	494	318
23:00	172	81	51	51	51

Bedroom

Thermal loss due to ventilation and air infiltration in the bedroom with an air infiltration rate of 0,8ACH during winter.

Winter	Strategy 1 (Wh)	Strategy 2 (Wh)	Strategy 3 (Wh)	Strategy 4 (Wh)	Strategy 5 (Wh)
00:00	325	281	325	427	427
01:00	325	281	325	519	473
02:00	325	281	325	566	473
03:00	386	334	386	673	562
04:00	386	334	386	673	562
05:00	386	334	386	673	562
06:00	386	334	386	673	562
07:00	319	276	146	146	146
08:00	319	276	146	146	146
09:00	298	258	136	136	136
10:00	298	258	136	136	136
11:00	298	258	136	136	136
12:00	257	223	118	118	118
13:00	257	223	118	118	118
14:00	257	223	118	118	118
15:00	257	223	118	118	118
16:00	257	223	118	118	118
17:00	257	223	118	118	118
18:00	237	205	108	108	108
19:00	237	205	108	108	108
20:00	237	205	108	108	108
21:00	257	223	118	118	118
22:00	257	223	118	118	118
23:00	325	281	325	334	334

Thermal loss due to ventilation and air infiltration in the bedroom with an air infiltration rate of 0,4ACH during winter.

Winter	Strategy 1 (Wh)	Strategy 2 (Wh)	Strategy 3 (Wh)	Strategy 4 (Wh)	Strategy 5 (Wh)
00:00	251	207	251	538	445
01:00	251	207	251	538	445
02:00	251	207	251	584	445
03:00	298	246	298	695	529
04:00	298	246	298	695	529
05:00	298	246	298	640	529
06:00	298	246	298	640	529
07:00	246	203	73	73	437
08:00	246	203	73	73	73
09:00	230	190	68	68	68
10:00	230	190	68	68	68
11:00	230	190	68	68	68
12:00	199	164	59	59	59
13:00	199	164	59	59	59
14:00	199	164	59	59	59
15:00	199	164	59	59	59
16:00	199	164	59	59	59
17:00	199	164	59	59	59
18:00	183	151	54	54	54
19:00	183	151	54	54	54
20:00	183	151	54	54	54
21:00	199	164	59	59	59
22:00	199	164	59	59	59
23:00	251	207	251	445	260

Thermal loss due to ventilation and air infiltration in the bedroom with an air infiltration rate of 0,8ACH during autumn and spring.

Autumn/spring	Strategy 1 (Wh)	Strategy 2 (Wh)	Strategy 3 (Wh)	Strategy 4 (Wh)	Strategy 5 (Wh)
00:00	141	122	141	246	185
01:00	141	122	141	246	205
02:00	141	122	141	246	205
03:00	141	122	141	246	205
04:00	141	122	141	246	205
05:00	141	122	141	246	205
06:00	121	104	120	210	176
07:00	33	28	15	15	15
08:00	12	11	6	6	6
09:00	12	11	6	6	6
10:00	12	11	6	6	6
11:00	12	11	6	6	6
12:00	0	0	0	0	0
13:00	0	0	0	0	0
14:00	0	0	0	0	0
15:00	12	11	6	6	6
16:00	12	11	6	6	6
17:00	12	11	6	6	6
18:00	12	11	6	6	6
19:00	53	46	24	24	24
20:00	53	46	24	24	24
21:00	53	46	24	24	24
22:00	74	64	34	34	34
23:00	141	122	141	145	145

Thermal loss due to ventilation and air infiltration in the bedroom with an air infiltration rate of 0,4ACH during autumn and spring.

Autumn/spring	Strategy 1 (Wh)	Strategy 2 (Wh)	Strategy 3 (Wh)	Strategy 4 (Wh)	Strategy 5 (Wh)
00:00	109	90	109	234	193
01:00	109	90	109	234	193
02:00	109	90	109	254	193
03:00	109	90	109	254	193
04:00	109	90	109	254	193
05:00	109	90	109	234	193
06:00	93	77	93	200	165
07:00	25	21	8	8	45
08:00	10	8	3	3	3
09:00	10	8	3	3	3
10:00	10	8	3	3	3
11:00	10	8	3	3	3
12:00	0	0	0	0	0
13:00	0	0	0	0	0
14:00	0	0	0	0	0
15:00	10	8	3	3	3
16:00	10	8	3	3	3
17:00	10	8	3	3	3
18:00	10	8	3	3	3
19:00	41	34	12	12	12
20:00	41	34	12	12	12
21:00	41	34	12	12	12
22:00	57	47	17	17	17
23:00	109	90	109	193	113

APPENDIX G

APPENDIX H

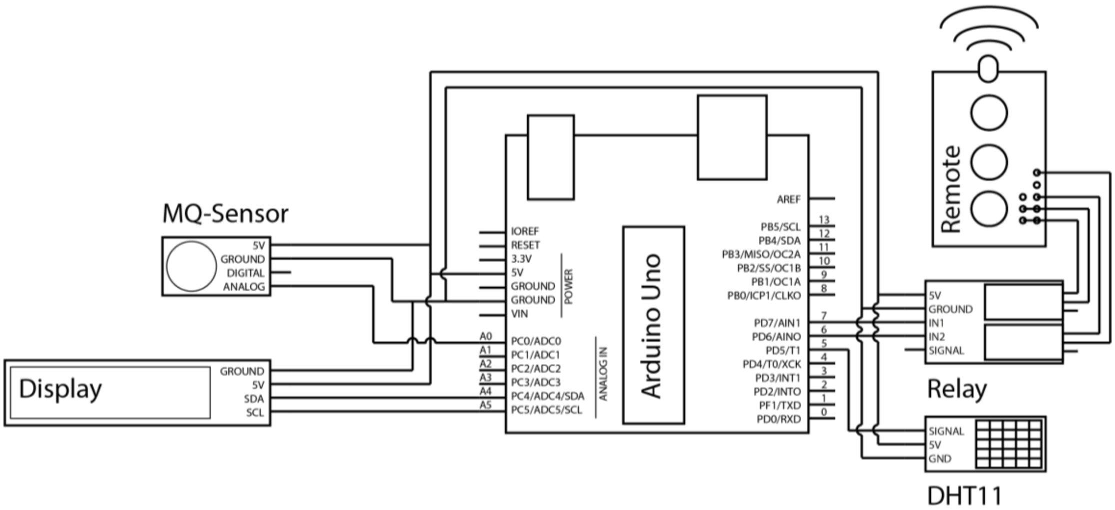
```
char auth[] = "BLYNKAUTH";
char ssid[] = "WiFiID";                              //fill in your own wifi ID
char pass[] = "WiFipassword";                 //fill in the corresponding password

#include <ESP8266mDNS.h>
#include <WiFiUdp.h>
#include <ArduinoOTA.h>
#include <ESP8266WiFi.h>
#include <BlynkSimpleEsp8266.h>
#include <Wire.h>

#define relay1 D0                             //connect relay 1 with D0
#define relay2 D1                             //connect relay 2 with D1
#define BLYNK_PRINT Serial

BlynkTimer timer;

BLYNK_CONNECTED() {
  Blynk.syncAll();
}
void setup(){
Serial.begin(115200);                         //upload script to esp8266 at freq. 115200
Blynk.begin(auth, ssid, pass);
Serial.println("Booting");
WiFi.mode(WIFI_STA);
Blynk.begin(auth, ssid, pass);
while (WiFi.waitForConnectResult() != WL_CONNECTED) {
Blynk.begin(auth, ssid, pass);
Blynk.begin(auth, ssid, pass, "blynk-cloud.com", 80);
Serial.println("Retrying connection...");
}
}
BLYNK_WRITE(V20) {                                   // in Blynk, make virtual button (V20) corresponding with D0
  int value = param.asInt();
  if (value == 1) {
     digitalWrite(relay1, HIGH);
    timer.setTimeout(10000L, []() {                  // button pressed for10 seconds
     digitalWrite(relay1, LOW);
     Blynk.virtualWrite(V20, LOW);


    });

}}
BLYNK_WRITE(V21) {                                   // in Blynk, make virtual button (V21) corresponding with D1
  int value = param.asInt();
  if (value == 1) {
```

```
    digitalWrite(relay2, HIGH);
   timer.setTimeout(10000L, []() {                                        // button pressed for10 seconds
    digitalWrite(relay2, LOW);
    Blynk.virtualWrite(V21, LOW);

});

}}
void loop(){
  Blynk.run();
  ArduinoOTA.handle();
  timer.run();
}
```

APPENDIX I

Built 1

The following scheme shows the mechanism with the MQ 135 sensor.



Used code:

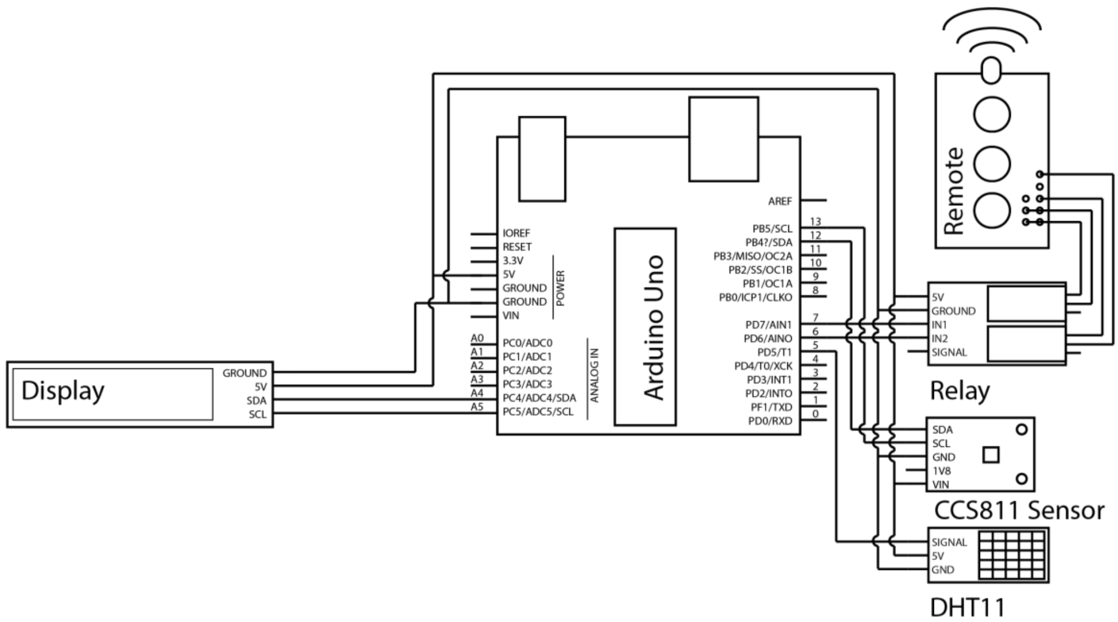
```
#include <LiquidCrystal_I2C.h>
#include <dht.h>
#define sensor    A0
#define DHT11_PIN 7

LiquidCrystal_I2C lcd(0x27, 2, 1, 0, 4, 5, 6, 7, 3, POSITIVE);

int gasLevel = 0;
String quality ="";
String window= "";
String IAQ= "";
String temp="";
String temp1="";

dht DHT;

void setup() {
  Serial.begin(9600);
  pinMode(sensor,INPUT);

  lcd.begin(8, 2);
  lcd.setCursor (0,0);
  lcd.print("                ");
  lcd.setCursor (0,1);
  lcd.print("                ");
  lcd.setCursor (0,0);
  lcd.print("   Air Sensor   ");
  lcd.setCursor (0,1);
  lcd.print("   Warming Up   ");
```

```
  delay(2000);

  lcd.setCursor (0,0);
  lcd.print("                ");
  lcd.setCursor (0,1);
  lcd.print("                ");

}

void loop() {
  gasLevel = analogRead(sensor);

  if(gasLevel<40)
{
    window= "W. closed";
    IAQ= "Good";
}
  else if (gasLevel>40)
{
    window= "W. opened";
    IAQ= "Bad";
}



  lcd.setCursor (0,0);
  lcd.print("                ");
  lcd.setCursor (0,1);
  lcd.print("                ");

  lcd.setCursor (0,1);
  lcd.print(window);

  lcd.setCursor(0,0);
  lcd.print("IAQ ");
  lcd.print(IAQ);

  int chk = DHT.read11(DHT11_PIN);

  if(((DHT.temperature * 0.255) + (18.9 - 3.5)) > 16)
{
    temp= "!";
}
  else if(((DHT.temperature * 0.255) + (18.9 - 3.5)) < 16)
{
    temp= " ";
}
  if(((DHT.temperature * 0.255) + (18.9 + 3.5)) < 16)
{
    temp1= "*";
}
  else if(((DHT.temperature * 0.255) + (18.9 + 3.5)) > 16)
{
    temp1= " ";
}
```

```
  lcd.setCursor(12,0);
  lcd.print(temp);
  lcd.setCursor(13,0);
  lcd.print(temp1);

  delay (300000);

}
```

Built 2

The following scheme shows the mechanism with the CCS811 sensor.



Used code

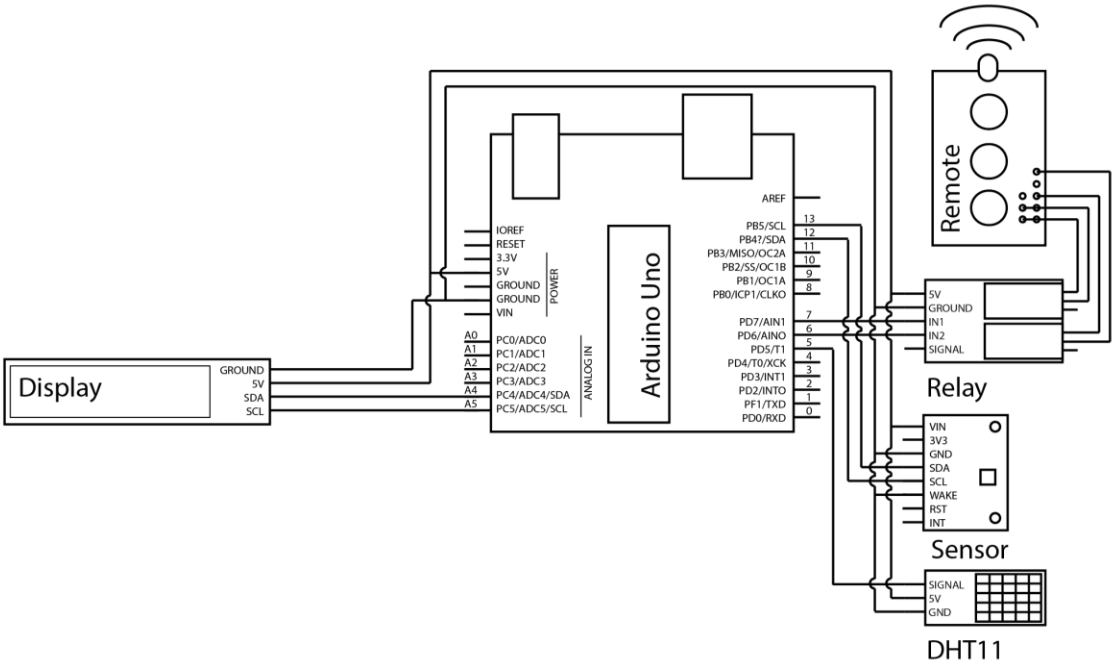
```
#include <Adafruit_CCS811.h>
#include <Wire.h>
Adafruit_CCS811 ccs;

#include "DHT.h"
#define DHTPIN 5
#define DHTTYPE DHT11
DHT dht(DHTPIN, DHTTYPE);

#include <LiquidCrystal_I2C.h>
LiquidCrystal_I2C lcd(0x27, 2, 1, 0, 4, 5, 6, 7, 3, POSITIVE);

const int relay1 =  6;
const int relay2 =  7;

const float h = dht.readHumidity();
const float t = dht.readTemperature();
}
```

```
void setup() {
  Serial.begin(9600);
  Serial.println("CCS811");
dht.begin();
  if (! ccs.begin()){
    Serial.println("Sensor not found :(");
    while (1);
  }
  pinMode(relay1, OUTPUT);
  pinMode(relay2, OUTPUT);

  lcd.begin(16, 2);
int counter = 0;
void loop() {

  float h = dht.readHumidity();
  float t = dht.readTemperature();
  float hic = dht.computeHeatIndex(t, h, false);


  if(ccs.available()){
    float temp = ccs.calculateTemperature();
    if(!ccs.readData()){
      Serial.print("CO2: ");
      Serial.print(ccs.geteCO2());
      Serial.print("ppm, TVOC: ");
      Serial.print(ccs.getTVOC());
      Serial.print("ppb   Temp:");
      Serial.println(temp);
}

if ((ccs.geteCO2< 1000) and (hic < 24.6)) {
     digitalWrite(relay1, HIGH);
      delay (10000);
      digitalWrite(relay1, LOW);
}
else if (ccs.geteCO2> 1200) {
      digitalWrite(relay2, HIGH);
      delay (10000);
    digitalWrite(relay2, LOW);
}
else if (hic > 24.6) {
      digitalWrite(relay2, HIGH);
      delay (10000);
    digitalWrite(relay2, LOW);
}

lcd.clear();
      lcd.setCursor(0, 0);
      lcd.print(String ("CO2    = ")+ String(ccs.geteCO2)+ String("PPM"));
      lcd.setCursor(0, 1);
      lcd.print(String ("Tindex = ")+ String(hic)+ String("C"));

  delay(300000);
```

```
 }
```

Built 3

The following scheme shows the mechanism with the SGP30 sensor.



Used code:

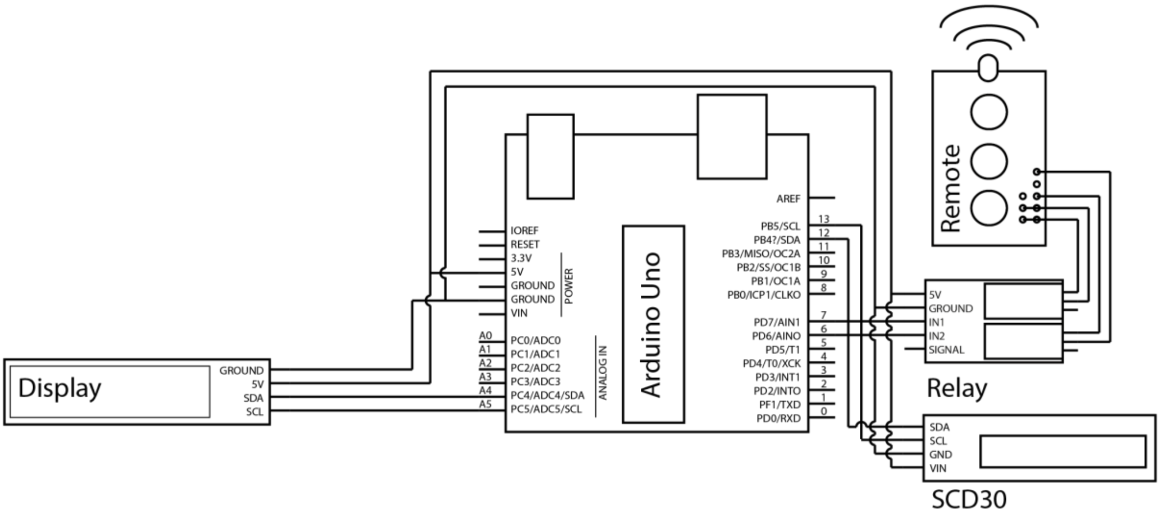
```
#include <Wire.h>
#include "Adafruit_SGP30.h"

#include "DHT.h"
#define DHTPIN 5
#define DHTTYPE DHT11
DHT dht(DHTPIN, DHTTYPE);

#include <LiquidCrystal_I2C.h>
LiquidCrystal_I2C lcd(0x27, 2, 1, 0, 4, 5, 6, 7, 3, POSITIVE);

const int relay1 =  6;
const int relay2 =  7;

Adafruit_SGP30 sgp;

const float h = dht.readHumidity();
const float t = dht.readTemperature();

uint32_t getAbsoluteHumidity(float t, float h) {
const float absoluteHumidity = 216.7f * ((h / 100.0f) * 6.112f * exp((17.62f * t) / (243.12f + t)) / (273.15f + t)); // [g/m^3]
const uint32_t absoluteHumidityScaled = static_cast<uint32_t>(1000.0f * absoluteHumidity); // [mg/m^3]
return absoluteHumidityScaled;
}

void setup() {
  Serial.begin(9600);
```

```
  Serial.println("SGP30 test");
dht.begin();
  if (! sgp.begin()){
    Serial.println("Sensor not found :(");
    while (1);
  }
  pinMode(relay1, OUTPUT);
  pinMode(relay2, OUTPUT);

  lcd.begin(16, 2);

  Serial.print("Found SGP30 serial #");
  Serial.print(sgp.serialnumber[0], HEX);
  Serial.print(sgp.serialnumber[1], HEX);
  Serial.println(sgp.serialnumber[2], HEX);

sgp.setIAQBaseline(0x8E68, 0x8F41);  // Will vary for each sensor!
}

int counter = 0;
void loop() {

  if (! sgp.IAQmeasure()) {
    Serial.println("Measurement failed");
    return;
  }

  float h = dht.readHumidity();
  float t = dht.readTemperature();
  float hic = dht.computeHeatIndex(t, h, false);

 sgp.setHumidity(getAbsoluteHumidity(t, h));

  Serial.print("eCO2 "); Serial.print(sgp.eCO2); Serial.println(" ppm");
  Serial.print(("Humidity: ")); Serial.print(h); Serial.println(" %");
  Serial.print(("Temperature: ")); Serial.print(t); Serial.println(("°C "));
  Serial.print(("Heat index: ")); Serial.print(hic); Serial.println(("°C "));



if ((sgp.eCO2 < 1000) and (hic < 24.6)) {
     digitalWrite(relay1, HIGH);
      delay (10000);
      digitalWrite(relay1, LOW);
}
else if (sgp.eCO2 > 1200) {
      digitalWrite(relay2, HIGH);
      delay (10000);
    digitalWrite(relay2, LOW);
}
else if (hic > 24.6) {
      digitalWrite(relay2, HIGH);
      delay (10000);
    digitalWrite(relay2, LOW);
}
```

```
lcd.clear();
    lcd.setCursor(0, 0);
    lcd.print(String ("CO2    = ")+ String(sgp.eCO2)+ String("PPM"));
    lcd.setCursor(0, 1);
    lcd.print(String ("Tindex = ")+ String(hic)+ String("C"));

  delay(300000);

  }
```

Built 4

The following scheme shows the mechanism with the SCD30 sensor.



Used Code:

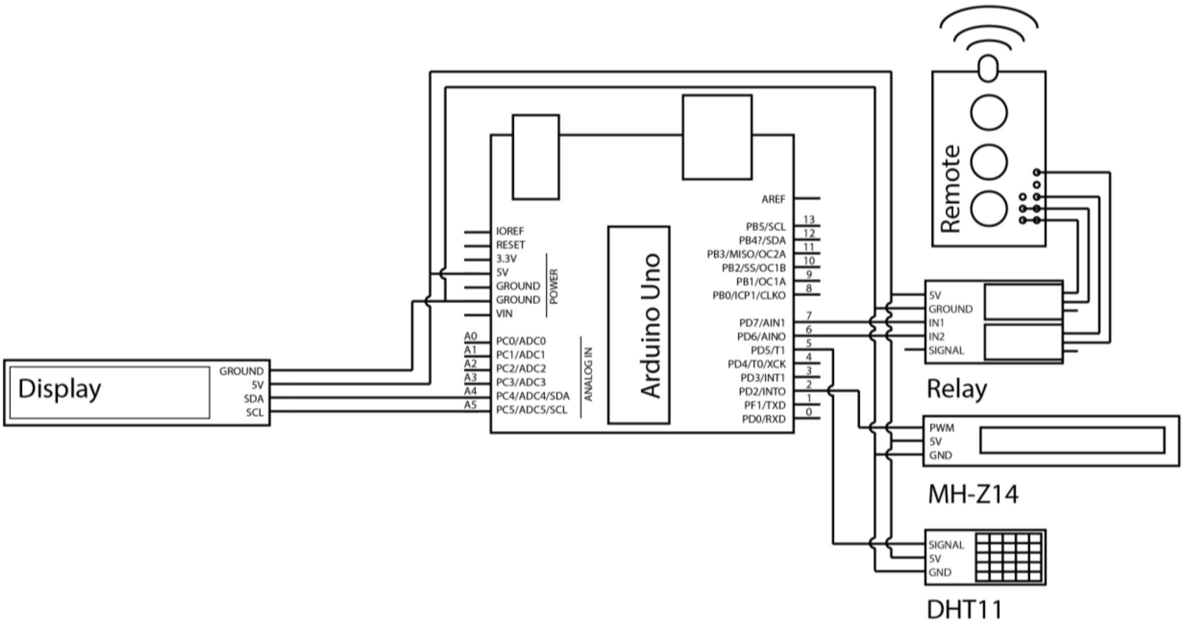
```
#define INTERVAL_MESSAGE1 2000
#define INTERVAL_MESSAGE2 300000

#include <Wire.h>
#include "SparkFun_SCD30_Arduino_Library.h"
#include <LiquidCrystal_I2C.h>

#define temp airSensor.getTemperature() -3

LiquidCrystal_I2C lcd(0x27, 2, 1, 0, 4, 5, 6, 7, 3, POSITIVE);
SCD30 airSensor;

const int relay1 =  6;
const int relay2 =  7;

unsigned long time_1 = 0;
unsigned long time_2 = 0;

long previousMillis = 0;

void print_time(unsigned long time_millis);
```

```
void setup() {
   Serial.begin(9600);

  Wire.begin();
  Serial.begin(9600);
  lcd.begin(16, 2);

  pinMode(relay1, OUTPUT);
  pinMode(relay2, OUTPUT);

  Serial.begin(9600);
  Serial.println("SCD30 Example");

  airSensor.begin();
}

void loop() {
unsigned long currentMillis = millis();

   if(millis() > time_1 + INTERVAL_MESSAGE1){
   time_1 = millis();
      print_time(time_1);
      lcd.clear();
     lcd.setCursor(0, 0);
     lcd.print(String ("CO2 = ")+ String(airSensor.getCO2())+ String("PPM"));
     lcd.setCursor(0, 1);
     lcd.print(String ("T = ")+ String(temp)+ String("C"));

   Serial.print("CO2(ppm):");
   Serial.print(airSensor.getCO2());

   Serial.print(" temp(C):");
   Serial.print(airSensor.getTemperature(), 1);


   Serial.print(" temp(C):");
   Serial.print(temp, 1);

   Serial.print(" humidity(%):");
   Serial.print(airSensor.getHumidity(), 1);

   Serial.println();
}

if(millis() > time_2 + INTERVAL_MESSAGE2){
      time_2 = millis();
      print_time(time_2);

if ((airSensor.getCO2() < 1200) and (airSensor.getTemperature() < ((16 * 0.255) + (18.9 + 8.5)))) {
   digitalWrite(relay1, HIGH);
   Serial.println("relay 1 high");
   delay(10000);
   digitalWrite(relay1, LOW);
   Serial.println("relay 2 low");
```

```
   }

else if ((airSensor.getCO2() < 1200) and (airSensor.getTemperature() > ((16 * 0.255) + (18.9 + 3.5)))) {
   digitalWrite(relay2, HIGH);
   Serial.println("relay 2 high");
   delay(10000);
   digitalWrite(relay2, LOW);
   Serial.println("relay 2 low");
   }

else if (airSensor.getCO2() > 1600){
   digitalWrite(relay2, HIGH);
   Serial.println("relay 2 high");
   delay(10000);
   digitalWrite(relay2, LOW);
   Serial.println("relay 2 low");
    }
    }}

void print_time(unsigned long time_millis){
   Serial.print("Time: ");
   Serial.print(time_millis/1000);
   Serial.print("s - ");
}
```

Built 5

The following scheme shows the mechanism with the MH-Z14 sensor.



Used code:

```
#include <Wire.h>


#include "DHT.h"
#define DHTPIN 5
#define DHTTYPE DHT11
DHT dht(DHTPIN, DHTTYPE);

#include <LiquidCrystal_I2C.h>
LiquidCrystal_I2C lcd(0x27, 2, 1, 0, 4, 5, 6, 7, 3, POSITIVE);

const int relay1 =  6;
const int relay2 =  7;

const float h = dht.readHumidity();
const float t = dht.readTemperature();

const int sensorPin = 2;
long CO2ppm=0;
unsigned long duration;

void setup() {
  Serial.begin(9600);
  dht.begin();

  pinMode(relay1, OUTPUT);
  pinMode(relay2, OUTPUT);
  pinMode(sensorPin, INPUT);

  lcd.begin(16, 2);
}
```

```
int counter = 0;
void loop() {

  duration = pulseIn(sensorPin,HIGH,2000000);
  CO2ppm = 1.36*(5000 * (((duration)/1000)-2)/1000);

  float h = dht.readHumidity();
  float t = dht.readTemperature();
  float hic = dht.computeHeatIndex(t, h, false);



  Serial.print("CO2 "); Serial.print(CO2ppm); Serial.println(" ppm");
  Serial.print(("Humidity: ")); Serial.print(h); Serial.println(" %");
  Serial.print(("Temperature: ")); Serial.print(t); Serial.println(("°C "));
  Serial.print(("Heat index: ")); Serial.print(hic); Serial.println(("°C "));



if ((CO2ppm < 1000) and (hic < 24.6)) {
     digitalWrite(relay1, HIGH);
      delay (10000);
      digitalWrite(relay1, LOW);
}
else if (CO2ppm > 1200) {
      digitalWrite(relay2, HIGH);
      delay (10000);
    digitalWrite(relay2, LOW);
}
else if (hic > 24.6) {
      digitalWrite(relay2, HIGH);
      delay (10000);
    digitalWrite(relay2, LOW);
}

lcd.clear();
      lcd.setCursor(0, 0);
      lcd.print(String ("CO2    = ")+ String(CO2ppm)+ String("PPM"));
      lcd.setCursor(0, 1);
      lcd.print(String ("Tindex = ")+ String(hic)+ String("C"));

  delay(300000);

  }
```

APPENDIX J

Sensor module, price substantiation

The sensor	Product	Cost
Bedroom	MH-Z14a	20 euro/unit
	Calibration and validation	30 euro/unit
	Housing, wiring	20 euro/unit
		70 euro/unit
Living/kitchen	MH-Z14a	20 euro/unit
	Sensirion PM	40 euro/unit
	Calibration and validation	30 euro/unit
	Housing and wiring	20 euro/unit
		110 euro/unit

Controller, price substantiation

Controller	Product	Price
	Arduino (similar product)	10 euro/unit
	Housing and wiring	20 euro/unit
		30 euro/unit

Actuators, price substantiation

Actuator	Product	Price
Retrofit	AXA Remote	75 euro/window
Renovation	Schuco TipTronic	600 euro/window*

Installment, price substantiation

Labor cost	Installation time	Price/hour	Price
Hand operated	4 h*		220 euro/system*
Retrofit	16 h*	55 euro/h	880 euro/system*
Renovation	14 h*	55 euro/h	770 euro/system*

Overhead

Additional cost	Price
Material to hide wires	300 euro/system
Overhead	200 euro/system
General operating expenses	6 %
Profit and risk	3 %

Total price for the building mentor

	Amount of units		Price/unit		Price	
Bedroom sensors	4	x	70	euro	280	euro
Living room sensors	2	x	110	euro	220	euro
Controller	1	x	30	euro	30	euro
Labor cost					220	euro
Additional cost					300	euro
Overhead					200	euro
General operating expenses					6	%
Profit and risk					3	%
Total cost					1365	euro

Total price for the residence assist

	Amount of units		Price/unit		Price	
Bedroom sensors	4	x	70	euro	280	euro
Living room sensors	2	x	110	euro	220	euro
Controller	1	x	30	euro	30	euro
Actuator	7	x	75	euro	525	euro
Labor cost					880	euro
Additional cost					300	euro
Overhead					200	euro
General operating expenses					6	%
Profit and risk					3	%
Total cost					2.658	euro

Total price for the residence assist deluxe

	Amount of units		Price/unit		Price	
Bedroom sensors	4	x	70	euro	280	euro
Living room sensors	2	x	110	euro	220	euro
Controller	1	x	30	euro	30	euro
Actuator	7	x	600	euro	4200	euro
Labor cost					770	euro
Additional cost					300	euro
Overhead					200	euro
General operating expenses					6	%
Profit and risk					3	%
Total cost					6.550	euro