Literature study

Graduation

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1. Introduction

Buildings are responsible for approximately 40% of total energy consumption and 36% of CO2 emissions in the EU. About 35% of the EU's buildings are over 50 years old, where 75% of the building stock is declared 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 a significant energy savings (European Commission, 2018). In 2013, national agreements have been made to stimulate a healthy and sustainable growth. Agreements have been made for buildings, which include that all buildings will need an average energy label A by 2030 (Sociaal-Economische Raad, 2013). However, the calculated energy savings for all the energy labels that are used in the built environment 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 38% in practice. This is due to the difficulty of determining the 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 due to the air tight buildings. These high performing buildings can lead to an indoor accumulation of air pollutants and high humidity, 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 on a regular basis could create a safer indoor environment. The opening of windows could 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).

The occupants, not buildings, are the primary energy consumers because they behave proactively and perform energy related tasks in order to seek comfortable personal conditions (Hong, Yan, D'Oca, & Chen, 2016). The influence of user behavior on the heating demand and air quality becomes more important when buildings become more air tight, have a more complex ventilation system or higher insulation value. It is important to accurately simulate user behavior in order to accurately predict energy consumption, but it is more important to educate or assist an user to behave sustainable.

1.1. Problem statement

User behavioral characteristics can lead to thermal energy loss, due to opened windows and heating of unoccupied rooms, and accumulation of indoor air pollutants, due to outdoor air pollutants and high humidity, and therefore have a high and unpredictable effect on the heating demand and air quality of a high performing residential building in the Netherlands.

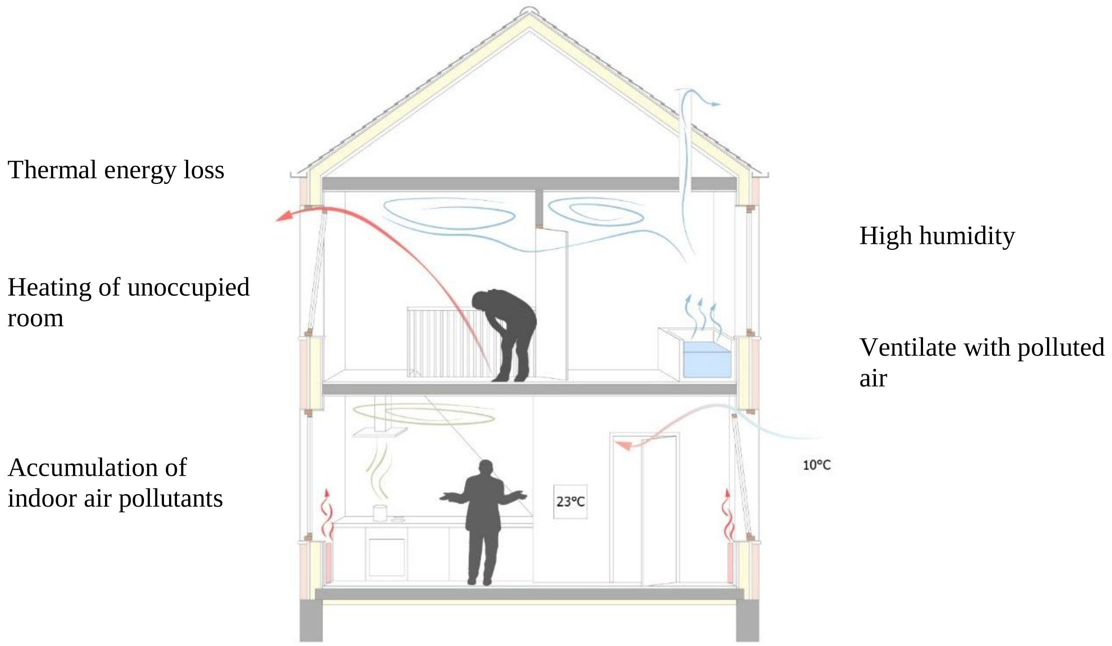


Figure 1 user behavior (own illustration)

1.2. Focus and restrictions

The influence of user behavior on the heating demand and air quality will be restricted to operable openings of the building, windows and doors, and the thermostat setting. These parts of the building can be operated by an 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 pollutants levels in the air to determine a *safe* indoor climate. The level of *comfort* will be depended on the indoor temperature and interaction, which is different for every occupant. An *effective action* is an action that influences the behavior of the occupant sustainable and reliable, which creates the best outcome on 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. For dwellings, this is almost always done with operable openings, 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.

The creation of a simulation of algorithm for user behavior will not be created. This research focusses on the creation of a product that assist users, not predict user behavior. The focus of this research is to find a product 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.

1.3. Aim and objective

The general aim of this research is to investigate the knowledge base on ways of saving energy and increase indoor air quality by addressing user behavior characteristic. The objective is to identify the impact of user behavior on the indoor air quality and energy demand .

1.4. Research questions

The following questions will be answered in the literature research

Q1: What is an effective way to design a product that will assist an user in sustainable behavior?

Q2: What is current knowledge on heating loss due to window opening behavior and indoor comfort or safety?

- *Why do people open their operable façade elements?*
- *How much influences has user behavior on heating demand due to window and door opening?*
- *What is a comfortable indoor temperature and how can this comfort be created in an efficient way?*
- *What can create a safe or uncomfortable IAQ for the occupant and building?*
- *What ventilation type improves the indoor air quality of a dwelling and what are the thermal potentials?*

1.5. Approach and methodology

The literate research project is part of a my thesis that is based on a research through design methodology, whereby the design will play a central role in order to gain new knowledge. An interactive top-down approach is required in order to establish the wishes and demands of the end user and the communication process required to facilitate the design, production and maintenance. This interactive top-down approach 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 material recycling/disposal

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. This paper only consist out of **step 1**, which is considered as the knowledge phase. This literature study will be initiated through a study on design strategies and precedent work. Afterwards, the current knowledge on heating loss due to window opening behavior and indoor comfort or safety will be investigated. Different parameters will be determined in order to create indoor comfort and safety. The end of the literature study will consist out of an hypothesis, which is a result of this literature study.

1.6. Relevance

The graduation project seeks to address the unpredictable effect on the heating demand and air quality, due to user behavior characteristics in the built environment. This user behavior is hard to simulate, therefore energy usage of buildings become impossible to predict. This factor has been a known problem for years, but becomes a bigger problem due to higher performing buildings and difficult to operate systems. This graduation project allows exploration of new systems and viewpoints on user assisting products.

2. 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 opening can cause an increase in heat loss from the dwelling, which will depend upon the duration and extent of opening. The chapter will investigate precedent work, the energy impact of user behavior, how indoor comfort can be created and various strategies that could be applied while designing the product.

2.1. Design strategy

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. A performance assessment using only threshold levels for single parameters is difficult, because comfort is different for every user and hard to measure. Observation of behavior, questionnaires or surveys or even end-user involvement during design phases are used to identify the needs and level of comfort of an end-user. But most people cannot identify their own mental or physical needs or behave differently to the same input. Emotional and cognitive factors influence behavior, per individual, and can change over time. The relationship between the indoor environment and human behavior is complicated. Nevertheless, this indoor environment must meet the diverse needs of different users whose interests frequently conflict and change.

Managing the indoor quality needs to communicate between all stakeholders. It is a dynamic issue that has to take changes in time and stakeholder into account. During a bottom-up approach, 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, an interactive 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 an 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.

A system consist of interrelated components, where the design must be viewed as a whole. Breaking down the system into components, study them individual and their interrelationships. Afterwards, put the system back together and verify its results. This method is referred as the system engineering approach. The steps in the creation of a building product according to the system engineering approach are;

Step 1: system requirements
Step 2: conceptual design
Step 3: preliminary system design
Step 4: detail system design and development
Step 5: production and construction phase
Step 6: operational use and system support phase
Step 7: system retirement and material recycling/disposal
(Bluyssen, 2009)

Before the first step, precedent work will be investigated in order to get an overview on what is already done.

2.1.2. Precedent

Multiple 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 CO2 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.

They started by collecting data 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 testing in models, evaluating trigger parameters for window use. An automatic system was developed with sensors, a data logger, an adaptive control algorithm and window actuators (Figure 2). This system was installed and monitored in multiple classrooms for 10 days.

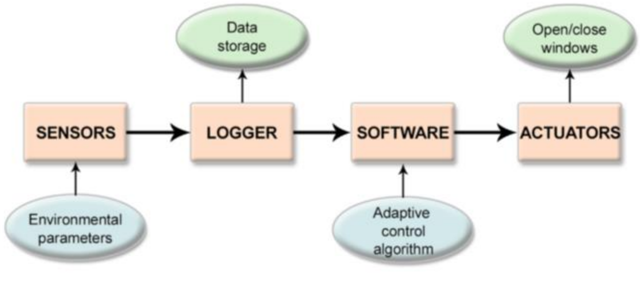


Figure 2 automated window diagram (Francesca, Naspi, Ulpiani, & Di Perna, 2017)

The automatic system guaranteed a more comfortable environment, with CO2 concentration below 1500 ppm, and increase in thermal satisfaction. But the automatic system efficacy in CO2 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.

Theofanis Psomas 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 3). Multiple strategies, the rate of opening of the windows and the determination of the desired temperature, have been compared and showed potential.

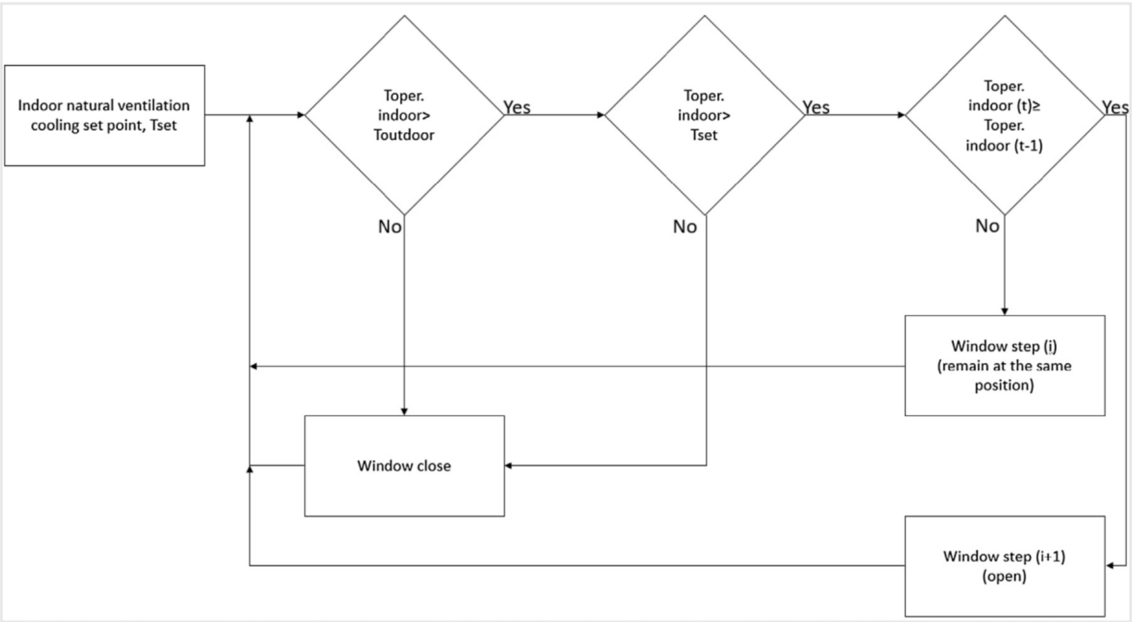


Figure 3 automated window system algorithm (Psomasa, Fiorentini, Kokogiannakis, & Heiselberg, 2017)

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

2.1.3. 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. Nevertheless, the focus has been directed at matters beyond the user's control, for instance improvement of energy efficiency. To further reduce the impact of the "in-use" phase matters within the user's control should be addressed. 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 in inducing sustainable behavior, four are focused on behavior adaptation and one is focused on product adaptation. 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 4 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 5 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.

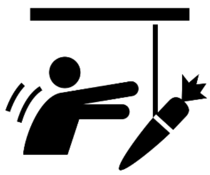


Figure 6 steer (Prado, n.d.)

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 of the undesired behavior. The effectiveness and acceptability of this design strategy are good.

Figure 7 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).

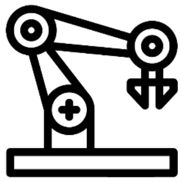


Figure 8 match (Corredor, n.d.)

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 will be used as a case study to investigate the effectiveness of an user assisting product for a residential building. This comparable product is a the smart thermostat.

A smart thermostat provides knowledge about energy usage, the indoor temperatures and much more, while heating and cooling the building. These current energy related information's can be monitored live 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 monitors parameters and it has internet connectivity.

Programmable schedule - Steer and match
Research has been done on the energy saving potential and usability of two-way communicating 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 used 12% more energy on thermal comfort. This was contradicting to the what the participants

expected and wanted from this product. Around 5% of the participants had to drop out due to compatibility issues between the different machines and misunderstood functionalities (Lopes & Agnew, 2010).

Sensor and monitors - Enlighten and spur

Smart thermostat provides advanced and detailed energy monitoring, 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 successful. 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 output of an user, but should performance desired actions by itself. Therefore, product adaptation should be applied as an user assisting strategy for the proposed design.

2.2. 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;

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

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 can provide the ventilation necessary to meet current codes.

Elham Delzendeh, Song Wu, Angela Lee and Ying Zhou 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 (

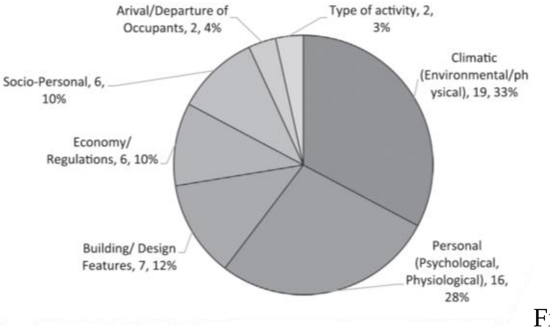


Figure 9).

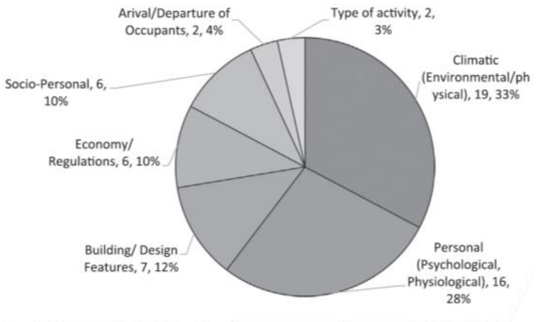


Figure 9 Influential parameters on occupants energy behavior (Delzendeh, Wu, Lee, & Zhou, 2017)

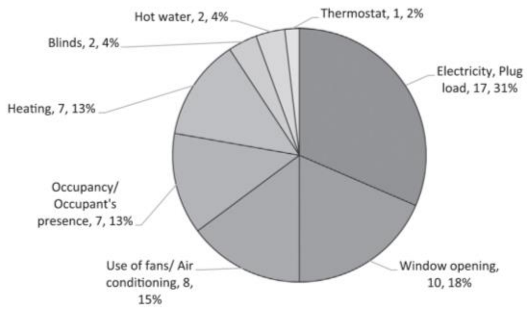


Figure 10 Different types of occupants interactions (Delzendeh, Wu, Lee, & Zhou, 2017)

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 10). Window opening is the second most performed activity, with 10 to 18%. Activities, that influence energy demand, related to heating a building is performed 7 to 13% of the time that an activity is performed. At the bottom is thermostat operation, which happens around 1 to 2% of the time (Delzendeh, Wu, Lee, & Zhou, 2017).

Liddament reviewed several studies on occupant behavior and ventilation, and found 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 many circumstances when opening a window is not practical such as noise, rain or high winds, outdoor pollutants, cold drafts, privacy, security and safety issues, energy loss, or the window may be difficult to operate. These observations suggest that window opening or closing 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 model 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 variation in ventilation losses between deterministic and probabilistic scenarios. This deviation varies per climate, but in every type of climate, the influence of user behavior has a negative effect on the energy demand compared to the controlled system. 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 winter decreased by 5%. In subtropical continental climates, this energy demand during winter is increased by 61% and during winter 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 an insight into the relative effect that window opening could have. 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 11). It has insulated cavity walls and loft insulation with an unknown Rc-value, but a poor thermal mass due to its timber construction. The infiltration of the building is measured at 15$m^3/h/m^2$, which is higher than the 10m^3/hm^2 limit required of new dwelling in the current building regulations in the United Kingdom. The total Heat Loss Coefficient (HLC) of this residential building is in theory 180W/K and in practice around 170W/K.

Figure 11 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 12, which shows the additional heat loss that a variety of window behaviors 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 12).

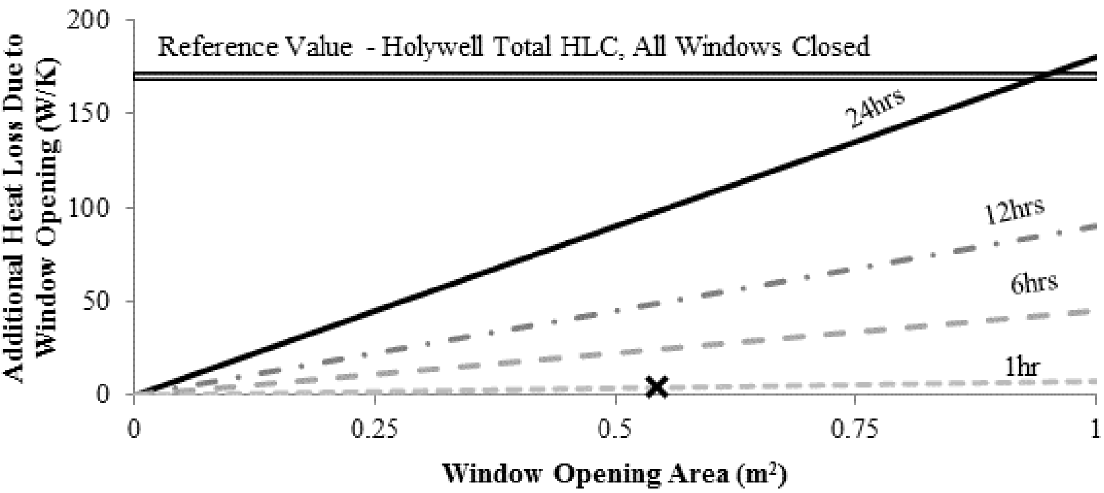


Figure 12 heat loss due to window opening (Jack, Loveday, Allinson, & Lomas, 2015)

The different window opening scenario show the potentials and the effect of window opening behavior. The 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 the a building with a high 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 environmental 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

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

There are two main methods to asses and predict thermal comfort; the predicted mean vote method, which calculated local thermal comfort, and the adaptive control algorithm.

2.3.1.1. Predicted mean vote

The parameters that influences or determines the thermal comfort of the indoor environment for an occupant can be described according to:

- heat
- air velocity and turbulence
- occupant
- relative humidity

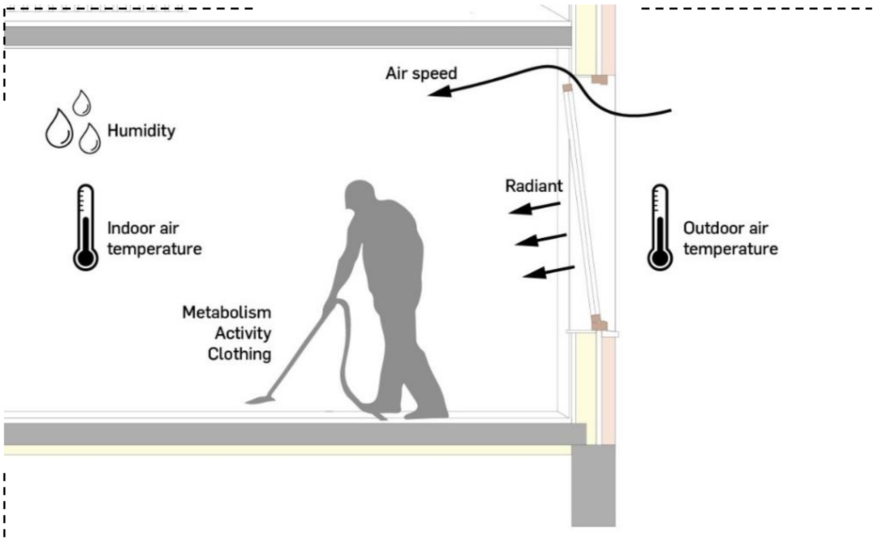


Figure 13 thermal comfort parameters (own illustration)

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 and heat loss must be low. 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 can be calculated with the following formula:

$$PMV = \left[0{,}303 \cdot \exp(-0{,}036 \cdot M) + 0{,}028\right] \cdot \left\{ \begin{aligned} &(M-W) - 3{,}05 \cdot 10^{-3} \cdot \left[5\,733 - 6{,}99 \cdot (M-W) - p_a\right] - 0{,}42 \cdot \left[(M-W) - 58{,}15\right] \\ &-1{,}7 \cdot 10^{-5} \cdot M \cdot (5\,867 - p_a) - 0{,}0014 \cdot M \cdot (34 - t_a) \\ &-3{,}96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4\right] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \end{aligned} \right\}$$

$$t_{cl} = 35{,}7 - 0{,}028 \cdot (M-W) - I_{cl} \cdot \left\{3{,}96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4\right] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\right\}$$

$$h_c = \begin{cases} 2{,}38 \cdot \left|t_{cl} - t_a\right|^{0{,}25} & \text{for} \quad 2{,}38 \cdot \left|t_{cl} - t_a\right|^{0{,}25} > 12{,}1 \cdot \sqrt{v_{ar}} \\ 12{,}1 \cdot \sqrt{v_{ar}} & \text{for} \quad 2{,}38 \cdot \left|t_{cl} - t_a\right|^{0{,}25} < 12{,}1 \cdot \sqrt{v_{ar}} \end{cases}$$

$$f_{cl} = \begin{cases} 1{,}00 + 1{,}290\, I_{cl} & \text{for } I_{cl} \leqslant 0{,}078 \text{ m}^2 \cdot \text{K/W} \\ 1{,}05 + 0{,}645\, I_{cl} & \text{for } I_{cl} > 0{,}078 \text{ m}^2 \cdot \text{K/W} \end{cases}$$

M	=	metabolic rate, in watts per square meter (W/m2)
W	=	effective mechanical power, in watts per square meter (W/m2)
Icl	=	clothing insulation, in square meters kelvin per watt (m2K/W)
fcl	=	clothing surface area factor
ta	=	air temperature, in degrees Celsius (°C)
tr	=	mean radiant temperature, in degrees Celsius (°C)
var	=	relative air velocity, in meters per second (m/s)
pa	=	water vapor partial pressure, in pascals (Pa)
hc	=	convective heat transfer coefficient [W/(m2K)]
tcl	=	clothing surface temperature, in degrees Celsius (°C)

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.

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

The PPD predicts the number of thermally dissatisfied individuals in a large group, the rest of the group feels thermally neutral. The PPD can be calculated using the following equation:

$$\mathrm{PPD} = 100 - 95 \exp(-0{,}033\ 53\ \mathrm{PMV}^4 - 0{,}217\ 9\ \mathrm{PMV}^2)$$

In determining the acceptable range of operative temperature according to this International Standard, clothing insulation value should corresponds to the local clothing habits and climate. This is due to adaptation of the user to the outdoor climate. Extended acceptable environments may be applied for occupant controlled and naturally conditioned spaces. Field experiments have proven that occupants of naturally ventilated and occupant controlled buildings accept a higher bandwidth of temperature than those predicted by the PMV (Normcommissie 302 005 "Ergonomie van de fysische werkomgeving", 2005).

2.3.1.2. Adaptive control algorithm

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

$$Tc = 0{,}31 \times Tout + 17{,}8$$

Tc = comfort temperature (°C)

Tout = outside temperature (°C)

The equation were 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 14). 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

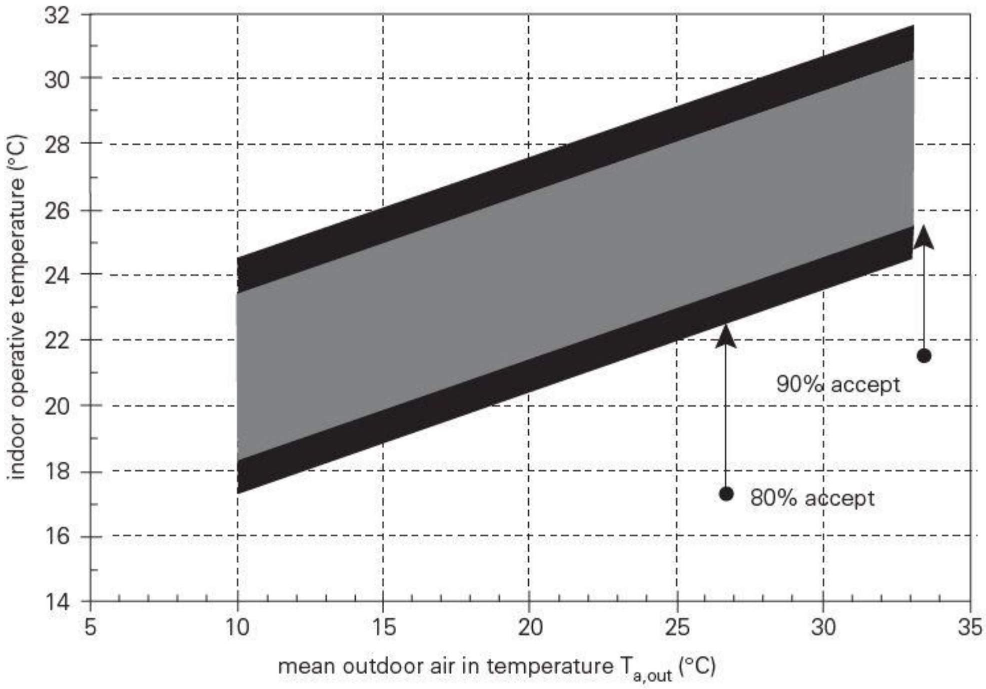


Figure 14. Proposed adaptive comfort standard (de Dear & Brager, 2002).

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). User activity and metabolism should be taken into consideration in determining the ideal indoor temperature. That's is why an user should be in control of the indoor environment, in order to seek comfort by itself. This can be done by calculating the indoor temperature according to the adaptive control algorithm and letting the occupants increase or decrease the temperature by two or three degrees. These systems are normally used in the utility sector, not so much in the residential sector.

This adaptive approach doesn't take air velocity and relative humidity into account. Air velocity or wind speed is defined as the change of position, which is expressed in meters per second (m/s). 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 (Normcommissie 302 005 "Ergonomie van de fysische werkomgeving", 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 1).

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 1 Local temperature of whole body and head (Angela & Bjarne, 2013)

Air velocity can offset high temperature, creating comfort in during summer, but individual differences exist between people with regard to their preferred air velocity. Therefore, the elevated air velocity must be under the control of the affected occupants. ISO 7730 recommend adjustable steps no greater than 0,15 m/s in order to find comfort for the occupant. Also according to Fountain and Edward, it is not clear today what air velocity levels are appropriate for the range of temperatures found indoors. Draft risks and desirable occupant cooling are two important aspects of moving air. But every situation is different and should be addressed as a separate issue, therefore a single recommendation cannot be produced from existing research, according to Fountain and Edward. Air velocity limits for indoor comfort have been steadily dropped. Lower air velocities are more favorable nowadays, where around 0,12m/s is a comfortable air velocity rate below 20 degrees and this can rise for higher temperatures. The duration of a comfortable exposure to windspeeds differs per person. Therefore, according to Fountain and Edward, no set limit can be determined for a comfortable air velocity in an indoor climate (Fountain & Edward, 1993).

Heat discomfort also depends on the humidity, which can vary due to activity of the user, health of the user or 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 of air that is measured by most thermometers. This temperature is measured, while shielded from radiation and moisture. The wet-bulb temperature is the temperature read by a thermometer that is covered in a water-soaked cloth over which air is passed. The Relative humidity is defined as the ratio of the mole fraction of water vapor in a given air sample to the mole fraction in an air sample saturated at the same temperature and pressure. 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 15).

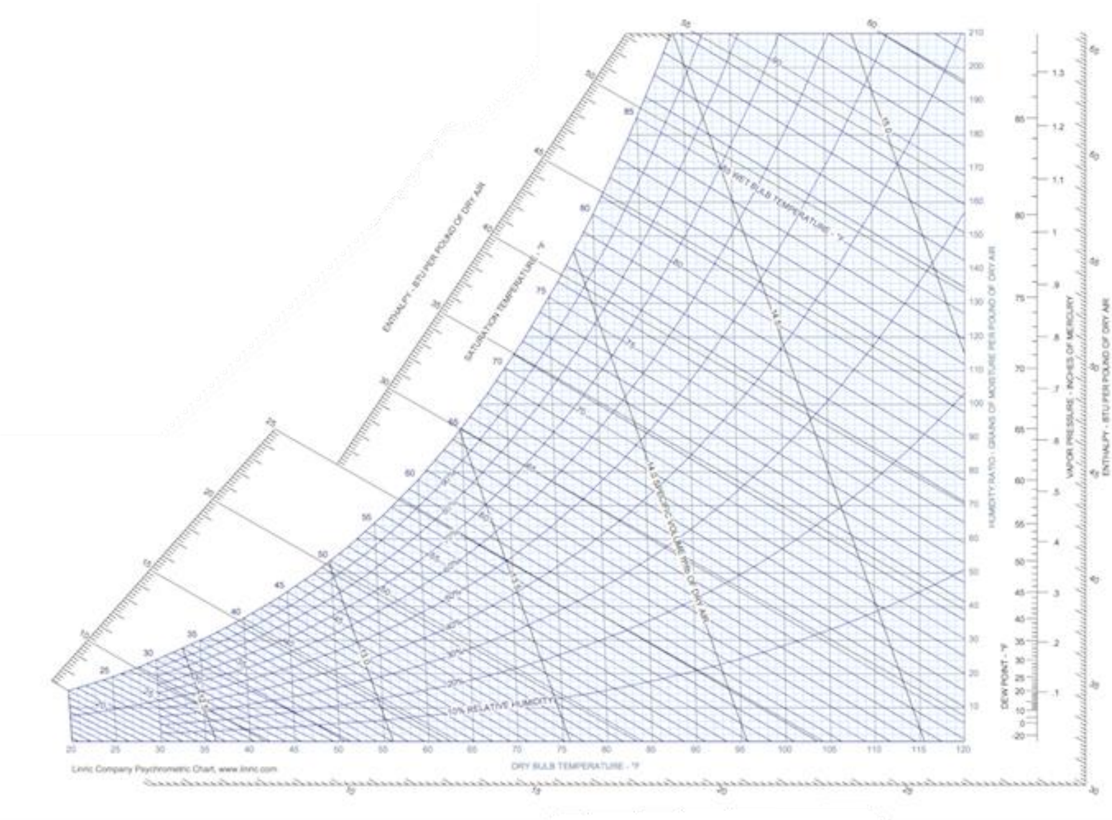


Figure 15 psychrometric chart

2.3.2. Indoor air comfort

Hazardous substances emitted from indoor and outdoor sources, such as cooking or heating, lead to a broad discomfort, a range of health problems and can even be fatal. 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 has 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 NO_2, $PM_{2.5}$, PM_{10} and O_3, 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).

Blauw Research measured the concentration of CO2, PM2.5, relative humidity and air temperature of 749 households over a period of 9 months. The conducted research showed an unacceptable air quality for one in every seven households, due to particulate matter. Measurements showed that the CO2 concentration rises at the beginning of the night, when most people are at home. This CO2 concentration 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).

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 exposer can be defined as the concentration of the pollutants in $\mu g/m^3$. 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

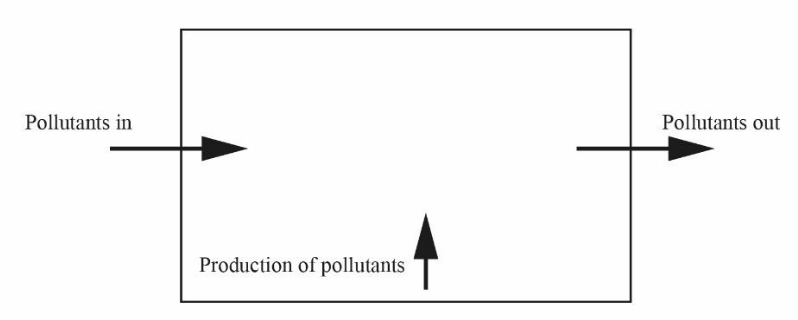


Figure 16 pollutants diagram (own illustration)

The pollutants concentration of a room can be calculated the given formula;

$$c = \left(\frac{p}{n\,V}\right)\left[1 - \left(\frac{1}{e^{n\,t}}\right)\right] + (c_0 - c_i)\left(\frac{1}{e^{n\,t}}\right) + c_i$$

c	=	concentration in the room (m^3/m^3)
p	=	production in the room (m^3/h)
V	=	volume of the room (m^3)
n	=	number of air shifts per hour (1/h)
t	=	time (hour, h)
c_i	=	concentration in the inlet ventilation air (m^3/m^3)
c_0	=	concentration in the room at start, t = 0 (m^3/m^3)

2.3.2.1. 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. Pollution source in the ventilation air can originate from outdoor sources and ventilation system components. Outdoor sources include traffic and industry related activities. Pollutants from ventilation systems components include 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.

Air quality for comfort can be determined with odour detection level of common, less harmful, fumes and gasses. Table 2 shows the lowest odour detection levels of various fumes and gasses that are emitted by a human. This doesn’t mean that it causes discomfort, but it only means that the odour can be detected.

	Source	Odour detection level
Acetaldehyde	Human breath, building materials	0,2 µg/m3
Benzaldehyde	Perfumes and paints	0,8 µg/m3
Butyric acid	Anaerobic fermentation of fat or dairy	1 µg/m3
Coumarin	Food additive	0,007 µg/m3
Dimethylsulfide	Food flavoring	2,5 µg/m3
Dimethyldisulfide	Food flavoring	0,1 µg/m3
N-decanal	Citrus	0,25 µg/m3
Ethanethiol	Additive to gas	0,1 µg/m3
Hydrogen sulphide	Breakdown of organic matter	0,7 µg/m3
Methylmercaptan	Breakdown of organic matter	0,04 µg/m3
Phenylacetic acid	Fruits	0,003 µg/m3

Table 2. Odor detection level

Some gasses are hazardous and have a lower odor detection level than their safe doses. show various gasses that are hazardous and can be found in a dwelling. The save doses according to the World Health Organization set thresholds.

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 of dust particles that originate from bacteria, viruses, moulds, insects, bird, pollen and animals.

Fume	Source	Odor detection level		Save doses		
Benzene	Fuel	300	mg/m3	0,17	µg/m3	
Carbon monoxide	Incomplete combustion	No detection		100	mg/m3	1/4h
				35	mg/m3	1h
				10	mg/m3	8h
				7	mg/m3	24h
Carbon dioxide	Burning fossil fuel	70200	mg/m3	2250	mg/m3	
Formaldehyde	Building materials	1,47	mg/m3	0,1	mg/m3	1/2h
Naphthalene	Mothballs	0,44	mg/m3	0,01	mg/m3	Avg.

Nitrogen dioxide (NOx)	Combustion of fossil fuel	2	mg/m3	200 40	µg/m3 µg/m3	1h Avg.
Ozon				40	µg/m3	Avg.
Polycyclic aromatic hydrocarbons	Incomplete combustion	Unknown		0,012	mg/m3	
Radon	Radioactive matter	No detection		0,0000 06	Bq/m3	
Trichloroethylene	Solvent for organic matter	1,134	mg/m3	2,3	µg/m3	
Tetrachloroethylene	Solvent for organic matter	5,2	mg/m3	0,25	mg/m3	Avg.

Table 3. 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 breath in by a human. These particles originate from chemical reactions, soot and smoke, mechanical actions, for instance abrading of car tires and train tracks and nature, like pollen and sea salt. These particulate matters are classified in pm2.5 and pm10, which means the section 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 it can be breathed out. Particles below 2,5µg will penetrate until the alveoli, where the smallest particles will enter the bloodstream (Gezondheidsraad, 2018). Table 4 show the save doses of the particulate matter that can be found indoor and outdoor.

Particulate matter	Source	Doses	
pm2.5	Mostly chemical reactions	15	µg/m^3
pm10	Mostly mechanical actions	50	µg/m^3

Table 4. Particulate matter (World Health Organization, 2010).

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 PM10 spikes are the results of children playing, but the largest spike is from making pancakes at 18:30 (Figure 17). 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. Table 5shows the maximum measured concentration during the measurements for each source or activity.

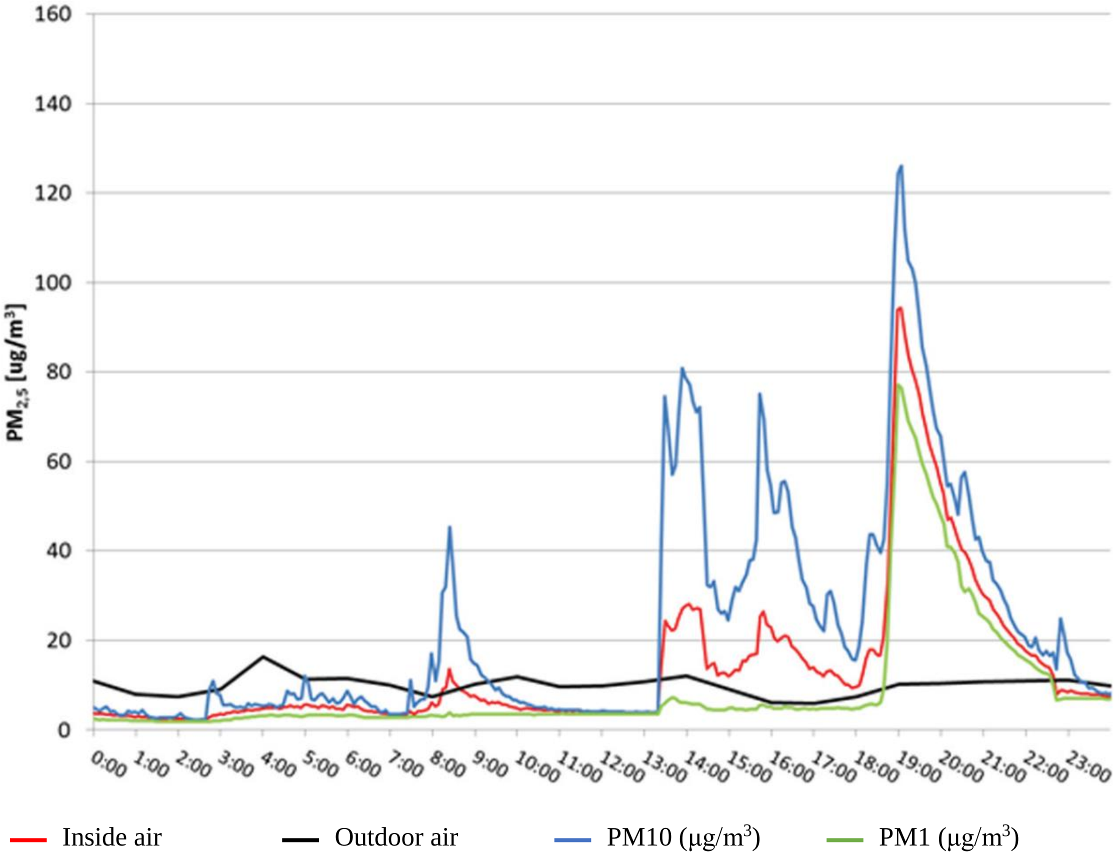


Figure 17 PM concentration during the day (Jacobs, Fijnstof bronnen in en rondom woningen, 2017)

Activity or source	PM10 production
Cooking	2000 µg/m^3
Hairspray	140 µg/m^3
Deodorant spray	350 µg/m^3
Outdoor firework	75 µg/m^3
Candles	40 µg/m^3
Playing children	35 µg/m^3
Smoke recoil from stove	35 µg/m^3
Firepit in the garden	50 µg/m^3

Table 5 PM10 production (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 17 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.

Relative humidity (Φ) or RH is the ratio partial pressure to saturation pressure. A low relative humidity, between 0% to 30% relative humidity, can lead to eye and skin irritation.. A high relative humidity can lead to condensation, which is due to saturation of the contained water molecules in the air. This usually occurs when the temperature of the air is decreased below the point at which air is saturated. High relative humidity and condensation can lead to fungi grow, increase in the amount of dust mites, bacteria and protozoa, which can affect the occupant and the building (Health Council of the Netherlands, 2013)

Biological	Location	Source	Outcomes	Humidity
Dust mites	Indoor	carpet rug mattress	allergies	45-50% <
Fungi	Indoor	everywhere	Various effect on health and building	80 - 100%
Bacteria	Indoor and outdoor	everywhere		wet or damp
Protozoa				

Table 6. Microbial contaminants due to humidity (World Health Organization, 2009).

2.3.2.2. Air exchange rate

Air exchange efficiency determines how fresh air distributes in a room. There are three types of ventilation situations, short-circuit, mixing and displacement, see **Fout! Verwijzingsbron niet gevonden.**.

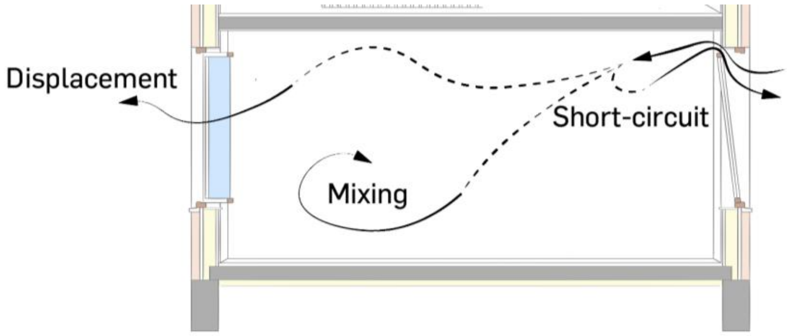


Figure 18 Air exchange situations (own illustration)

Short-circuit is the situation in which the air supplied is almost immediately exhausted, where the air exchange efficiency depends on the location of the inlet and exhaust. Normally, this will have a low air exchange efficiency. Dilution of the indoor air with incoming air is called mixing, whereas displacement is air displacement without dilution. A combination of these two situation are 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.

Natural ventilation and mechanical ventilation are the main systems to exchange indoor 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 as follows:

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

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 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 7 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	CO2 or timer operated grill	Sensors are required

Table 7 natural ventilation inlets

The two main drivers causing natural ventilation flows are pressure differential due to temperature difference and pressure differential due to wind. The pressure differential due to wind is given by;

$$P_{wind} = \frac{\rho v^2}{2} C_p$$

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		

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

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

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

The wind pressure coefficient, C_p, 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 have a large influence on the Cp value. This can be simplified by altering the geometry to a simple isolated rectangular building, where C_{p0} is the wind pressure coefficient at the front side, which is approximately 0,6. The wind pressure coeffic

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

The pressure differential due to temperature difference is given by;

$$P = \rho g h \left(\frac{\Delta T}{T} \right)$$

P	=	pressure (Pa)		
ρ	=	density of air (kg/m^3)		
g	=	acceleration due to gravity (m/s^2)	=	9,81m/s^2

h	=	height (m)
T	=	temperature (°C)

When the pressure differences are calculates, the orifice equation can be used to calculate the airflow rate through a given opening.

$$Q = C_d\, A \sqrt{\frac{2\, \Delta P}{\rho}}$$

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

Mechanical ventilation is mainly used when natural ventilation cannot meet the requirements, due to outdoor conditions (noise or pollutants), 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;

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

Q_{me}	=	electrical power necessary for ventilation (W)
q_v	=	amount of ventilation (m3/s)
v	=	flow velocity (m/s)
ΔP	=	pressure difference (Pa)

η = ventilator efficiency

Long-term monitoring studies show that there are large differences in the indoor air quality and energy performance of code compliant residential ventilation systems. Rob van Holsteijn and William Li have monitored the energy performance and CO2 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 CO2 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 every 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 of the IAQ-performance, only the energy potentials are calculated.

The Dutch building codes, Bouwbesluit 2012, state that a residential area must have 0,9 dm3/s/m2 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 has a ventilation rate of 21 dm^3/s and wet rooms have an 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, 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 differs from an high level of ventilation, for very sensitive persons with special requirements like handicapped, sick, very young children and elderly, to an acceptable and moderate level. These ventilations rates are continuously operated during occupied hours and are completely mixing.

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 8 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 (Normcommissie 351 074 "klimaatbeheersing in gebouwen", 2007).

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 μg/m^3, with an hourly average of 327 μg/m3, 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 ventilation losses. Also, this solution is less preferred by an end users 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, but to realize these high exhaust flows, addition measures for inlets should be arranged (Jacobs, Cornelissen, & Borsboom, 2017).

2.4. Mechanism

Precedent research has found limited knowledge on the mechanism of a similar system. My hypothesis is that this system is a domotica system that consist of a interface for the user that is similar to a thermostat, sensors and the operative components for the windows. These components should be a coherent addition to a residential building, not disturbing the comfort or the functionality of the window. The current knowledge of these products will be investigated.

Criteria

- Aesthetically pleasing or concealing
- easy to operate
- sensors need to be accurate enough for its use
- Integrated in window profile, so small or foldable
- Needs to work with turn tipping windows, going inside and outside
- Weather proof
- Manually and automatically operable

2.4.1.1. User interface

The interface of 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 19). A newer iteration of the thermostat is the programmable thermostat, which is designed to adjust the temperature according to a series of programmed settings. An 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 20). 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 2.1.3, these additional features requires active participation of the user and accurate inputs in order to be beneficial.

Figure 19 Round T87F (Honeywell, n.d.)

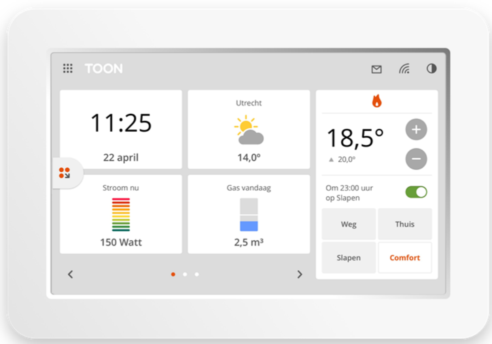


Figure 20 Toon (Toon, n.d.)

The interface 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.

2.4.1.2. Sensors

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, worldwide, to collect air quality data beyond reference monitoring stations, new low cost platforms are currently available and new devices are continually introduced.

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 21) and the pollutant or the absorption of light (Figure 22). Particulate matter is measured by light absorption or scattering, where algorithms relate the signal to the particle size or composition. These sensors range from €20 to €100. New types of commercially available sensor is increasing at a rapid pace, so new measuring techniques and prices may come in the near future.

Figure 21 electrochemical sensor (Winsen, n.d.)

Semiconductor gas sensor (methane)

- type = MQ-5
- cost = €1,-
- dimensions = 20 x 16,4 mm
- expected life span = 2 years
- average energy consumption = unknown
- accuracy = unknown

(HANWEI ELECTRONICS, n.d.)

Figure 22 light absorption sensor (Winsen, n.d.)

Infrared Gas Sensor (methane)

- type = MH-440D
- cost = €2,-
- 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 (PM10 and PM2,5). The results show that even for identical sensors and platforms, the performance can vary from sensor to sensor. According to Aleixandre and Gerboles, this inaccuracy is due to interference of the electrochemical sensor with the temperature and the relative humidity. The stability is probably the worst problem of this kind of sensors. The response changes over time and the sensors needs to be recalibrated. Manufactures do no provide much information about the drift or stability (Aleixandre & Gerboles, 2012). Each low-cost sensor behaves unique, 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 PM10 are capable of offering coarse information about air quality (Castell, et al., 2016).

The sensors for humidity 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.

2.4.1.3. Operative components of the windows

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 23). 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 an gear operated actuator cannot be operated by hand, unless it is designed to do so. The chain operated windows are the most common used for residential buildings (Figure 24). This is because they are small and concealable in window frames. 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. Some designs recognize small movements in the door, that activates the automated door to open.

Figure 23 gear operated actuator (Vektiva, n.d.)

Figure 24 chain operated actuator

Figure 25 automatic door closer (HBopeners, n.d.)

A new design for this actuator should be made that opens and closes the window in a safe manner, while being small or aesthetically pleasing, without hindering operation by hand.

3. Hypothesis

This hypothesis is based on previous observations and the gathered existing knowledge. Stakeholders will be determined for the proposed design, followed by a description of the system. An operation diagram will be created, similar to precedent work. Finally, a location for a case study will be determined which could be used for testing different heating and ventilation strategies.

3.1. Stakeholders

In order to determine the system requirements, every stakeholder should be identified with their interest.

End-user

The end user needs to be involved in the design process to make their wishes and demands clear. But, 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. A presentations, suggestions and meetings can help the end user to point out what he or she actually wants.

The end-user doesn't want an intervention that interferes with any activity within the residential building. Comfort shouldn't be hindered and should be improved. The end-user still wants to have influence on the indoor environment, which improves accepting a wider range of indoor conditions. The product shouldn't intervene safety during operation and when it is in nonuse.

Architect

The architects main focus is aesthetics. The product should look and feel like it is for residential buildings. Automated windows and doors are normally found in hospitals, utilitarian buildings or shops.

Municipality

The interest for the municipality is the performance of the intervention. The municipality need to monitor if the building stock is build conform the national and local ambitions, Dutch building regulations and NEN-norms.

Contractor

The main interest of the contractor is that it can be ordered and build. The contractor will steer the design towards products that are easy to order, manufacture or install.

Maintainer

The product needs to be easy to maintain.

Owner/investor

The initial investment cost should be low and the building time should be short. The product should have a favorable exploitation with low maintenance cost. 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.

Stakeholder	Interest
End-user	Doesn’t interfere with any activity Comfort shouldn’t be hindered, but sometimes improved It’s safe Keep control over the indoor environment
Architect	Aesthetics
Municipality	Energy demand lowers Intervention is conform Dutch building codes Indoor air quality is pleasant and causes no sickness
Contractor	Easy to install Easy to order parts
Maintainer	Easy to maintain
Owner/investor	Investment cost is low Cost turnover is fast Maintenance is efficient and not too costly Adaptability Doesn’t hinder the structural integrity of the building

Different interest from all stakeholders should be taken into consideration during the design phase of the products.

3.2. System

The system is a coherent addition to a residential building, that doesn’t resemble other automated systems that an user can recognize from a public accessible or utilitarian building. It shouldn’t interfere with any indoor activity by the user, windows and doors should be manually and automatic operable. The windows and doors can’t be operated via a smartphone or online application and when the occupant is asleep or away from home. Collected data is inaccessible via the internet, this data is stored locally, preventing privacy issues and improving safety.

Multiple inputs should form the requirements for a comfortable indoor climate. Thermal comfort will be defined according to the adaptive control algorithm, corresponding to 90 and 80% thermal acceptability. The additional 10 to 20% acceptability can be met with easy to use controls, increasing or decreasing the temperature by a couple of degrees. Used methods in utilitarian buildings, like adjusting the set temperature by a couple of degrees, can give a user enough adjustability in order to create comfort. The system determines an efficient way to heat or cool a building, in order to lower the energy demand, by opening or closing operable façade elements or internal doors. Complete control over the indoor climate is also possible, which will disable the adaptive control algorithm. The only input for the system at that point is the need of the occupant.

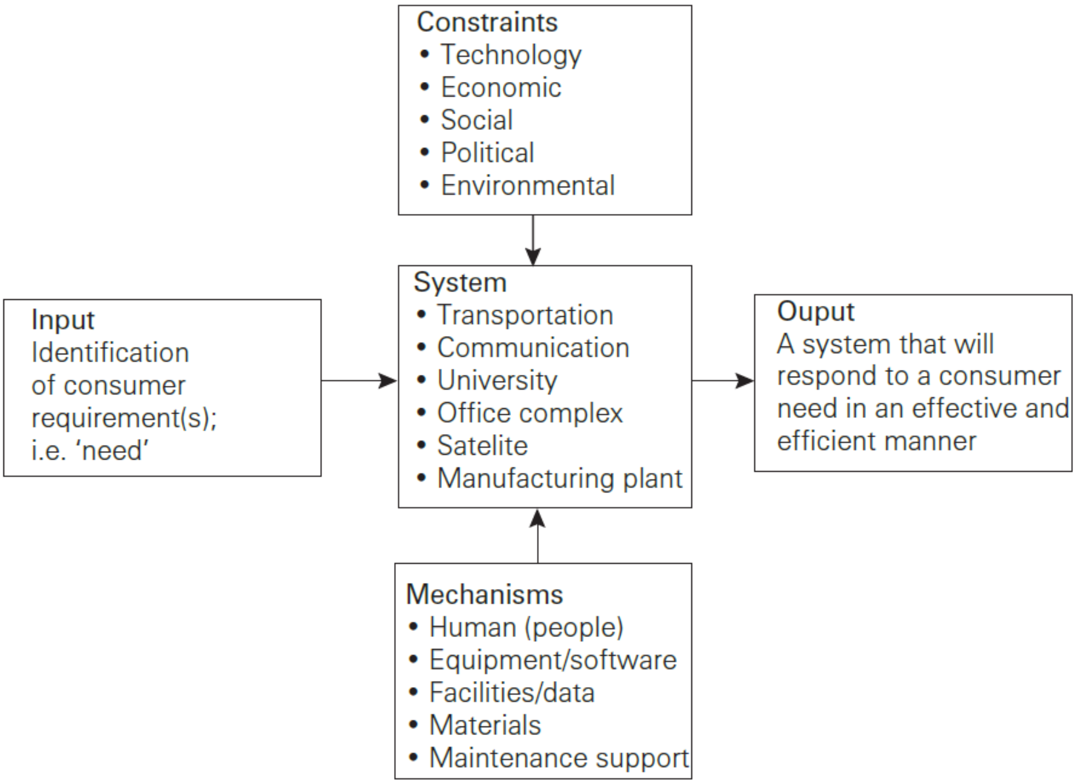
Comfort due to air quality is different for everyone. Odour levels of non-hazardous fumes and gasses can be measured when a user performs an action, opening a window, in order to restore comfort. This data can be collected in order to measure the threshold for that particular household. The system learns from these patterns, creating thresholds for aerating the house. Hazardous fumes and gasses should be aerated according to the WHO stated thresholds.

Relative humidity can be used to create indoor comfort, for the occupant and building. The mollier diagram can be used to cool the building during summer. Humidity levels shouldn't exceed 80% in order to prevent mold growth and shouldn't be lower than 40% which encourages spread of dust mites (World Health Organization, 2009). Humidity levels shouldn't be lower than 30%, which could cause eye and skin irritation (Health Council of the Netherlands, 2013).

For light primarily sedentary work, the max air velocity should be below 0,82 m/s. Elevated air velocity must be under the control of the affected occupants.

Investment cost should be low, which is possible by using mostly 'off the shelf' parts instead of custom parts. These 'off the shelf' parts are easy to order, already familiar by contractors and pre-engineered and tested. Broken parts can easily be order or maintained. The system should be able to expand if extensions are built for the building, or updated if new regulations or guidelines are determined for thermal comfort or air quality. During the conceptual design phase, the technical requirements are determined for the requirements of the system. According to Blanchard, a system has;

- inputs; consumer requirement
- 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

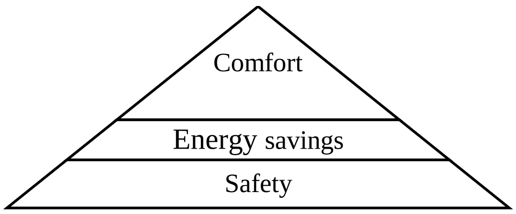


This system comprises a set of interrelated components that work together with a common objective, which is lowering the energy demand of a residential building in a comfortable way. A hierarchy within the inputs for this system should be determined. The inputs for this systems are the required data in order to create comfort for the end-user and reducing the heating demand. The follow parameters, with substantiations, are used as inputs;

- indoor air quality profile for safety
    - air pollutants measured and compared with threshold stated by WHO
    - humidity measured
    - windspeed
- outdoor air quality profile for safety
    - air pollutants measured and compared with threshold stated by WHO
    - humidity measured
    - windspeed
- indoor air quality profile for comfort
    - threshold measured by data collected from user behavior
    - humidity measured
    - windspeed
- outdoor air quality profile for comfort

  - threshold measured by data collected from user behavior
  - humidity measured
  - windspeed
- indoor thermal profile
  - adaptive control algorithm
  - set temperature from occupant
  - humidity measured
  - windspeed
- outdoor thermal profile
  - temperature measured
  - humidity measured
  - windspeed
- windows and doors
  - opened
  - closed

Safety has the highest priority, which is indoor and outdoor air quality for safety and the state of the windows and doors, an unsafe environment for the occupant and building should be prevented. Energy saving potentials from indoor thermal comfort has the second highest priority, because this system will only be accepted if energy is saved and comfort is created. Air quality for comfort has the lowest priority, because this will not compromises the physical health of the occupant.



3.3. Operation

The system is the brain of the operation, where all different inputs, constraints and mechanisms form an output. At this stage, the system determines if a window should be closed or opened. This system cycles through statements where each statement is followed by a different statement or an action (Figure 26). Air pollution is checked first, determining the air pollution. If the air pollution exceeds the thresholds made by the WHO, the windows will go open for maximum air displacement. When air is only polluted with levels that can intervene comfort, the windows will go open with comfort in mind. If the air quality is within the threshold for air pollution, the thermal comfort will be determined according to algorithms and inputs.

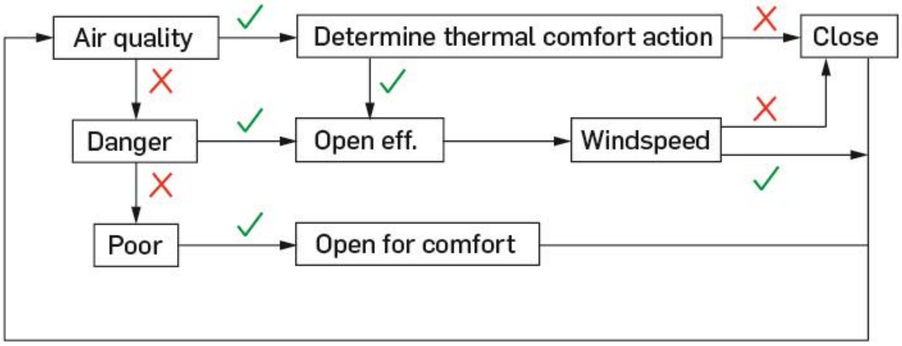


Figure 26 statement cycle

Air quality	=	Air quality > Comfort
Danger	=	Thresholds stated by World Health Organization
Poor	=	Air quality < Comfort, includes high humidity
Open eff.	=	Open windows for maximum displacement
Open for comfort	=	Open for maximum comfort
Air speed	=	Indoor windspeeds for comfort
Determine thermal	=	Statements determining window operation for thermal comfort

The most intricate step is the statement that determines the action for thermal comfort. A line of statements have been made that determines if the indoor air needs to be heated or cooled. First, the inside temperature is compared to the outside temperature and the set temperature with the inside temperature. The set temperature is the sum of the adaptive control algorithm and the input of the occupant. These statements produce a value, zero or one, which correspond to an action, windows opened or closed.

S1	=	If Toutside < Tinside
		1, 0
S2	=	If Tset < Tinside
		1, 0
S3	=	If Toutside < 17,8
		1, 0
S4	=	If S1+S2+S3=0
		windows open for warmth
S5	=	Else if S1+S2+S3=1 OR Else if S1+S2+S3=3
		windows closed
S6	=	Else if S1+S2+S3=2
		windows open for cooling

Tset	=	Tcomfort + Tinput

Tcomfort = 0,31 x Tout + 17,8

Tinput = Input thermostat (-3,-2,-1,0,+1,+2,+3)

Toutside = Temperature outside

Tinside = Temperature inside

Examples are made in order to verify that these lines of statements provide the correct result (Appendix B).

3.4. Case study

For tests and calculations, the Ramplaankwartier can 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 level of gas consumption, due to the low amount of energy awareness during this time. Many of these residential buildings have been renovated and have an improved energy label, Figure 27 for the certified energy labels of the buildings in the Ramplaankwartier.

Figure 27 certified energy labels Ramplaankwartier (Meer Met Minder, n.d.)

Many of these buildings have 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. Modern day dwellings have an average gas consumption of 1000m^3 (Milieu Centraal, n.d.). The average consumption of the 1960’s dwellings in the Ramplaankwartier is almost 1800m^3. Therefore, these buildings are in need of an intensive renovation.

3.4.1. Situation

Rollandslaan 84 at the Ramplaankwartier is a row house that will be used for the calculation, which is a typical Dutch row house with neighbors on either side. 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, n.d.)

3.4.2. Program

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, with 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.

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 house separating walls. 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.

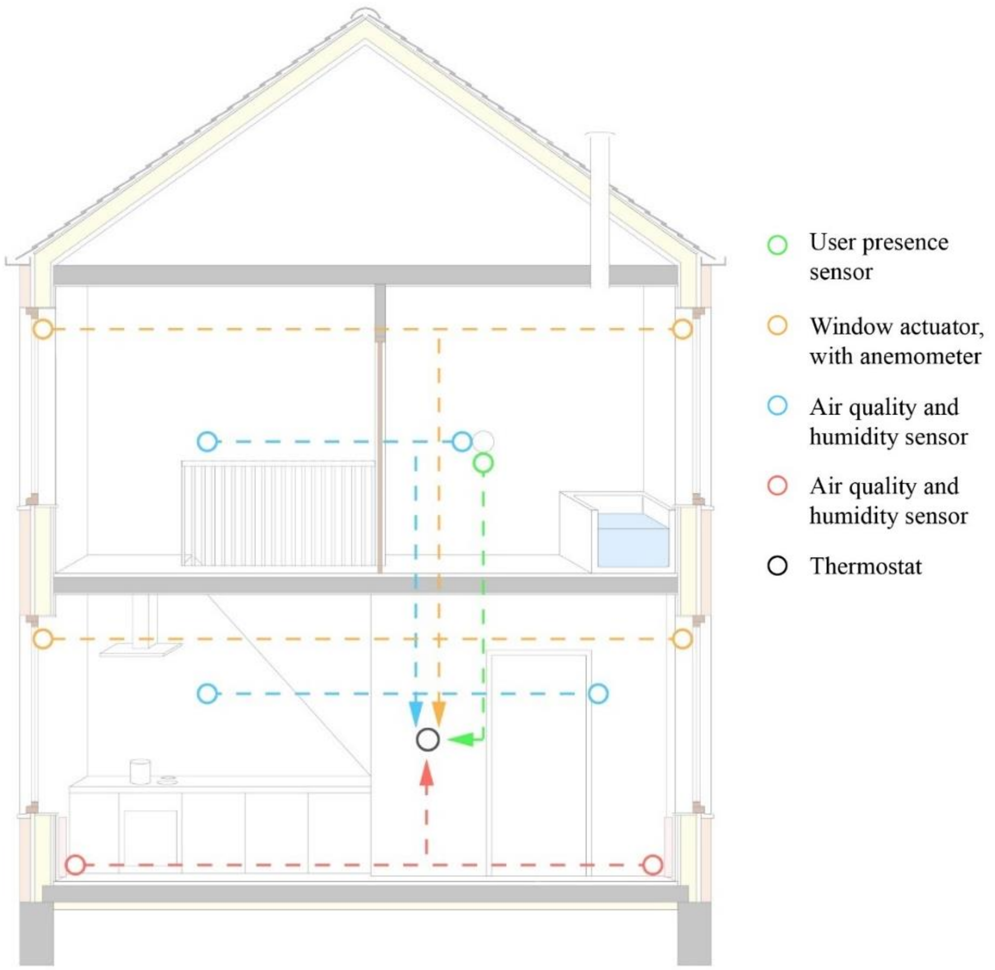
Throughout the passing years, large portions of the windows have been replaced with some form of double glazing, like HR++ glass. But there are still some windows with single glazing.

3.4.3. Actual demand

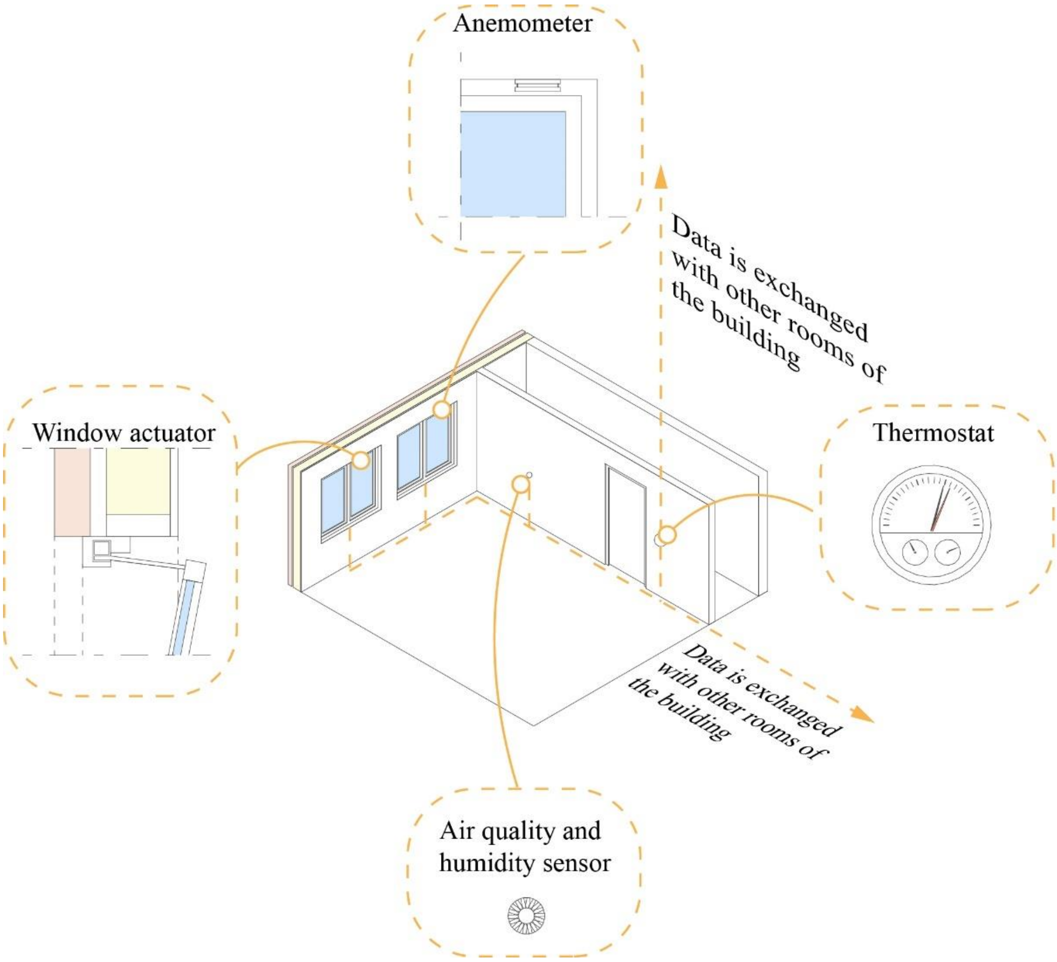
The current owners in this building consume 4000kWh of electricity and 2260m^3 of gas in 2016. Electricity is used for the main appliances, like lighting, washing machine, fridge etc. Gas is used for heating, hot domestic water and cooking. Heating is provided by high temperature radiators in each room. A compact HR combi boiler provides hot domestic water and heating. Hot water in the kitchen is provided by a small electric boiler.

3.5. Conclusion

To conclude the hypothesis, the system consist out of a thermostat that functions as the brain of the entire system with multiple inputs from sensors and actuators. Every room has an user presence sensor, which can be pressed or sense that an user occupies a room for a duration that it needs to be climatized for comfort. This presence sensor has two buttons in order to decrease or increase the calculated temperature by a couple of degrees.



This information is fed to the central thermostat that determines an efficient way to climatize the room by opening or closing windows, increasing or decreasing the heating system or opening and closing internal doors. During presence of the occupant, the system uses sensor to monitor the internal air quality on NOx and PM10 and relative humidity. These two pollutants can be detected with reliable and affordable sensors, more sensors can be added in the future. These sensors are mounted at a height of 1,1 meters above the ground. The system operates the windows and doors in order to guarantee a save indoor climate and improve comfort for the occupant. This action is only done when an occupant is present and awake, due to safety reasons.


Anemometer
Window actuator
Data is exchanged with other rooms of the building
Thermostat
Data is exchanged with other rooms of the building
Air quality and humidity sensor

4. Conclusion

What is an effective way to design a product that will assist an user in sustainable behavior?

In order to establish the wishes and demands of the user and the communication process required to facilitate the design, production and maintenance, an interactive top-down approach is required. The needs and wishes of every stakeholder have to be understood, both for now and in the future.

A smart system should not rely on the output of an user, but should performance desired actions by itself. Therefore, product adaptation should be applied as an user assisting strategy for the proposed design. Therefore, the product can be designed to facilitate sustainable behavior that the users already want to perform but consider themselves unable of doing, which is referred as “match”. 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.

Why do people open their operable façade elements?

Liddament reviewed several studies on occupant behavior and ventilation, and found 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. According to Moghadam, Soncini, Fabi, & Corgnati, people in warmer climates tend to open their windows more frequently. Elham Delzendeh, Song Wu, Angela Lee and Ying Zhou determined that window opening behavior is the second most occurring user activity that influences the energy demand of a building, number one is electrical and wall plug related activities. Parameters that influence this activity is climatic related, personal related, due to building or design features, the economy, socio-personal related and other user activities. These observations suggest that window opening or closing is not always in response to ventilation needs.

How much influences has user behavior on heating demand due to window and door opening?

This depends on the window opening behavior and the performances of the building. Simulation show that there is a deviation per climate, but in every type of climate, the influence of user behavior has a negative effect on the energy demand compared to the controlled system. Different simulations give different results. 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. Some models show that during winter, the energy demand in warm climates can increase by 196%, and in winter decreased by 5%. In subtropical continental climates, this energy demand during winter is increased by 61% and during winter decreased by 14%.

The effect of window opening on the measured heat loss of a single detached house was tested by the department of Civil and Building engineering at Leeds Beckett University in Loughborough. There test house showed that normal window opening behavior, as described by the researchers, increases the HLC with 4,1W/K, which is 2,4% of the total heat loss coefficient of the building. This heat loss increases when buildings become more airtight and better insulated.

How can a comfortable indoor temperature be determined and created?

A comfortable indoor temperature differs for an occupant differs from activity, metabolism, outdoor temperature, clothing and the possibility to natural ventilate. Therefore, a comfortable indoor temperature is hard to determine. The international standards presents methods for predicting the general thermal sensation and degree of discomfort of people with a predicted mean vote (PMV) index. The PMV may be calculated for different combinations of metabolic rate, clothing insulation, air temperature, mean radiant temperate, air velocity and air humidity in order to calculate local thermal comfort. The adaptive control algorithm can be used to determine the indoor temperature that satisfies 80 to 90% of the people. This algorithm determines an indoor temperature based on the outdoor temperature. This method doesn't take air velocity and humidity into account.

Higher air velocities can be used to offset the increase in temperature, creating comfort by cooling. Stated in NEN-7730, the max air velocity should be below 0,82 m/s for light primarily sedentary work, which results in a max temperature offset of 3 degrees. Individual differences exist between people with regard to their preferred air velocity. Therefore, the elevated air velocity must be under the control of the affected occupants. Occupants that have control over the indoor climate with natural ventilation prefer a wider range of conditions, that reflect outdoor climate patterns, which can decrease the heating demand. User activity and metabolism should be taken into consideration in determining the ideal indoor temperature. That's is why an user should be in control of the indoor environment, in order to seek comfort by itself.

Heat discomfort also depends on the humidity of the skin, which can vary due to activity of the user, health of the user or relative humidity of the air. 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 and create passive cooling comfort.

What can create a safe or comfortable IAQ for the occupant and building?

Air quality for comfort can be determined with odour detection level of fumes and gasses. Various fumes and gasses have different odour detection levels for an occupants. This doesn't mean that it causes discomfort, but it only means that the odour can be detected. Some gasses are hazardous and have a lower odour detection level than their safe doses. Discomfort is detected in the form of skin irritation, eye watering or even airway irritation. The World Health Organization has set the safe doses for common air pollutants that are hazardous. Relative humidity can also lead to discomfort for the occupant and create an undesired effect on the building. A low relative humidity can lead to eye and skin irritation, which is between 0% to 30% relative humidity. The effects and symptoms differ from people and ages. A high relative humidity can lead to condensation, which is due to saturation of the contained water molecules in the air. High relative humidity and condensation can lead to fungi grow, increase in the amount of dust mites, bacteria and protozoa, which can affect the occupant and the building.

The Dutch building codes, bouwbesluit 2012, has created building codes in order to create an safe and comfortable IAQ. It states 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 of place to stay must have a ventilation rate of 0,7 $dm^3/s/m2$, with a minimum of 7 dm^3/s. A room that is designated for cooking has a ventilation rate of 21 dm^3/s and wet rooms have an ventilation rate of 14 dm3/s. Nevertheless, 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. Nederlandse Norm provides guidelines for indoor air quality in NEN-EN 15251. The required ventilation differs from an high level of ventilation, for very sensitive persons with special requirements like handicapped, sick, very young children and elderly, to an acceptable and moderate level.

What ventilation type improves the indoor air quality of a dwelling and what are the thermal potentials?

Ventilation systems can be categorized in two groups, natural ventilation and mechanical ventilation. Natural ventilation is passive way to exchange air with the outdoors, where the airflow depends on wind and air density differences. This ventilation system can only improve the indoor air quality due to dilution and displacement of air pollution. Displacement has the highest air exchange efficiency, but occupant behavior and activities can impair these systems, making them hard to use for residential buildings. Also, ventilation speed is harder to set with natural ventilation, where high wind speeds can cause discomfort. Mechanical ventilation can filter and purify income air with different techniques. Heat recovery systems can be installed, extracting heat from exhausted air and using it to pre-heat the incoming air. But occupants become more finely adapted to the narrow constant conditions that can be provided in a residential buildings with HVAC systems. Occupants of naturally ventilated buildings tolerate a wider range of conditions that reflect the outdoor climate.

A ventilation system that applies a mechanical component in the air exchange, inlet or exhaust, performs significantly better in energy performance and reducing the CO2 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 and the requirement of an active occupant.

Window opening during and after cooking improves the IAQ, where the average PM1 concentration can be reduced by five times, but at the expense of significant ventilation losses. This solution is less preferred by an end users because of possible draught problems and extra heating or cooling demand. Mechanical ventilation can extract polluted air near to the source, with a higher capacity and with less heat loss.

5. Reflection

General base knowledge is created on the given topic, but more literature should be investigated and gathered during the upcoming phases. Request to view ISSO 74 is pending at the TU Delft library, which will hopefully be accepted soon. This publication presents new guidelines for the indoor thermal climate in buildings via an adaptive algorithm. Also, the request to view “The impact of occupants' behaviour on building energy demand” by Frédéric Haldi and Darren Robinson is pending. This report consist out of an extensive field survey data which is acquired over the past 8 years at the Solar Energy and Building Physics Laboratory at EPFL in Switzerland. Comprehensive models of occupants presence, opening and closing of windows and the raising and lowering of blinds have been developed and presented.

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7. Appendix A

Calculations

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.

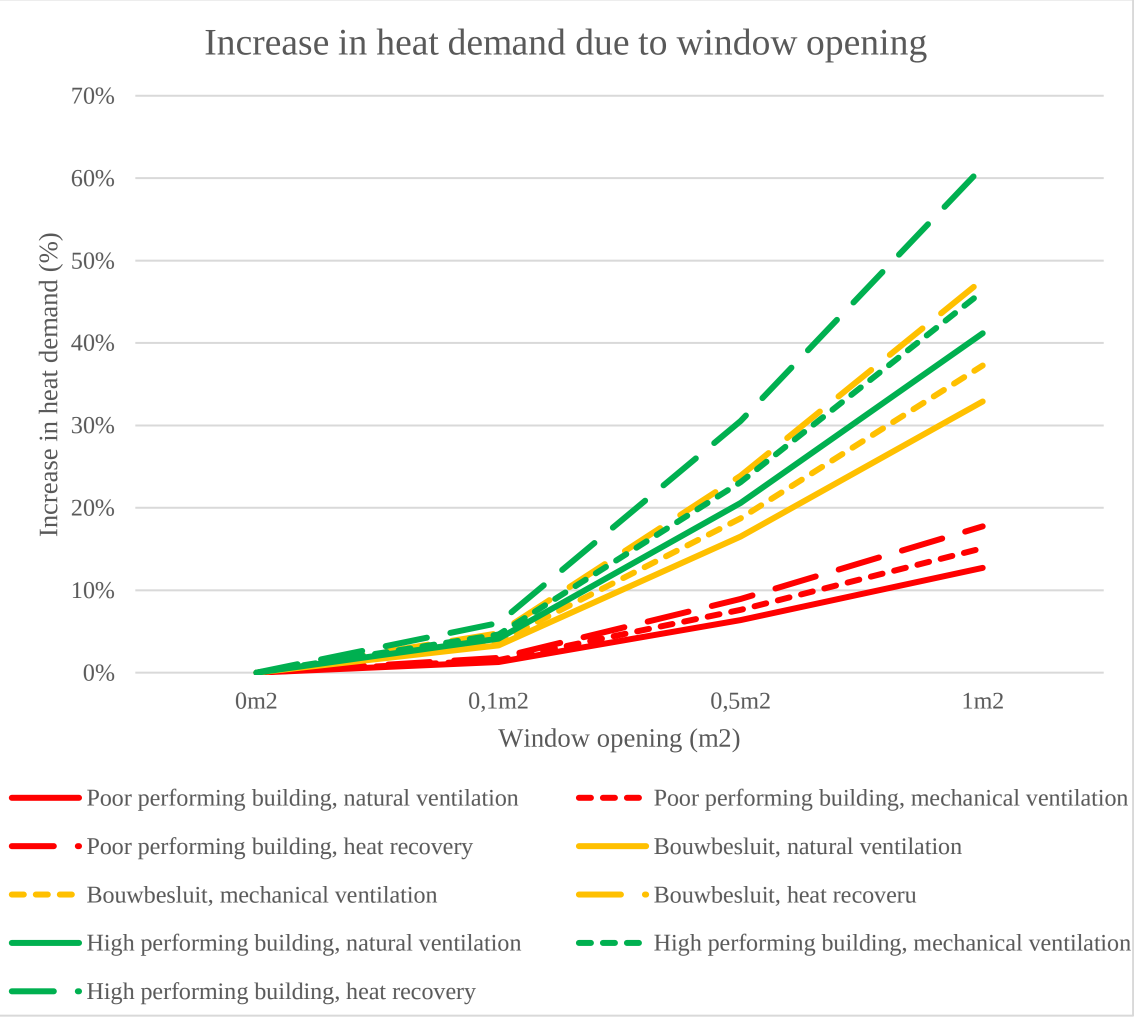
Infiltration (Dutch standards)	= Poor performing	=	0,90 $l/s/m^2$	
	= Bouwbesluit cf.	=	0,60 $l/s/m^2$	
	= High performing	=	0,15 $l/s/m^2$	
Rc values	= Poor performing	=	avg.	= $0,9m^2K/W$
	= Bouwbesluit cf.	=	floor	= 3,5 m^2K/W
		=	roof	= 6,0 m^2K/W
		=	wall	= $4,5m^2K/W$
	=High performing	=	avg.	= $8,0m^2K/W$

The infiltration rate of the test building is 4,2l/s/m², 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, see table XXX. These range from no window opening (0,0m² opening) till "unrealistic" high window opening (1,0m² opening) behavior.

Building type	0,0m² opening (l/s/m2)	0,1m² opening (l/s/m2)	0,5m² opening (l/s/m2)	1,0m² opening (l/s/m2)
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

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



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 an user and can have a 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%		

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%

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

8. Appendix B

Examples

Winter situation

Tinside	=	17°C
Toutside	=	10°C
Tset	=	21°C

S1=	If Toutside < Tinside	=	10 < 17	=	true	=	1
S2=	If Tset < Tinside	=	21 < 17	=	false	=	0
S3=	If Toutside < 17,8	=	20 < 17,8	=	false	=	0
S5=	Else if S1+S2+S3	=	1	=	true	=	windows closed

Summer situation

Tinside	=	25°C
Toutside	=	20°C
Tset	=	21°C

S1=	If Toutside < Tinside	=	20 < 25	=	true	=	1
S2=	If Tset < Tinside	=	21 < 25	=	true	=	1
S3=	If Toutside < 17,8	=	20 < 17,8	=	false	=	0
S6=	Else if S1+S2+S3	=	2	=	true	=	windows open for cooling

Autumn or spring situation

Tinside	=	17°C
Toutside	=	20°C
Tset	=	21°C

S1=	If Toutside < Tinside	=	20 < 17	=	false	=	0
S2=	If Tset < Tinside	=	21 < 17	=	false	=	0
S3=	If Toutside < 17,8	=	20 < 17,8	=	false	=	0
S4=	Else if S1+S2+S3	=	0	=	true	=	windows open for warmth

Winter, leaving the house

Tinside	=	20°C
Toutside	=	10°C
Tset	=	14°C

S1=	If Toutside < Tinside	=	10 < 20	=	true	=	0
S2=	If Tset < Tinside	=	14 < 20	=	true	=	0
S3=	If Toutside < 17,8	=	10 < 17,8	=	true	=	0
S4=	Else if S1+S2+S3	=	3	=	true	=	windows closed