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Impact of mechanical ventilation systems on the indoor air quality in highly energy-efficient houses

How it affects human health

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Samenvatting

Binnen de woningbouwsector liggen veel mogelijkheden om energie te besparen. Het verbeteren van de isolerende werking van de bouwschil van woningen is één van die mogelijkheden. Mede hierdoor worden woningen elk jaar energie-efficiënter. West Europese landen leggen verschillende richtlijnen op met minimale isolatiewaarden voor nieuwbouwwoningen die vanuit de Europese Unie worden vastgelegd. De isolatie verbeteringen in woningen zorgen ervoor dat woningen steeds luchtdichter worden.

Het Rijksinstituut voor Volksgezondheid en Milieu heeft een enorme stijging in astmapatiënten en andere ademhalingsproblemen gerapporteerd. Woningen zijn sinds de oliecrisis van 1973 steeds meer luchtdicht gemaakt. Deze trend zet ook nu nog door. Wetenschappers zien deze twee trends niet als toeval en schrijven dan ook over een correlatie tussen de toename in astmapatiënten en woningen die steeds luchtdichter worden. De binnenluchtkwaliteit wordt als oorzaak gezien voor de toename in klachten met betrekking tot luchtwegproblemen.

Op dit moment is mechanische ventilatie met warmteterugwinning het meest gebruikte ventilatie systeem in Nederlandse nieuwbouwwoningen. Helaas zorgt dit veelbelovende ventilatiesysteem in de praktijk vaak niet voor voldoende ventilatie. Deze scriptie heeft als focuspunt de werking van mechanische ventilatiesystemen met warmteterugwinning in energiezuinige woningen. De hoofdvraag is:

> *Wat is het effect van mechanische ventilatiesystemen op de binnenluchtkwaliteit in energiezuinige woningen en hoe beïnvloedt dit de gezondheid van de bewoners?*

Deze vraag zal beantwoord worden door eerst de werking van mechanische ventilatiesystemen te beschrijven en daarbij ook het effect van bewonersgedrag mee te nemen. Verschillen in de ventilatie toevoeren en de gevolgen daarvan zullen onderzocht worden. De meest voorkomende en meest schadelijke luchtverontreinigende stoffen binnenshuis zullen beschreven worden. Mogelijke gezondheidsproblemen van deze luchtverontreinigende stoffen zullen ook uitgelicht worden. Als indicator voor de binnenluchtkwaliteit zal de CO_2-concentratie gebruikt worden. Met behulp van een model zullen de verandering in luchtkwaliteit in kaart gebracht worden. Hiervoor zullen verschillende bewonersscenario's en verschillende luchtdichtheden van nieuwbouwwoningen gebruikt worden. Een eerste scenario zal kijken naar het effect van drie mogelijke standen waarin het mechanische ventilatiesysteem gezet kan worden door de bewoners. Een tweede scenario zal kijken naar het effect van het openen van ramen op de binnenlucht kwaliteit. Er zal gekeken worden naar het openen van een kiepraam tot 10 cm (W1) en het openen van een raam tot 40 cm (W4). Als laatste zal er ook gekeken worden naar het effect van een toename in het aantal personen in een woning op de CO_2-concentratie binnenshuis.

De verbeteringen van de isolerende werking van de bouwschil zorgen voor een verminderde ventilatie. Hierdoor neemt de CO_2-concentratie in de binnenlucht toe. Dit onderzoek laat zien dat de meest gebruikte stand van het mechanische ventilatiesysteem (MV1) in extreem energiezuinige woningen niet meer in staat is om de CO_2-concentratie onder de grenswaarde van 1200 ppm te houden. Het openen van een raam (W1) kan de ventilatie toevoer vergroten ter grootte van één stand op het mechanische ventilatiesysteem. MV2 is de aanbevolen stand van het mechanische ventilatiesysteem. Met het gebruik van deze stand door de bewoners zal de CO_2-concentratie in de binnenlucht waarschijnlijk met 32% toenemen in extreem energiezuinige woningen ten opzichte van de huidige woningen.

Naast de toename in CO_2-concentraties binnenshuis kan een verminderde ventilatie ook zorgen voor de toename van andere luchtverontreinigende stoffen. De toenemende luchtdichtheid van woningen zou er voor kunnen zorgen dat nog meer bewoners deze klachten zullen ervaren. Het is nog niet duidelijk welke luchtverontreinigende stoffen verschillende ziekten veroorzaken. Deze scriptie laat zien dat energiebesparende maatregelen om woningen energiezuiniger te maken kan leiden tot een toename in gezondheidsproblemen. Het wordt door dit onderzoek duidelijk hoe belangrijk ventilatie wordt als woningen steeds meer geïsoleerd worden.

Summary

The residential sector contributes for a large part to the worldwide energy saving potential. Modern houses are becoming more energy efficient each year. Western European countries present guidelines with minimum insulation values for the building envelope, imposed by European legislations. Within the residential sector, this is resulting in an increase of the airtightness of the building envelopes. The Netherlands also has to increase the insulation capacity level of its residential sector.

In recent years, an increase has been seen in asthmatic diseases and respiratory symptoms in western countries. The Dutch National Institute for Human Health and Environment presented a four and sixfold increase of asthma prevalence in the period from 1972-2004. After the oil crisis of 1973, the residential sector started to become more airtight. Scientists write extensively about the possible association between the increase in asthmatic diseases and the increase of the airtightness of the building sector. The inside air quality has been considered to be the explanation for the reported health problems.

Airtight houses achieve very low values of indirect ventilation which makes them very energy efficient. In order to sustain a healthy indoor air, adequate ventilation rates must be supplied into these houses. In the Netherlands, most newly-built energy-efficient houses are built with mechanical ventilation systems with heat recovery to further increase the energy efficiency of the houses. However, energy-efficient houses often do not have adequate ventilation rates.

The focus of this thesis will be on the working of mechanical ventilation systems with heat recovery in energy-efficient houses. The effect of different ventilation rates will be investigated and the influence of resident behaviors will be scrutinized. The main research question is:

> *What is the effect of mechanical ventilation systems on the indoor air quality in highly energy-efficient houses and how does this affect human health?*

This question will be answered by clarifying the working of mechanical ventilation (MV) systems and the effect of resident interference with the system. Possible indoor air pollutants will be described and their prevalence and origin of existence will be discussed. A system model will clarify the degree of decreased indoor air qualities in different situations using the CO_2-concentration as an indicator of indoor air quality. Several scenarios will show the effect of residential behaviors and the effect on increasing the building envelope on the indoor air quality. One scenario will look at the effect of the three possible power levels of the MV system which can easily be changed by the residents. A second scenario will show the effect of window opening behavior on the indoor air quality. The two options are W1 which reflects a window opened with 10 cm and W4 which reflects a window opened for 40 cm. Furthermore, the effect of increasing the amount of residents on the indoor air CO_2-concentration will also be modeled.

Increasing the insulation capacity of the building envelopes results in decreased ventilation rates and thus increased indoor air CO_2-concentrations. The mostly used power level of the MV system (MV1) is not capable of keeping the indoor air CO_2-concentration below the limit value of 1200 ppm in highly energy-efficient houses. Opening a window (W1) can already increase the ventilation speed equal to one power level of the MV system. MV2 is the recommended power level and if resident actually will use this level, the indoor air CO_2-concentration will increase with 32% within highly energy-efficient houses compared to current houses.

Besides the increase of indoor air CO_2-concentrations, a decrease in ventilation may also cause an increase of other indoor air pollutants. Respiratory health problems, such as asthma, have

increased a lot lately. This thesis shows that increasing the energy-efficiency of houses possibly increases the occurrence of respiratory health diseases. Until now, it is unclear which specific air pollutant causes which specific health problem. However, this research shows the importance of ventilation when the airtightness of the residential sector keeps increasing.

1. Introduction

Throughout the world, the residential sector uses a lot of direct and indirect energy. The most important energy user in the residential sector is by far space heating. In European countries, more than 50% of the buildings end-use comes from space heating. This results in the fact that space heating contributes to a large share of the CO_2 emissions in the world. Therefore, the residential sector reflects a large part of the saving potential. So, it is not surprising that researchers focus on energy efficiency in the residential sector. The most effective way of decreasing the energy use of residential buildings is to improve the building envelope. The building envelope is the physical separator between the inner and outer environment of buildings. One way to improve the building envelope is by wall insulation.

Improving the insulation capacity results in more airtight houses, which can save a lot of energy. Because of the high saving potential, legislation on minimum insulation properties are implemented. Multiple European countries are working towards highly energy-efficient houses with zero carbon emission production by 2020. In order to develop zero carbon houses, the building envelope needs to be almost completely airtight.

One commonly used ventilation system in newly-built highly energy-efficient houses in Europe is mechanical ventilation with heat recovery (MVHR). Especially in cold climates this system has the opportunity to save energy, which triggers an increased interest in the development and research on MVHR systems in these countries. Also in the Netherlands, MVHR systems are widely installed. It is important to know if MVHR systems are able to maintain a good indoor air quality (IAQ) in airtight houses. Recently, the development of insulation capacity in the residential sector caused a growth in attention for the subject human health. Increasing the air-tightness of the building envelope in order to improve energy efficiency may have possible adverse consequences on the indoor air quality. Highly insulated houses can become increasingly airtight, which means that a limited amount of fresh air is able to enter the houses. Without adequate additional ventilation, air contaminants can build up inside houses and decrease the IAQ. A poor indoor environment may cause health problems to develop for residents. Since humans spend about 70% of their time indoors, the IAQ influences for a large part the total exposure level to pollutants.

Mechanical ventilation systems are the prime suspect of insufficient ventilation rates within highly energy-efficient houses. Ventilation systems function properly in the laboratory tests and reach the minimum requirements. In practice however, these mechanical ventilation systems do not reach their full potential. Incorrectly designed, installed, maintained or operated ventilation systems contribute to the harmful effects on the IAQ. Furthermore, it is suspected that usage patterns by the residents are often the reason why theoretical ventilation rates are not being reached practically. Occupant behavior can intervene with a proper working of the MV system. The most common behavior is changing the power settings of the MV system. It is suspected that noise nuisance is an important reason why people lower or turn off the MV system. Intervening behaviors can lower the working of the MV system, causing the ventilation to decrease. A decrease in ventilation rates corresponds with a decrease of the IAQ, which may cause an increase in health problems.

There are severe concerns about the possible adverse consequences of poor indoor air quality on human health. A high insulation level can increase the likelihood of condensation on the inside of walls and ceiling cavities in the heating season. This poses a risk for mold growth and the associated risk for rot and reduced insulation performance. Besides that, the metabolism of fungi could release volatile organic compounds in the air. These microbial volatile organic compounds can cause severe respiratory health problems, such as allergies and asthmatic symptoms.

The goal of this research will be to determine if mechanical ventilation systems are able to maintain a good IAQ in airtight houses, especially when taking into account human behavior on the working of the system. The effect from indoor air quality in highly energy-efficient houses on human health will be researched. This research design will lead to the following main research question:

What is the effect of mechanical ventilation systems on the indoor air quality in highly energy-efficient houses and how does this affect human health?

The following sub questions will lead to the answer:

1. Why is the residential building sector becoming more airtight?
2. How do mechanical ventilation with heat recovery (MVHR) systems work in highly energy-efficient houses?
3. What types of pollutants are released in highly energy-efficient houses?
4. What is the effect of human behavior on the working of mechanical ventilation systems?
5. How does indoor air quality (IAQ) affect human health?

Scope, methodology and outlook

The research will focus on the residential sector of the Netherlands. Dutch guidelines will be used. Energy efficient houses with a building envelope leakage of 0.5 air changes per hour (ACH) will be compared to highly energy efficient houses with a building envelope leakage of 0.2 ACH.

The European guidelines and the theoretical working of MVHR systems within the building sector in newly-built houses will be analyzed using the literature and producer information. Different scenarios with a variance in ventilation rates and occupant behavior are modeled using the dynamic modeling program STELLA. The model determines the influence of human behavior on the working of the ventilation system. Actual air supply rates with power levels MV1, MV2 and MV3 are established according to results from a large-scale experimental study (Balvers *et al.*, 2012). Pollutants in the indoor environment and possible health effects from exposures to poor IAQ are derived from literature studies.

Chapter 2 will answer the first research question and will go deeply into the European and Dutch insulation guidelines. In chapter 3, the working of MVHR systems will be investigated. This chapter will answer sub question two. The most common possible indoor air pollutants will be described in chapter 4. In chapter 5, the effect of occupant behavior will be described. Furthermore, the underlying reason for the behavior will be explained. Modeling the IAQ with indoor air CO_2-concentrations will be performed in chapter 6. Multiple scenarios will be described and results will be presented. In chapter 7, possible human health problems which might occur due to poor IAQ will be described. The effect of the earlier discussed indoor air pollutants on human health will be further explained. The focus will lie on respiratory health problems. At last, chapter 8, 9 and 10 will complete the thesis with a conclusion, discussion and some recommendations for further research.

2. Housing insulation and European guidelines

Awareness of possible energy shortage in the future started to rise due to the oil crisis in 1973. The crisis resulted in an increase of energy costs and raised more interest in ways to increase energy efficiency. Awareness of the fact that energy consumption is damaging the environment was triggered and research in alternative energy sources started to develop. Global warming became a hot topic and people started to think about possible ways to save energy. The Kyoto Protocol, signed by 55 countries in 1997, was the real beginning of global governmental agreements of reducing greenhouse gas emissions. A large part of possible saving opportunities can be achieved by improving the efficiency in the building sector, as the building sector is one of the largest energy consumers. In Europe, the building sector represents about 40% of the final energy consumption (European Commission, 2002).

2.1 Potential savings

Reaching potential energy savings in the building sector can be achieved in multiple ways. The most effective way is by improving the building envelope. The building envelope is the physical separator between the inner and outer environment of buildings. The best way to improve the building envelope is by increasing the insulation. Thermal insulation of buildings may consist of wall, roof and floor insulation and installation of double pane windows. These adjustments can diminish heat losses through the building's envelope and thereby reduce the annual energy consumption. In Europe, the energy use for heating in the residential sector varies widely between north, central and south regions. An energy use of respectively 150, 70 and 50 kWh/m^2 is caused by climate variances. On average, actual energy savings on space heating in insulated houses varies between 20-40% (Balaras *et al.*, 2000). These savings result from insulation improving actions and show that there is a high potential for reducing energy use in the residential sector.

2.2 European insulation guidelines

European insulation guidelines for newly-built houses are described in the Energy Performance of Building Directive (EPBD). The European Parliament and the council of the European Union composed this document on 16 December 2002, bearing the name: "Directive 2002/91/EC" (European Communities, 2002). This European guideline is an important step in the transition to an energy-efficient residential sector. The main goal of the EPBD is to reduce the global greenhouse gas emissions. The EPBD was implemented in 2003 and forced the EU Member States to implement the agreements into their national legislation. For example, Member States had to redefine their energy requirements in order to be expressed as kWh/m^2. This way, it is possible to compare energy use between all European countries. In summary, national regulations have to follow the concept of the EPBD and have to harmonize it as much as possible.

One important goal of the EPBD is to improve the energy performance of buildings. This can be achieved by an Energy Performance Certification scheme (EPCs). The EPBD obligates all EU Member States to implement this into their national regulations. The EPCs needs to meet the Energy Performance Certification requirements written in article seven of the European Directive (European Communities, 2002). The revision of the EPBD (Directive 2010/31/EU) in 2010 had stricter rules and increased the importance of the EPCs (European Union, 2010). The EPBD also prescribes the EPC to cover the IAQ in the provided certificate, by describing the minimal controlled ventilation.

2.3 EPCs implementation in the Netherlands

The EPCs is implemented differently in EU Member States. In most countries, the system is based on the familiar A-G format seen on household appliances. In the Netherlands, the EPCs was already applied before it became mandatory by the EPBD. Already in 1995, the energy performance (EP) of houses was calculated and minimum values were required by law. These EP values reflected the level of energy efficiency of buildings and the Dutch government referred to them as energy performance coefficient values. EP-coefficient values were tightened every few years by the Dutch legislation. However, since 2003, the tightening needs to measure up to the EPBD guidelines. The revision of the EPBD in 2010 had stricter values and as a result, the maximum EP-coefficient value decreased from 0.8 to 0.6 in 2011. Table 1 shows the decrease of the EP-coefficient value in the Netherlands from the beginning in 1996 until its future prospective in 2021.

Table 1 - Required energy performance coefficient for new residential houses (Praktisch Duurzaam, 2012)

Year	EP-coefficient value
1996	1.4
1998	1.2
2000	1.0
2006	0.8
2011	0.6
2015	0.4
2021	0.0

Table 2 – EP-coefficient value and corresponding energy label for newly-built houses (Lente Akkoord, 2012)

EP-coefficient value	Label
$EP \leq 0.2$	A++++
$< 0.2\ EP \leq 0.4$	A+++
$< 0.4\ EP \leq 0.6$	A++
$< 0.6\ EP \leq 0.8$	A+

2.3.1 Energy label

The Dutch energy certificate is required to be applied to newly-built residential houses since the first of January 2008. The energy certificate consists of a letter from A to G, in which A is very energy-efficient and G not energy-efficient at all (figure 1). In the Netherlands, this certificate is called an energy label. The energy certificate provides insight into the energy performance of buildings and houses. The energy label is assessed by means of EP-coefficient calculations. For newly-built houses the energy label has to be an A+ or higher (till A++++). The required EP-coefficient value for a specific label is determined by law and tightened every couple of years. The correspondence of energy labels and EP-coefficient values for newly-built residential houses can be seen in table 2.

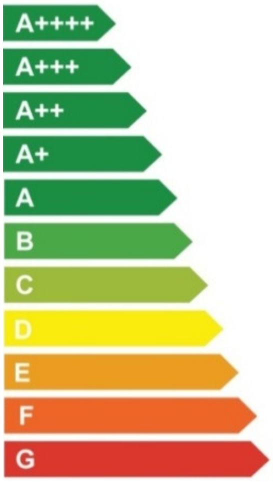

Figure 1 – Dutch energy labels

2.3.2 *Energy performance in buildings*

The energy performance of buildings (Energie Prestatie Gebouwen, EPG) is an overall determination method to determine the energy performance of buildings. The Dutch standardization institute NEN (NEderlandse Norm) composes NEN-standards for the EPG and other methods. The method for EP-coefficient determination is described in the NEN-7120. The standard describes terms, definitions and the method for the determination of the energy performance of buildings. The decrease in mandatory EP-coefficient values is the result of tightening the NEN-norm, which in its place is led by the EPBD. Another important NEN-standard is the NEN-8088-1. This is the standard for ventilation requirements inside houses. A schematic overview of the above-mentioned terms and regulations can be seen in figure 2.

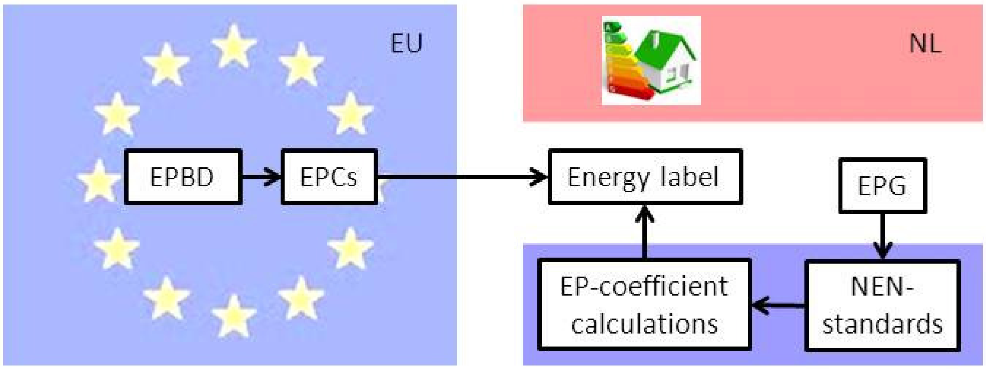

Figure 2 – Schematic overview of the European guidelines and the Dutch legislation

2.3.3 *Competence*

More than a hundred certified companies (for example consultancy companies in construction or real estate agents) with certified experts are able to calculate the EP-coefficient value of buildings in the Netherlands (BPIE, 2010). Since November 2008, an individual exam is required before having the right to issue an energy certificate (Ekerschot van and Heinemans, 2008). An EP-coefficient value calculation for newly-built houses is mandatory before a building permit is provided. Local authorities may check whether this calculation is correct. Before the building receives its actual energy label, the EP-coefficient value and corresponding certificate will be tested in reality.

2.3.4 *Economic point of view*

The purpose of an energy label is to motivate people to improve the insulation in their houses. Householders have to deal with an increasing energy bill due to the increase in energy price. Therefore, energy costs will become a larger part of the housing expenses. Expectations are that banks will become more careful with offering a high mortgage for low-energy label houses.

Some suggest that knowledge from the certificate should be made public. Making this kind of information public can encourage energy performance improvements in the building sector (Dyrbol *et al.*, 2010). It would be helpful if the certificate influences builders and real estate owners to implement energy saving measures and build houses with greater energy efficiency.

3. Mechanical Ventilation with Heat Recovery systems

Highly energy-efficient houses differ from less efficient houses in multiple ways. Before energy efficiency became such an important goal of governmental legislation, houses were poorly insulated. These houses had, and may still have, little cracks and fissures in the building envelope. Energy-efficient houses have become increasingly airtight. These houses are built in a way that will minimize the possibility of little cracks and fissures in the building envelope. This chapter will first discuss the difference between the so-called natural ventilation in older buildings and mechanical ventilation in energy-efficient houses. The working of a mechanical ventilation system with heat recovery will also be explained.

3.1 Ventilation

Little cracks and fissures in the building envelope are actually small ‘gaps’ causing a constant air flow through the house. This air flow, together with air flow through open windows, is known as natural ventilation. Natural ventilation causes enough air flow to adequately refresh the inside air. Nowadays, energy saving is a major item on the agenda of governments worldwide. Since the building sector has such a great saving potential, energy efficiency improvements are inevitable. As a result, the building envelopes are becoming extremely airtight, causing a very low permeability of air. Ventilating houses by opening windows defeats the purpose of tightening the building envelope. An alternative means of providing adequate ventilation was required. With the use of mechanical ventilation (MV) systems, houses could be adequately ventilated. MV systems meet the purpose of saving energy, since they do not use a lot of energy and prevent heat loss to a certain extent. Heat demand for houses using mechanical ventilation was compared with window ventilation in a research of Maier *et al.* (2009). The researchers showed that natural ventilation leads to an uncontrolled air exchange and therefore, a rapidly rising heat consumption. Depending on the weather conditions, slightly opening windows already causes an air exchange rate between 0.8 and 2.5 ACH. The minimum required ventilation rate, according to Maier *et al.* (2009), lies between 0.3 and 0.5 ACH. So, opening windows can be seen as a waste of energy. Ventilation rates above 1.25 ACH causes the heat demand to increase up to 150 kWh/m^{2}y. At this ventilation rate, the total share of heat demand for ventilation increases to almost 70%. Figure 3 shows a graphical display of this phenomenon (Maier *et al.*, 2009).

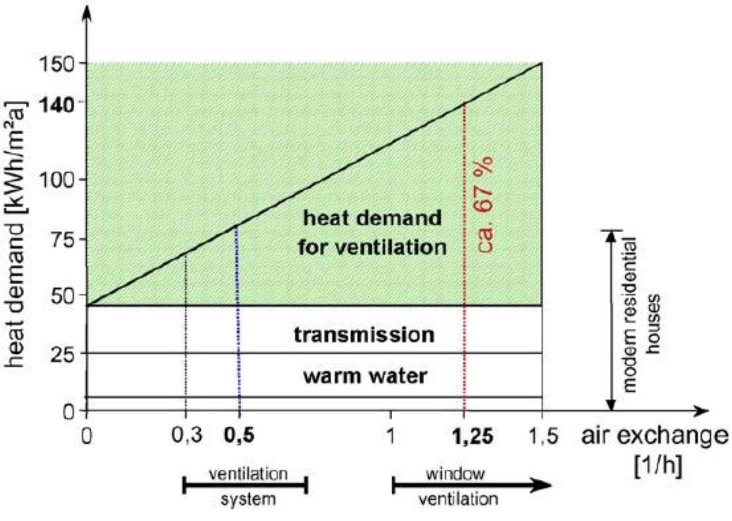

Figure 3 – Heat demand versus air exchange (Maier *et al.*, 2009).

3.2 Mechanical ventilation

In the Dutch building sector, nearly all newly-built houses are equipped with a mechanical ventilation system. The Dutch minimum required ventilation rate for newly-built houses is determined in the Dutch Building Code (Rijksoverheid, 2011). Minimum air supply rates (mechanical or natural) in the living room and bedrooms are set at 0.7 liter/s/m^2. As for a regular house of 80 m^2, this will mean a minimum air change rate of 0.8 ACH. Air exhaust rates (mechanical) in the kitchen, bathroom and toilet need a minimum level of respectively 21, 14 and 7 liter/s. Before municipalities approve of a building permit, plans to reach the acquired ventilation rate need to be worked out in a building plan. In any case, a mechanical ventilation (MV) system is necessary to reach the minimum values. A newly-built dwelling can be equipped with a mechanical exhaust ventilation (MEV) system (with natural supply) or a balanced ventilation system (with mechanical exhaust and supply). Balanced ventilation systems are usually combined with a heat recovery system. In literature, this combination of complete mechanical ventilation and a heat recovery unit is referred to as mechanical ventilation with heat recovery (MVHR). MVHR systems have a significant impact on the calculation of the EP-coefficient value. In theory, this system can reduce energy consumption to a great extent. Therefore, a lot of newly-built dwellings are equipped with MVHR systems.

Working of MVHR systems

When dwellings are equipped with a MVHR system, air is extracted from multiple rooms inside the house via metal air ducts. Fresh air is supplied into other rooms inside the house. Space under the internal doors causes air to flow from one room (with air supply valves) to another room (with air exhaust valves). The MVHR system itself is usually installed in the attic. The heat recovery unit has two separate valves, one to discharge polluted air outside the house and one to supply the house with fresh outside air. The intake air flows through an air filter to protect the system from pollution and to clean the supply air. Before the exhaust air leaves the house, the air flows through the heat recovery unit and heats up the supply air (figure 4). Both air flows do not physically have contact with each other. The cold outside air can be heated up to almost the same temperature as the inside air, resulting in an efficiency rate up to 95% of the system (AGPO FERROLI, 2002).

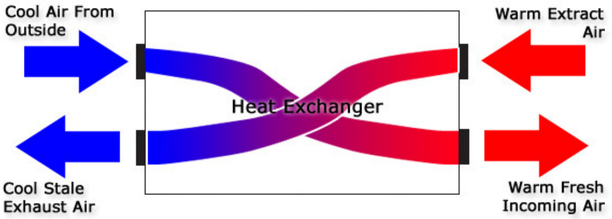

Figure 4 – Working of the heat recovery system.

Figure 5 shows a schematic picture of the working of the system. Incoming fresh and pre-heated air is supplied to the living room and all bedrooms. Through the exhaust valves, stale or moist air is taken away from the kitchen, bathroom and toilet. Most new MVHR systems are also equipped with a bypass. A bypass has been found necessary when the outside air has a lower temperature than the inside air, which can happen during the summer months. Some or all of the exhaust air can be led around the heat exchanger. This way, the bypass gives an opportunity to release the warm inside air without heating up the cooler supply air from outside. The MVHR system has three user-control settings (figure 6), in which 1 is the lowest and 3 the highest.

Residents are advised to keep the power on level 2 for normal use. Level 1 is for when nobody is at home and level 3 needs to be used when residents are using the shower or when they are cooking.

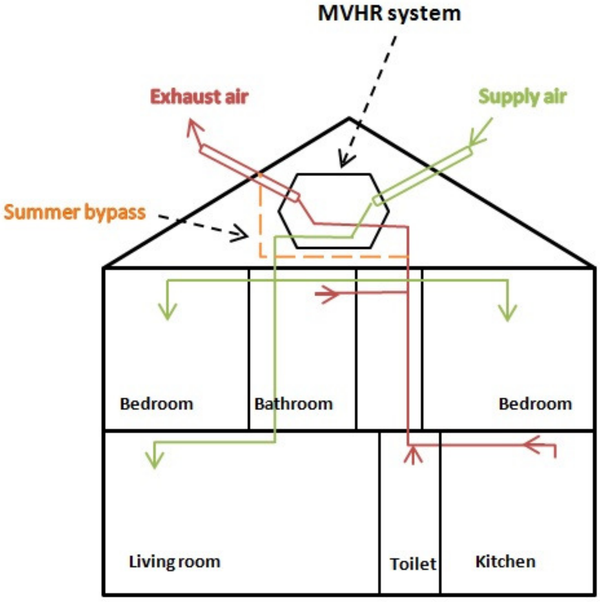

Figure 5 – Schematic picture of the working of the MVHR system

Figure 6 – User-control setting MVHR system

3.3 Working of MVHR systems in highly energy-efficient houses

MVHR systems are widely used in the Netherlands, but only since the past ten years. There is a lot of discussion about the proper working of the ventilation system. Balvers *et al.* (2012) did research on the technical shortcomings of ventilation systems in the Netherlands. They researched the ventilation capacity of MVHR systems in 150 dwellings. The total air supply was insufficient in 48% of the houses and 85% of the houses had at least one room which did not meet the minimum required ventilation rate according to the Dutch Building Code (>0.7 liter/s/m^2). The total exhaust rates did not meet the minimum rate in 55% of the houses (Balvers *et al.*, 2012). The numbers from Balvers *et al.* (2012) reflect the working of the MVHR system in the highest level. However, level 3 is not developed for normal use, but as an extra power option for showering and cooking. Furthermore, research on occupants' behavior showed an improper use of the control switches (96%). It has been found that residents leave the setting on level 1 instead of 2 during the day. Level 2 is only used during cooking or showering instead of level 3. Level 3 is almost never used. This will mean that the actual number of houses with inadequate ventilation could be even higher than found in the research of Balvers *et al.* (2012).

3.3.1 Sound levels

Another problem with the working of MVHR systems is the fact that they produce noise. The engine of the system, which is mostly located in the attic, can produce enough noise to disturb the residents. Therefore, the Dutch Building Code includes a maximum sound level of 30 dB(A) for mechanical ventilation systems since 2012. In previous years, a maximum sound level was not included in the building code at all. At this point, the maximum sound level only applied to newly-built houses. However, in a couple of months it will also apply to existing houses with a MV system. Balvers *et al.* (2012) investigated the sound production of MVHR systems in highly energy-efficient houses completed around the year 2007. The researchers concluded that noise is a big problem in these houses. In 86% of the houses, sound levels were higher than 30 dB(A). The MVHR system setting was set at a level which provided a ventilation rate of at least 0.7 liter/s. If this minimum ventilation rate was not possible, the highest setting possible was used. In a research on the experiences and opinions of residents about the quality of ventilation and their health, 54% of the residents complained that the MV system made too much noise at the highest level (Leidelmeijer *et al.*, 2009). A research of Maier *et al.* (2009) also concluded noise to be a shortcoming in the physical performance of mechanical ventilation systems. In their research, 70% of the residents saw possibilities for improvements in the field of noise production. Researchers suggest that high noise levels could be caused by inadequate installation of the system or by its ductwork. Incorrect placement of the ductwork or sharp bends causes more air resistance, which makes the MV system work harder than necessary thus causing more noise (figure 7). Furthermore, maintenance is also an important aspect of keeping the system under the noise limit. For example, dust accumulation in the pipes is a sound amplifier. Dust can easily be prevented by periodic maintenance by a professional company. However, merely 38% of the residents researched by Jongeneel *et al.* (2011) answered 'yes' to the question if their MV system is maintained regularly.

Designers should pay more attention to sound-proofing the design in order to improve the capacity of the mechanical ventilation system. A silent working apparatus could prevent people to lower the power of the system because of the noise they experience. This way, improving the design may indirectly increase the air quality. Besides noise problems, an inadequate installation or malfunctioning of the MVHR systems also results in other shortcomings, such as drafts and pressures.

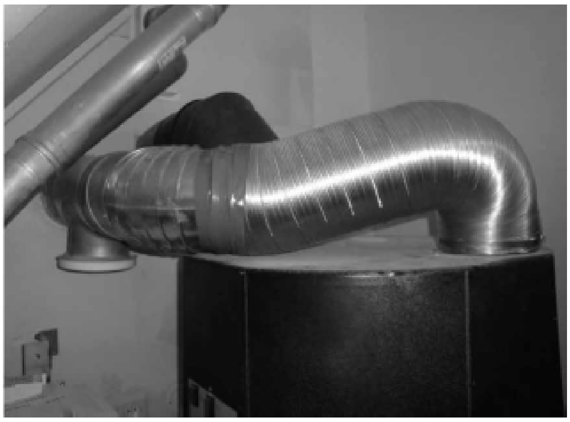

Figure 7 – Sharp bends in the ductwork of MVHR systems

3.3.2 Draft

All buildings experience two types of air leakage, namely direct and indirect leakage. Direct leakage occurs at direct openings to the outdoors. Air enters and exits at the same location, for example, by opening windows or external doors for ventilation. Indirect leakage occurs at different locations. Air enters houses at one location and moves through building cavities. The air leaves the building at a different location. Air always takes the path of the least resistance. If houses have pressure or temperature differences, air will move from high pressure and high temperature to low pressure and low temperature areas. A larger temperature or pressure difference means more air and heat flow. The amount of pressure difference is related to the wind outside. Wind creates a positive pressure on the windward side of the house, which creates a negative pressure on the other side of the house (figure 8). Since air moves from high pressure to low pressure, this will cause an air flow inside the house. The other aspect which causes air flow inside houses is the temperature difference. The stack effect enhances this event. The stack effect is the effect where warmer air rises and pushes out at the top. This creates suction at the bottom of the house, pulling in the cooler air (figure 9). If these air flows become too fast, residents experience this as draft. The stack effect causes these drafts to feel cold, making it even more discomforting. However, the wind and stack effect become smaller if houses are becoming more airtight. So, increasing the airtightness of the building envelope will decrease draft caused by indirect leakage. However, there is also another cause of drafts inside houses, which is increasing because of the airtightness of the building envelope. This type of draft is caused by pressure differences inside the house.

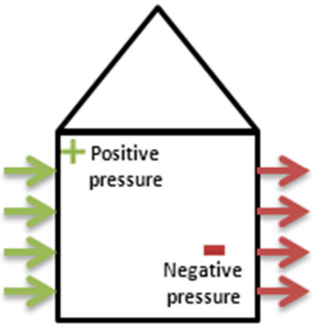

Figure 8 – Wind effect

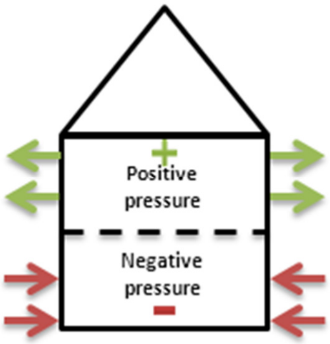

Figure 9 – Stack effect

3.3.3 *Pressures*

Pressure problems in houses seem to increase due to the implementation of MVHR systems. Houses which are equipped with MV systems can have increased pressure differences if the supply and exhaust rates do not match with each other. Incorrectly installed supply and exhaust systems can be the reason for this. Somewhere during the construction of houses installation of MV systems takes place. After completion of the house, there is often no check-up. If residents move into their newly-built house, there should be a control moment to investigate the supply and exhaust rates. Henk Seinen of Seinen Project Development admits that tuning and after-control is really important after delivery of the newly-built house. However, he says, in theory such controls are often not performed by construction installers (Seinen, 2013). Martin van Riezen is a construction installer who also installs MV systems. He indicates that he often sees houses which cope with poorly aligned supply and exhaust valves (Riezen van, 2013). Therefore, tuning and control of the MV system after delivery of the house is very important. Internal doors also have an impact on the working of the system and the air flow rates. Closed doors can prevent supply air from flowing to places where it should be exhausted. This will result in supply rooms with a positive pressure and exhaust rooms with a negative pressure (figure 10). Because of these pressure differences, a discomforting draft will be the result. Furthermore, pressure differences in houses also affect pressure differences across structures. This may cause pollutants to release from structures faster or more than they would do at normal pressures (Seppänen and Fisk, 2004). This happens especially with negative indoor pressures. Negative pressures can cause pollutants from the building envelope to be released inside. Another problem with pressure differences is that high indoor pressures can cause highly humid indoor air to flow into the colder building envelope. Then, the water vapor can condensate, which can cause molds to grow in the building envelope. If exhaust rates would be slightly higher in houses with positive pressures, the change on condensation of water vapor in the building envelope would become smaller (Seppänen and Fisk, 2004).

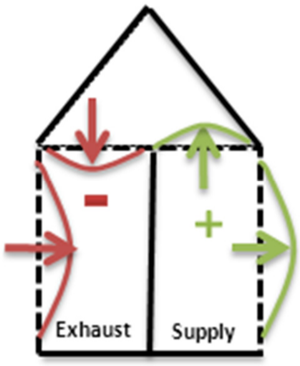

Figure 10 – Closed doors effect

4. Pollutants in the indoor environment

There are a lot of sources for indoor air pollutants. Air pollutants can be divided into two subgroups; chemical and biological pollutants. Potentially hazardous chemical pollutants can be released from emissions of building materials, consumer products, household equipment or combustion. Microbial pollution can also contaminate the indoor environment. Microbes can come from bacteria, fungi and molds growing indoors. This chapter will focus on the buildup of some possible pollutants in the indoor environment.

4.1 Effect on indoor air quality

The earlier mentioned perceived deficiencies decrease human comfort. The importance of human comfort will be discussed in paragraph 5.1: human needs. However, insufficient air supply and exhaust rates also cause a variety of pollutants to build up. Some of these may cause several health problems, especially within energy-efficient houses which are extremely airtight. The residents of these houses, together with insufficient ventilation, experience the effect of living in a plastic bag. The increase of indoor humidity and accumulation of all kinds of emissions occur in highly energy-efficient houses if ventilation rates are too low (figure 11). Previously, air quality research was mostly done on the outside air. Unfortunately, little research was performed on the IAQ. According to the Dutch National Institute for Human Health and Environment (Rijksinstituut voor Volksgezondheid en Milieu, RIVM), people are spending about 70% of their time in their own house (RIVM, 2012). Concentrations of substances are usually even higher indoors compared to the outdoors. Therefore, IAQ research has become more important these days. Fanger (2007) describes IAQ as the extent to which human needs must be met. These needs are met by reaching an IAQ which is not harmful to humans. However, there is only a small list of harmful chemicals and their maximum acceptable concentration in the air. Furthermore, the critical load for indoor air concentration of chemicals consists of a wide range if one looks at the literature. Therefore, determining the IAQ is mostly done by qualifying the air based on the percentage of acceptance. In these type of ratings, researchers use the sensory skills of a selected group of people to measure the air quality. If less than 15%, 20% or 30% of the people complain about the air quality, it can be valued as acceptable (Fanger, 2007). This definition would mean that a high IAQ is associated with a high percentage of people who valued the air as acceptable. But this will also result in a large number of unsatisfied people. The RIVM presented that 65% of the environmental health complaints are about the indoor environment (RIVM, 2012). Mold and humidity are the most frequently mentioned problems.

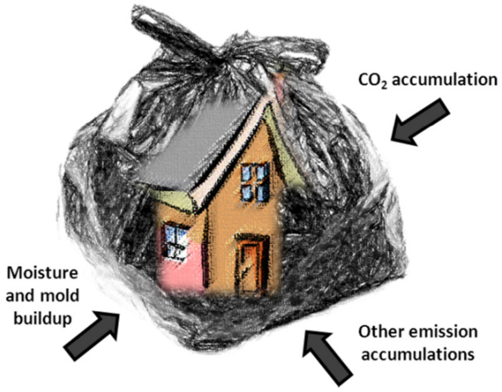

Figure 11 – The effect of living in a plastic bag

4.1.1 Humidity

Moisture is produced during a lot of human activities inside the house. For example, cooking, using the shower and washing up are activities which excrete moisture into the air. Residents also produce a lot of moisture themselves. Respiration and evaporation of water vapor from our skin yields an average of 1.4 liter per person a day (NKC-Advies, 2013). If houses are not ventilated properly, humid air lingers and humidity levels build up. Indoor humidity can condensate inside houses and provide ideal conditions for microbial growth. The level of moisture within houses is the primary factor for molds to grow.

Most of the times, microbes are removed from the indoor environment by ventilation. Besides adequate ventilation, other actions, such as cleaning and gravitational settling, are also causing the microbe concentration to decrease. So, bacteria and fungi do not significantly grow under normal conditions. A lack of moisture is the main reason for this. Most molds grow in humid and warm conditions. Therefore, energy-efficient houses with insufficient ventilation rates and high humidity levels are ideal conditions for molds to grow. Highly energy-efficient houses are depending on the working of their MV systems for ventilation, since their building envelopes became very airtight. If the system does not supply enough fresh air, then perfect humid conditions for molds to grow will develop.

High humidity levels can also affect the building structure, which may increase the release of other dangerous compounds. Research describes that the building material itself contains nutrients necessary for microbial growth. Not all building materials have the same offer in nutrients for fungal growth. It seems that building materials used in highly energy-efficient houses are providing more nutrients, causing an increase in the opportunity for microbes to grow (Nevalainen and Seuri, 2005).

So, it is very important to reduce the indoor air humidity, which can be accomplished by adequate ventilation. Emenius *et al.* (2003) found a correlation between air change rates (ventilation) and absolute indoor humidity. Low ventilation rates are correlated with high absolute humidity levels. The absolute humidity is the difference in humidity between the inner and outer air. A high absolute humidity score means an increased humidity production inside or a low exhaust through ventilation. They also concluded a strong correlation between outdoor and indoor humidity levels during the winter months (Emenius *et al.*, 2003). According to this finding, indoor air humidity is clearly influenced by outdoor humidity. Therefore, adequate ventilation rates are especially important during the winter. Because the outside humidity affects the inside humidity, a good way to study the humidity production inside houses is by using the absolute humidity.

A method for evaluation of indoor mold growth is by bio-aerosol (air) sampling. This method identifies the type of fungal species present and the number of colonies present per each identified species. The unit of measurement is colony forming units (cfu) per volume of air sampled (NYCOSH, 2013). So, <100 cfu/m^3 means less than 100 identified colonies per cubic meter of air sampled. It is important to measure the magnitude of the mold growth since mold accumulation inside houses can cause several health problems, which will be elaborated in chapter 6: modeling the indoor air quality. A commonly used ranking can be seen in table 3. Indoor concentrations of mold growth over 1,000 cfu/m^3 can be regarded as 'high'. Another problem with mold inside houses is that biological and chemical decay products often consist of volatile organic compounds. The detrimental effect of this will be discussed in the following paragraph.

Table 3 – Interpretation of indoor mold concentrations (NYCOSH, 2013).

Indoor concentration	Degree of growth
<250 cfu/m^3	Low/normal mold growth
250-1,000 cfu/ m^3	Moderate mold growth
>1,000 cfu/ m^3	Active mold growth
>5,000 cfu/ m^3	Very active mold growth

4.1.2 VOC

Volatile Organic Compounds (VOCs) are organic substances which are released from several products at room temperature inside houses. As mentioned above, they can be released from the decay of mold. Besides these microbial VOCs, VOCs can also be released from paint and cleaning products, and from building materials, such as insulation materials (Koivula *et al.*, 2005). Is has also been concluded that high humidity causes the increase of the chemical release of formaldehyde from building materials. Indoor air can consist of an enormous variety of VOCs. The INDEX project is an European project funded by the European Commission to establish indoor exposure limits. One of the project's scopes was to identify priorities of indoor air pollutants based on their health risks (Koistinen *et al.*, 2008). The research by Koistinen *et al.* (2008) came up with formaldehyde as the most hazardous polluter in the indoor environment. Formaldehyde has been found the most important sensory irritating compound in the research. Concentrations of 1 µg/m^3 have been considered a chemical concern. However, this is almost the background level in rural areas. This would mean that a small increase of formaldehyde indoors may already cause some problems. The project concluded that mild irritation of the eyes and odor perceptions can be experienced from about 30 µg/m^3. Therefore, they estimated a no-effect level (acute and chronic) to be at 30 µg/m^3. Within the INDEX project, the limit exposure which increases the chance of severe health problems, such as cytotoxic damage to nasal mucosa and upper respiratory tract cancer, has been set at 150 µg/m^3 (Koistinen *et al.*, 2008).

The Dutch National Institute for Human Health prescribes a maximum permissible long-term indoor air concentration of formaldehyde at 10 µg/m^3. Short-term exposures have a maximum permissible indoor air concentration of 120 µg/m^3 (RIVM, 2012). The RIVM also states a target-level of 1 µg/m^3 as the INDEX project did. The target-level is the value of the concentration which reflects a sustainable environmental quality. This standard also takes exposure to other indoor pollutants into account.

A RIVM report by Jongeneel *et al.* (2009) concluded that in 60% of the houses they measured, the formaldehyde concentrations were higher than the maximum permissible long-term indoor air concentration of 10 µg/m^3 (Jongeneel *et al.*, 2009). Theoretically, formaldehyde is present in all houses since it is processed in a lot of building materials. Energy-efficient houses with low ventilation rates may experience a faster buildup of formaldehyde and other VOCs. A buildup of VOCs higher than the health standard, can cause multiple health problems which will be discussed later in chapter 7: human health.

4.1.3 Inhalable dust

Another indoor air polluter inside houses is *inhalable* dust. A common term used for the mixture of solid particles and liquid droplets in the air is particulate matter (PM). In other words, PM is a collective name of dust particles small enough to enter the lungs. Homes can have a variety of particulate pollutants in the inside air. Inside-generated particles are formed by all kinds of normal indoor activities, such as cooking. Furthermore, having pets inside the house or walking across the carpet also cause particles to become airborne. Particulate matter is composed of both coarse and fine particles. Coarse particles (PM10) have an aerodynamic diameter between 2.5 mm and 10 mm. These particles become airborne due to mechanical disruption, evaporation of sprays and suspension of dust. All of these ways are possible within houses. The lifetime of PM10 is from minutes to hours (EPA, 2013). Particulate matter smaller than 2.5 mm, is called fine particles (PM2.5). These particles can become airborne during combustion inside houses, for example by the burning of gas with cooking. The lifetime of PM2.5 is longer, from days to weeks (EPA, 2013). There is no threshold value for PM concentrations indoors which cause health effects. However, knowledge from outside PM concentrations can be used to predict possible health effects from PM accumulation inside houses. The annual mean upper limit for PM concentrations outside has been set at 40 $\mu g/m^3$ (RIVM, 2012).

The most common sources of dust inside houses are cooking and vacuum cleaning. Cigarette smoke and chimneys are the largest producers of dust inside the house, but these producers are becoming rarer. Still, little is known about the health effects of dust accumulation inside houses. Scientists expect the health effects to be the same as for outside dust concentration. However, the substance composition may be different.

4.1.4 CO2

Carbon dioxide (CO_2) is released from the process of burning wood, oil and gas, causing global levels to rise. CO_2 is also released by respiration of humans. This is called metabolic CO_2 release. The increase of metabolic CO_2 release is not part of the global rise in CO_2 levels. However, airtight spaces can reach high CO_2-concentrations, depending on the number of residents and the time they spend inside.

The limit value for CO_2 inside houses is set at 1200 ppm (Rijksoverheid, 2011). The Dutch Building code states that a CO_2-concentration which is too high conflicts with the duty of care, written in the Housing Act. If the mean concentration of CO_2 is higher than 1200 ppm, health problems may occur. However, concentrations above 1000 ppm already cause headache and drowsiness. CO_2-concentrations between 800-1000 ppm can cause a perception of musty air. The establishment of the limit value was accomplished through subjectively measuring air quality by using an acceptable percentage of annoyed people (Fanger, 2007).

National studies show that some houses in the Netherlands cope with a mean CO_2-concentration higher than the limit value. A study from the Dutch municipal or communal health services (gemeentelijke of gemeenschappelijke gezondheidsdienst, GGD) concluded that 6% of the houses they researched had a CO_2-concentration higher than 1200 ppm (Lucht *et al.*, 1995). A more recent national study of the RIVM showed a far higher number of houses with CO_2-concentrations higher than the limit value. They concluded that about 47-59% of the houses have higher CO_2-concentrations in at least one room of the house (Jongeneel *et al.*, 2009).

5. The effect of occupant behavior on ventilation

Installing mechanical ventilation systems and providing houses with perfect indoor air qualities works theoretically. However, in practice houses are occupied by human beings. Research on the behavior of residents indicates that humans adjust household systems and appliances in order to establish a comfortable indoor environment. So, to answer the question what the effect of human behavior has on the working of mechanical ventilation systems, we need to understand the user responses to highly energy-efficient houses. An important factor in human responses is the distribution of human needs.

5.1 Human needs

The distribution of human needs has been described in an article from Maslow, explaining the theory of human motivation (Maslow, 1943). A graphical display of his theory has been called Maslow's hierarchy and can be seen in figure 12. The figure shows five human needs. People have to fulfill several needs for survival before they can work on fulfilling the next need. The first human need is the lowest layer of the pyramid, which are physiological needs. This need includes food, sleep and human health. If people are successful in fulfilling this need, the next layer can become their goal. The second layer is the need for safety. This need includes shelter and protection against danger. The third layer is social needs, the need for belonging. Then follows the need for esteem, both the need for self-esteem and esteem of others. At last, the need for self-actualization is written in the top layer, which means the need of achieving individual potential.

Professor Stevenson translated the Maslow's hierarchy pyramid into a pyramid based on a housing situation. Figure 13 shows her interpretation (Stevenson, 2011). Comfort has been written in the lowest layer, representing physiological needs. So, according to this theory, in a housing situation, the most important need is comfort. The second most important need is safety in the house. Safety in the house can be seen as IAQ. Pollutants deteriorate the IAQ and therefore decrease the safety in houses. Comfort on the other hand, is more a reflection of the perceived IAQ. It reflects the way in which residents feel comfortable in their house instead of the real quality of the air.

Figure 12 – Maslow's hierarchy (Maslow, 1943)

Figure 13 – Stevenson's hierarchy (Stevenson, 2011)

Comfort

The difficulty with comfort is the working of the human sensory track. The sensory perception of pollutants is not necessarily linked to their toxicity (Seppänen and Fisk, 2004). For example, CO_2 is not sensed at all. Therefore, perceived IAQ is not always representative of the real IAQ. Information from questionnaires about the IAQ can therefore be doubted. Humans use different environmental signals to judge the IAQ and evaluate the total perceived air quality. Comfort and discomfort are based on other perceptions than the perception of safety in the house. It is possible that certain indoor air pollutants that are harmful to humans are not sensed as safety threatening. Inside temperatures which are too high or too low can be perceived as discomfort, without being harmful to human health. Furthermore, the perception of comfort is influenced by more complex psychological factors. The difference between perception of the indoor air quality and actual air pollutants creates a gap. This makes it hard to achieve a safe indoor environment and offer houses with a good perceived indoor environment based on human comfort. Creating a save indoor environment without any harmful pollutants should be of most importance (from a human health protection viewpoint). However, it often differs from the perceived comfort which is an important aspect of the overall system, since it influences human behavior to a large extent. As has been shown in the translated version of the Maslow's hierarchy onto a housing situation, comfort is the first human need to fulfill. This dilemma results in interesting study subjects.

5.2 Occupant behavior

Mechanical ventilation systems affect humans in multiple ways. Seppänen and Fisk (2004) discussed a figure reflecting the different pathways (figure 14). Indoor air quality and climate, ventilation rates and the ventilation system all cause humans to respond. Sometimes even health problems occur. The effect of mechanical ventilation systems on human health will be described in chapter 7: human health. In this chapter we will focus on human responses that interact with the operation of mechanical ventilation systems in highly energy-efficient houses.

MVHR systems provide the option to change the power-settings. As described in paragraph 3.2: mechanical ventilation, MVHR systems usually have 3 levels. Improper use of the control switches is a common shortcoming related to residents' behavior. Balvers *et al.* (2012) concluded that in 96% of the dwellings the control switch is mostly used in a lower setting than recommended for proper ventilation. Research on the behavior of occupants who are changing the settings of the ventilation system is an ongoing study. Guerra Santin (2012) described the relationship between occupant behavior, building characteristics and energy consumption in energy-efficient dwellings. The author stated that behaviors that influence energy consumption may be affected or determined by several factors, referred to as determinants of behavior. Since 'use of the ventilation system' is also one of those behaviors, it is worth looking at these determinants. One of the determinants is the building characteristics. Building characteristics may affect human behavior through the interaction with the user and the building's system. This could be referred to as user-friendliness of the system.

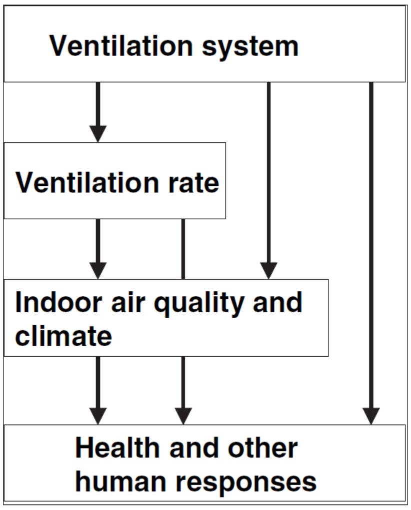

Figure 14 – Ventilation affects human responses through several pathways (Seppänen and Fisk, 2004)

The motivation of occupants' behavior to change the ventilation system settings and other building control systems is still unknown. Both internal and external causes influence occupant behavior. Personal background, attitudes and preferences are examples of internal causes which affect human behavior. Examples of external factors are outside air temperature and wind speed. Factors that cause residents to change the MV system are, for example, noise and drafts caused by the MV system. Noise levels are 60% of the time the reason for people to lower or turn off the MV system (Jongeneel *et al.*, 2011).

Since comfort has been found to be a major factor of human behavior, restoring comfort seems very logical. A theoretical basis of this concept is the so-called adaptive approach. This approach explains that people react in ways which restore their comfort. Different factors, for example draft, humidity levels, temperature and noise are part of this reaction to restore comfort. A house in which the MVHR system is not working properly can cause these factors to develop.

Research showed that occupants are more comfortable and suffer less from sick building syndrome symptoms if they are able to control the indoor environment. It seems important that occupants are able to adapt their indoor environment in an intuitive way. The need for a high degree of control opportunities and a freedom of choice is something which should be taken into account when designing low-energy houses. Especially since most of these houses are designed to control the indoor environment by themselves, so the houses require few occupant interactions. For example, Henk Seinen Project Development provides houses with computerized ventilation systems. These houses own sensor systems which measure the quality of the inside air and regulate the supply rates of the MV system.

However, discomfort through a lack of control could probably also be prevented by increasing knowledge. For example, if the MV system suddenly increases speed without any reason (in the residents' perspective) annoyance could rise. The human response in this controlled system could be to turn the system off, whereas knowledge could make residents understand the purpose of it and prevent the rise of annoyance. Therefore, it is important to clarify the function of a proper working MVHR system is. Unfortunately, according to research, merely 53% of the users received oral instructions about the working of the installed ventilation system (Jongeneel *et al.*, 2011).

Window opening behavior

Another aspect which strongly influences the energy consumption in households is window opening behavior. As described in chapter 3, window ventilation can cause a rapid increase in air changes. Hereby, the time of opening windows is important.

Window ventilation is an easy and fast way to provide houses with a lot fresh air. In certain situations, window ventilation can be very helpful in providing houses with healthy indoor air. For example, cooking, cleaning, showering and the increase of the number of residents in houses due to a party or meeting can cause the release of multiple pollutants to increase. Also, less common events, such as painting or special cleanings, increase the need for the supply of more fresh air. If MV systems do not provide houses with the minimal needed supply rates, window ventilation can be necessary to obtain more healthy indoor environments in normal living situations. This can help the poorly working MV systems to sustain houses with healthy indoor air.

The underlying reason of window opening behavior in highly energy-efficient houses is an important aspect. Both in summer and winter, one of the main reasons for residents to open their windows seems to be the desire for 'fresh' air and in some cases to cool the room faster than with using the thermostat (Roetzel *et al.*, 2010). The perception of the IAQ is an important factor in this desire. Window opening behavior is significantly lower during the winter than during the summer. The main reasons for this are the outside temperature and the speed at which the inside air cools down when opening windows. A decrease of window ventilation is due to a decrease of the total time windows are opened, not to the frequency per se. Fabi *et al.* (2012) concluded that outdoor temperature is the most important factor to determine window opening (and heating) behavior. Less window ventilation could result in lower indoor air qualities during the winter. Nicol (2001) also researched the influence of the outdoor temperature on window opening behavior and this is presented in figure 15. This figure shows the degree to which the decrease in temperature causes a decrease in window opening behavior. Other important factors which also result in less window opening behaviors are burglary risk (36%) and noise nuisance from outside (11%) (Jongeneel *et al.*, 2011).

Besides the already mentioned physical environmental aspects that motivate occupant behavior, there is also the aspect of education and knowledge. Anderson *et al.* (2009) showed this in their article about occupants' behavior with regard to the indoor environment. According to the article, some people ventilate their house by opening the windows for 10 minutes at the same time every day. This behavior was regardless of the environmental conditions inside the house. Health concerns about poor indoor environment caused this routine behavior.

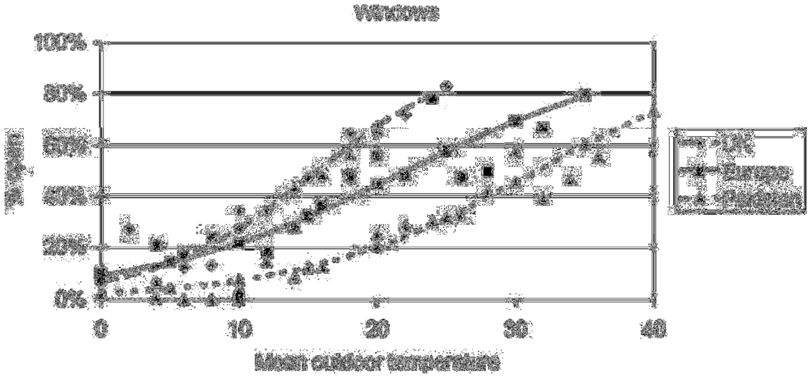

Figure 15 – proportion of windows open at different outdoor temperatures.

6. Modeling the indoor air quality

The IAQ will be modeled by using the indoor air CO_2-concentration as indicator for the IAQ. The establishment of the indoor environment consists of multiple complex relationships. Therefore, the simulation program STELLA, which is a program to model dynamic systems, has been chosen to clarify the underlying relationships in this thesis.

6.1 Carbon dioxide as indicator for ventilation

Research on inside air quality often uses CO_2 as a tracer gas. CO_2 can act as an indicator of ventilation efficiency. Inside CO_2-concentrations higher than the outdoor value can reflect the rate of ventilation inside houses. It shows if the relevant air supply rates are sufficient to dilute air contaminants. Therefore, ventilation guidelines use CO_2-concentrations as a value of ventilation. The IAQ is the most relevant when people are inside the house. Therefore, it is important to work with standard values for CO_2. This can easily be done, because people have stable CO_2 exhalation values which are also easily measured and modeled. The relationship between CO_2-concentrations and ventilation flow per person apply if it meets a couple of basic rules (Duijm, 2006). First, there needs to be a constant production of CO_2. The rate at which CO_2 increases depends on the physical activity of the residents. Guidelines are based on an average person with a low level of activity, so no labor or sports activities. Secondly, there must be a constant rate of ventilation. Ventilation systems can provide a constant ventilation flow, but unintended airflows caused by little cracks and fissures in the building envelope may influence this. Lastly, the air must be properly mixed in the house. To create well-mixed houses, there needs to be some space between the doors and the floor inside houses. A balanced concentration of CO_2 throughout the house can take a while to be reached. If the equilibrium has been reached, it can be disrupted very easily. Opening windows or internal doors influences this balance. CO_2-concentration levels reflect the degree of ventilation, attempting to show the extent to which the ventilation flow is sufficient or insufficient for air pollutants. CO_2 itself does not cause human health problems. The parallel increase of other pollutants (or the lack of oxygen) causes the symptoms. Indoor CO_2-concentrations correlate with the chance of unwanted effects at a certain ventilation rate. Air pollutants enter the human body by the respiratory track, so especially the probability of developing airway infections increases with the rise of CO_2-levels inside houses.

Throughout the western world, different classification standards are used to qualify a healthy indoor air. The maximum indoor CO_2-concentrations are often listed in the national ventilation standard. The Dutch national standard institute NEN presents ventilation guidelines which prescribe a maximum value of 1200 ppm, but also uses four qualification levels. These categories (IDA1-IDA4) are reflecting high, medium, moderate and low IAQ standards. The Dutch classification is not public, but the English classification standard is the same and public. In the UK, designers of low-energy sustainable buildings use this standard which is presented in the "CISBE Guide A: environmental design" (table 4). These standards are coupled with the corresponding ventilation range (L/s/person). Each group has its corresponding maximum rise in CO_2-concentrations, resulting in a total indoor value between 700-1600 ppm (table 5).

Table 4 – Ventilation and indoor air quality classification (UK)

Classification	Indoor air quality standard	Ventilation range / (L/s/person)	Default value / (L/s/person)
IDA1	High	>15	20
IDA2	Medium	10-15	12.5
IDA3	Moderate	6-10	8
IDA4	Low	<6	5

Table 5 – Maximum CO_2-concentrations associated with indoor air quality standards (UK)

Classification	Rise in indoor CO_2 concentration / ppm	Default value /ppm	Range in outdoor concentration / ppm	Total indoor value* / ppm
IDA1	<400	350	350-400	700-750
IDA2	400-600	500	350-400	850-900
IDA3	600-1000	800	350-400	1150-1200
IDA4	>1000	1200	350-400	1550-1600

** i.e. default value of the concentration rise plus outdoor value*

Indoor CO_2-levels are also dependent on the outdoor air CO_2-levels. The CISBE Guide A uses a range of 350-400 ppm for the outdoor CO_2-concentrations. However, this value varies in literature. For example, Duijm (2006) describes that these background levels can vary between 350-550 ppm, with an average of 470 ppm. (Duijm, 2006). Outside CO_2-levels have been found highest alongside busy roads and in big cities. Since background levels are higher in these places, houses should be better ventilated compared to smaller cities or houses at the countryside.

The ventilation rate is based on the amount of air changes in one hour. The number of air changes per hour will decrease the CO_2-concentration as well as the concentration of other substances. Multiplying this ventilation rate with the total content of the house in m^3, results in the air flow in m^3/h.

6.2 The basic model

The basic model (figure 16) represents a house of 80 m^2, which is the average floor area of a residence in the Netherlands. The floor area can be easily changed in the model by using the slider input device 'Floor_area'. Assuming that the average ceiling is located at a height of 2.5 meters, the modeled house has a volume of 200 m^3. This value has been calculated in the converter 'Volume_house'. The airtightness of houses can differ a lot, dependent on the way they are built. In the model, the slider input device 'ACH_envelope_leakage' can be used to change the envelope leakage in ACH. Controlled natural ventilation by the means of window ventilation can be put in the model by using the converter 'Window_m3hour'. This value will indicate the air flow in m^3 per hour. The actual airflows used in this converter will be discussed later on.

In the model, the CO_2-concentrations are modeled in grams per m^3. Therefore, all CO_2-concentrations are converted to grams per m^3. Accumulated concentrations of CO_2 from human exhalation are converted from liters CO_2 to grams per m^3. Outside air CO_2-concentrations are transformed from parts per million (ppm) to grams per m^3. However, the converter 'ppm_outside_air' has been kept constant in the model. This way, it will be possible to easily vary this value, as the outside air CO_2-concentration also varies from place to place.

The reservoir 'CO2_house', with a certain amount of grams CO_2, has been converted back to ppm to present the outcome in a better way. This has been done in the converter 'ppm_in_house', which is also the source of all results presented later on.

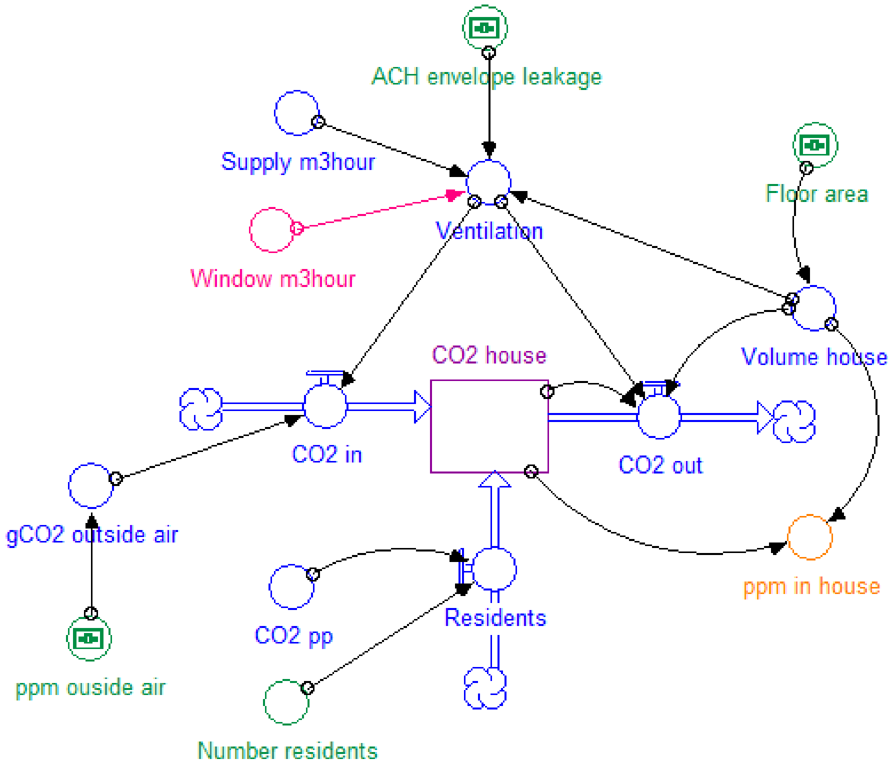

Figure 16 – Stella basic model

Calculations

The amount of CO_2 in grams has been calculated as follows: humans breathe on average 0.5 liters of air with every breath. The average frequency of breathing per minute is 16 times. Human expiration consists of 4-5% of CO_2. In my model I will use the value of 5%. On an hourly basis, this means an increase in CO_2 of 0.5*16*0.05*60=24 l/h. Because the model calculates CO_2 in grams, instead of liters, it needs to be converted. To do so, the density of CO_2 as a gas is needed. CO_2 weighs 1.986 g/L at normal conditions, which means at a temperature of 273 K (0 °C) and 1 atmosphere (101325 Pascal). Houses usually have a temperature around 20 °C (293 K). Converting the density (or pressure) to the required temperature can be done by using the following equation: $\rho_{(p,T)}=(p/p_n)*(T_n/T)*\rho_{(n)}$ in which;

- $\rho_{(p,T)}$ = *density in g/dm³ at required pressure and temperature*
- $\rho_{(n)}$ = *density at normal conditions (1.986 g/dm³)*
- p = *required pressure*
- p_n = *pressure at normal conditions (101325 Pa)*
- T = *required temperature*
- T_n = *temperature at normal conditions (273 K)*

Using this formula, the density of CO_2 is calculated to be: (273/293*1.986)=1.850 g/dm^3 (or g/L) at 20 °C.

Knowing the density makes it possible to calculate the molar volume of CO_2. This can be calculated by using the following equation: **$V_m=M/\rho$** in which;

- *V_m = molar volume (L/mol)*
- *M = molar mass (g/mol)*
- *ρ = mass density (g/L)*

The molar mass of CO_2 is 44.01 gram. The formula gives a molar volume of: 44.01/1.850=23.789 L/mol.

Another way to calculate V_m is by assuming that CO_2 acts like an ideal gas. Then, the ideal gas law can be used to calculate the molar volume of CO_2 by using an equation derived from the ideal gas equation: **$V_m= RT/P$** in which;

- *R = 8.3144621 J mol^{-1} K^{-1}*
- *T = required temperature*
- *P = pressure (1 atm = 101.325 kPa)*

Using this formula, a molar volume was obtained of: 8.3144621*293/101.325=24.043 L/mol.

For the next calculations, a rounded molar volume of 24 L/mol will be used. Since humans produce 24 liters of CO_2 per hour, the number of produced moles CO_2 is one. One mole of CO_2 equals 44.01 grams. So the converter 'CO2_pp' in Stella has been set at 44.

To calculate the amount of CO_2 entering the house by ventilation (and through walls), the concentration of CO_2 in the outside air is needed. This concentration is known in parts per million (ppm) and has a value of 390 ppm in the atmosphere at sea level. However, the concentration can rise up to values of 550 ppm in the streets of big cities. In the model, the CO_2-concentration of the outside air can vary as well, depending on the chosen location of the modeled houses. The converter 'ppm_outside_air' will be set at 400 ppm, if not stated otherwise. Because the model calculates CO_2 in grams, the ppm value had to be converted to grams of CO_2 per m^3. Therefore, we need to know how many moles fit in a cubic meter (m^3). Since 1000 liter is equal to 1 m^3, there are 1000/24=41.667 moles of gas needed to fill 1 m^3. Multiplying this value with the mass of one mole gives the total mass of 1 m^3 CO_2, which is 41.667*44.01=1833.8 gram. However, a cubic meter of air is not completely filled with CO_2. Therefore, the mass has to be multiplied with the concentration of CO_2 in the air. For example, with 400 ppm it has to be multiplied by (400/1000000). This gives an amount of 1833.8*400/1000000=0.73 gCO_2/m^3. This formula has been given to the converter 'CO2_outside_air'.

Window ventilation calculation

There are three different ways to ventilate houses. The most effective way to ventilate a room quick and with the lowest energy losses is by transfer ventilation (figure 17-A). Transfer ventilation needs the opening of windows opposite to each other. This way, the air refreshes itself very fast. The amount of refreshment with each m^2 of area has been described in a research of the National Center of Medical Environmental Sciences (LCM, Landelijk Centrum Medische Milieukunde). According to their calculation, each m^2 ventilation opening results in a ventilation rate of 1 m^3/s for transfer ventilation (Habets *et al.*, 2008).

When there is no transfer ventilation, the ventilation rate is far lower. Occasional ventilation results in the need of 5 m^2 of ventilation area for 1 m^3/s of ventilation speed. Occasional ventilation usually happens by opening one window somewhere in the room for a certain time (figure 17-B).

The last way of ventilation is more common in highly energy-efficient houses. This ventilation is called gap ventilation. With gap ventilation windows are only slightly opened, usually at the top using hinged windows (figure 17-C). The problem with this type of ventilation is that it barely refreshes the room because of the small opening to the outside air. Therefore, residents leave the window open for a long time. If windows are opened for a long time during the winter months, the windows and window frames cool down a lot. Because of this cooling down, the risk of condensation of water is a lot higher.

The model will use gap ventilation and occasional ventilation as window ventilation opportunities. 'W1' will reflect a slightly opened (10 cm) window with a width of one meter (gap ventilation). Option W1 will create a supply rate of 72 m^3/h (calculation: 1*3600/5*1/10). 'W4' will reflect a medium opened (40 cm) window with also a width of one meter (occasional ventilation). Option W4 will create a supply rate which is four times more than that of W1, which is 288 m^3/h.

The advantage of window ventilation is that it creates a temporally increase of the airflow in houses. This increase in airflow can decrease pollutant concentrations in the inside air, resulting in a better air quality. However, window ventilation causes much more energy loss (see also paragraph 3.1: ventilation). There is a risk of excessive 'over-ventilation' and the supply air needs to be heated inside, which is not the case with supply air of the MVHR system.

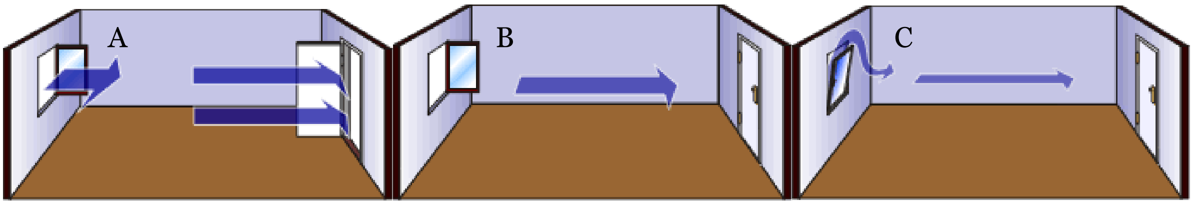

Figure 17 – Window ventilation shown as A) transfer ventilation, B) occasional ventilation and C) gap ventilation.

6.3 Scenarios

Scenario 1: Residential influences on air supply rates by MV system power settings
The Dutch Building code prescribes a certain amount of minimal air supply (and exhaust) rates in houses. Literature research states that the residential sector almost never meets these minimal supply rates. Actual supply rates from a recent large scale experimental study in newly-built houses are used in this scenario (Balvers *et al.*, 2012). The research presented mean air supply rates of the three MVHR systems levels, which were discussed in paragraph 3.2: mechanical ventilation. These three power levels will be referred to as MV1, MV2 and MV3. Based on literature about human behavior and mechanical ventilation systems, a fourth comparison was made: residents who decided to turn off their MV system, referred to as MV0. These four power levels of the MV system will be compared with the theoretical minimal supply rate from the Building Code (Rijksoverheid, 2011).
Scenario 1a will show the effect of the mentioned four air supply rates with an envelope leakage of 0.5 ACH. This number of air changes is common in houses built in the period between 2006 and 2008. From a future perspective, highly energy-efficient houses will become more airtight. Therefore, scenario 1b will look at an envelope leakage of 0.2 ACH. This value represents the maximum ACH for the passive house standard, which lies close to that of energy-neutral houses.

Scenario 2: Residential influences on air supply rates by window ventilation
Even within energy-efficient houses with MV systems it can still be necessary to provide them with an additional supply of fresh air. Window ventilation is an often used way to provide houses with additional air supplies. As discussed in chapter 5, window opening behavior differs a lot between residents. A constant airflow from open windows can decrease the CO_2-concentrations inside houses. However, there is no consensus about the necessary airflow in highly energy-efficient houses. Opening windows too wide or for too long could waste valuable energy. If there is more consensus about the ideal air supply from windows, more energy can be saved. This scenario will compare energy-efficient houses with the passive house standard envelope leakage of 0.2 ACH. The houses are equipped with a MV system with optional settings 3, 2, 1 and off. Each MV system setting has two lines after 12 hours, a solid line and a dotted line. The solid line represents opening one hanged window for 10 cm, resulting in an airflow of 72 m^3/h (W1). The dotted line represents in window openings of in total 40 cm, resulting in an airflow of 288 m^3/h (W4).

Scenario 3: Residential influences on CO_2-concentration rates by increasing the amount of residents
This scenario represents an anniversary or other event where a lot of people gather inside the house. Residents can decide to set their MV system at level 3, 2, 1 or off. Turning the system off can be decided because of noise complaints or draft and pressure experiences. Meetings and anniversary days are common events with a short (couple of hours) increase of people inside houses. This scenario will reflect the degree of increase in CO_2-concentrations when a large number of people are inside the house. After 12 hours, eight more persons enter the house in this scenario. The total number of residents has therefore become twelve. Theoretically, the ventilation rate should be higher in these situations. It has been advised to switch the MV system to level 3. However, in a lot of cases this behavioral change does not happen. The difference between the possible settings of the system will be plotted against each other.

6.4 Results

Scenario 1: Residential influences on air supply rates by MV system power settings

According to the Dutch Building Code, the minimum air supply needs to be 0.7 l/s/m^2 which is 201.6 m^3/h for a surface area of 80 m^2. This value is exactly the value found in the BBA study with the MV system at level 3 (MV3). Mean air supply rates for level 2 and 1 are respectively 129.6 m^3/h and 72 m^3/h.

Figure 18 shows the results of these air supply rates in scenario 1a with an envelope leakage of 0.5 ACH. The minimal air supply of 201.6 m^3/h results in a CO_2-concentration of 720 ppm. The MV system settings 2 and 1 result in respectively 820 ppm and 960 ppm. Turning off the MV system (MV0) results in a rapid increase up to 1360 ppm. All three MV system settings lie under the health risk boundary of 1200 ppm. However, turning off the MV system shows a significant increase in ppm values. Besides the possibility of headache and drowsiness for the residents, there is also a large risk of buildup of all other pollutants inside homes. Figure 19 shows the same pattern but with higher CO_2-concentrations. This graph represents scenario 1b in which a house is modeled with an airtighter building envelope. An envelope leakage of 0.2 ACH results in a CO_2-concentration of 800 ppm, 960 ppm and 1260 ppm for MV system settings 3, 2 and 1 respectively. In this scenario, MV system setting 1 is not sufficient anymore in providing a health CO_2-concentration (<1200 ppm). Turning off the MV system results in very high CO_2-concentrations, as they increase up to 2780 ppm.

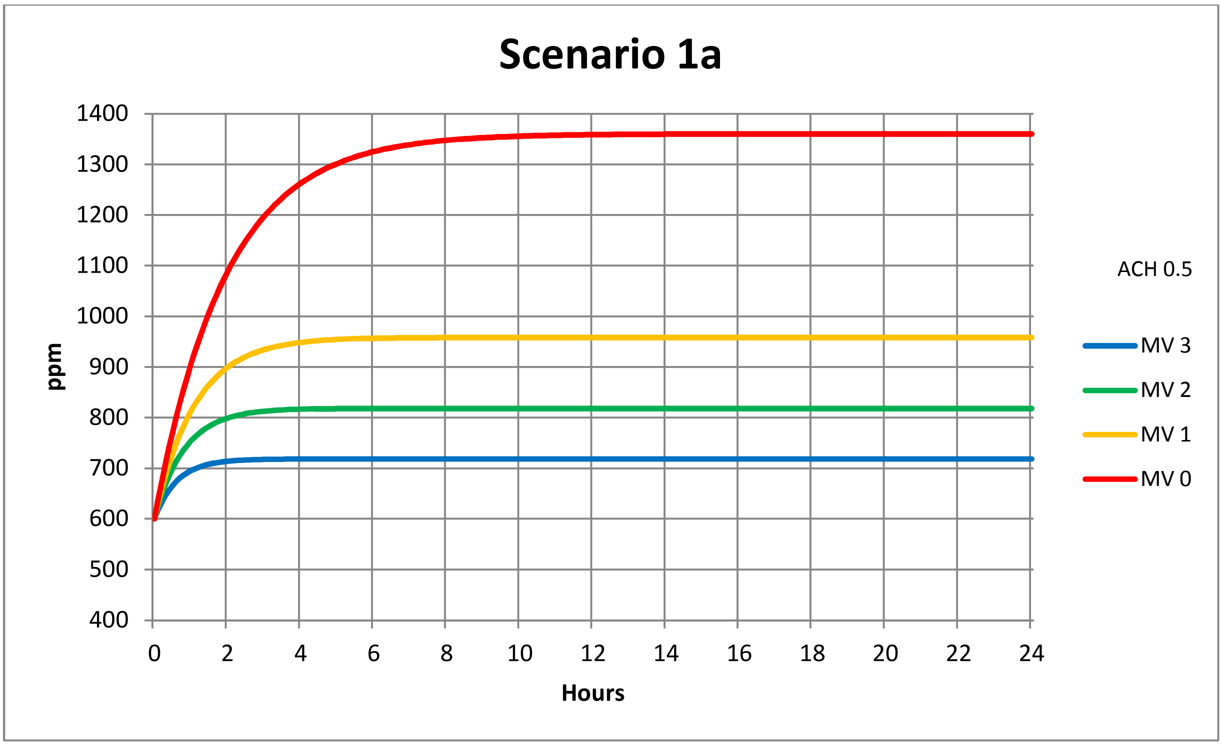

Figure 18 – CO_2-concentration with air supply rates for MV system control settings 3, 2, 1 and off with an envelope leakage of 0.5 ACH.

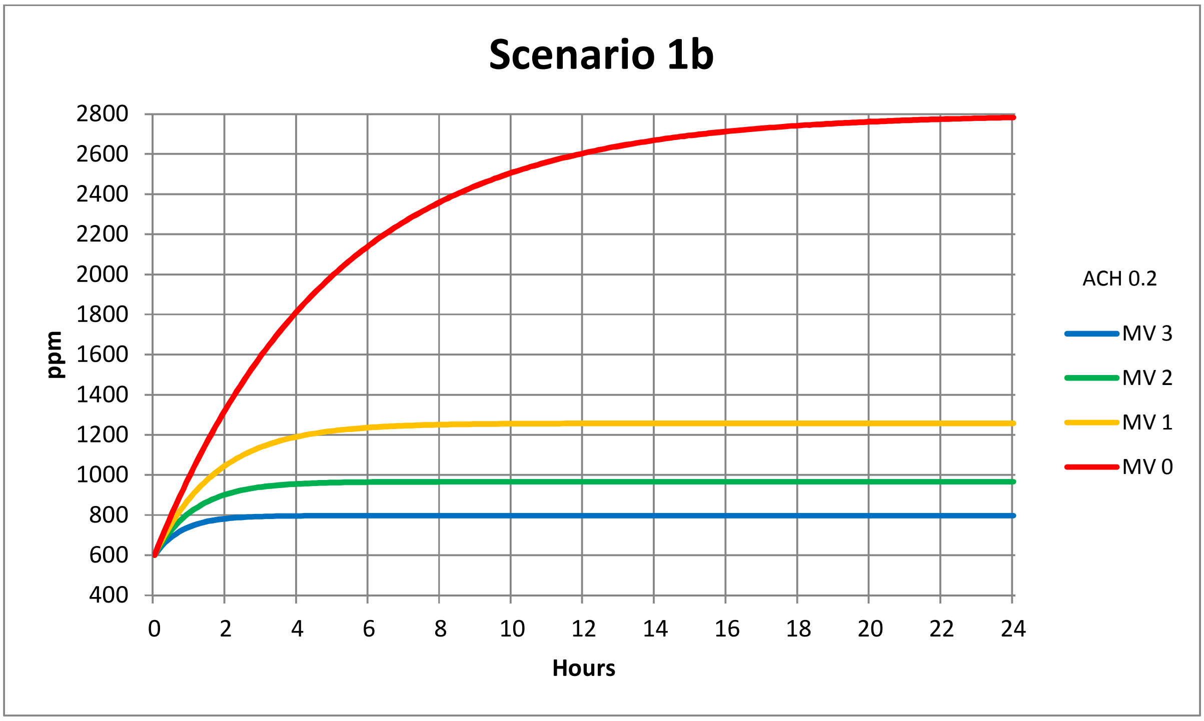

Figure 19 – CO_2-concentration with air supply rates for MV system control settings 3, 2, 1 and off with an envelope leakage of 0.2 ACH.

Scenario 2: Residential influences on air supply rates by window ventilation

Opening a window 10 cm (W1) helps decrease the CO_2-concentration. It decreases the CO_2 ppm concentration from 800 to 700 with the MV system setting at 3 (figure 20). Figure 20 shows the impact of window opening on the air refreshment. If the MV supply is lower, the impact from the same size of window ventilation (W1 and W4) is higher. This can be seen in the decrease from 2600 ppm to 1260 ppm (W1) with the MV system setting at off (MV0). However, this large decrease still results in a CO_2-concentration above the standard for a healthy indoor environment. Furthermore, the necessary time to establish the new concentration of 1260 ppm is about eight to ten hours.

Lots of people leave their MV system setting at 1 during the day, mostly because of the noise. This scenario shows the importance of opening a window. Without window ventilation, ppm concentrations would be too high (>1200 ppm). With window ventilation, these ppm values decreased to less than 1000 ppm.

The effect of window ventilation can be compared to the effect of ventilation of the MV system. In my model, which is based on the mean ventilation rates of window ventilation, power level MV1 has the same effect as opening one window for 10 cm. However, in practice the effect of opening a window strongly depends on the wind speed. Opening a window can also be regarded as increasing the power level with one level.

Window ventilation W4 results a strong decrease of the CO_2 ppm values at all MV power levels. Within two to three hours, CO_2-concentrations are decreased to 700 ppm or less. So, it even meets the advised maximum CO_2-concentration as presented by the literature (<700 ppm). Though, opening windows with a total width of 40 cm for more than 2 hours is not a very common behavior of residents.

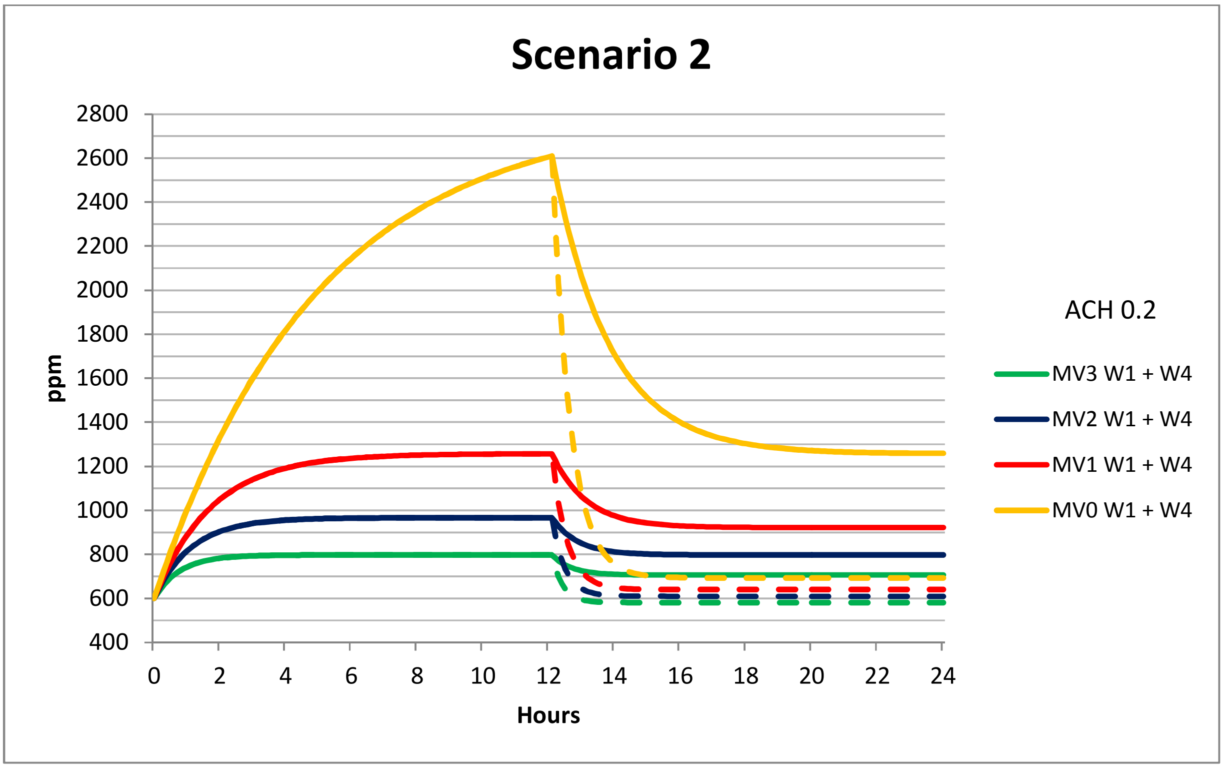

Figure 20 – CO_2-concentration with air supply rates for MV system control settings 3, 2, 1 and off with an envelope leakage of 0.2 ACH and window ventilation 10 cm (w1) and 40 cm (w4).

Scenario 3: Residential influences on CO_2-concentration rates by increasing the amount of residents

Within this scenario, the model shows large increases in CO_2-concentrations. As can be seen in figure 21, the CO_2-concentration rises up to 1600 ppm, even with the MV system power level at 3. These high CO_2 values are unhealthy for residents. People can start to experience headaches and drowsiness. Looking at the other possible settings of the MV systems makes it even worse. MV2 results in an increase up to 2100 ppm and MV1 even reaches 3000 ppm. It has been found that CO_2-concentrations around 3000 ppm can cause concentration losses with short-term exposures. This has been described in literature about high CO_2 values which have been found in some busy lecture rooms after a couple of hours (Twardella *et al.*, 2012). There is no research performed on these high CO_2-concentrations within houses and with long-term exposures.

The increase in CO_2-concentrations up to 7150 ppm by turning off the MV system is extremely high. If people do not open their windows, which happens often during the winter time, CO_2-concentration could increase up to 7000 ppm. These concentrations are very unhealthy and people should not be exposed to this environment for a long time.

This scenario showed that none of the MV system power levels is capable of sustaining a healthy indoor air. Additional window ventilation is needed in order to reach lower CO_2-concentrations.

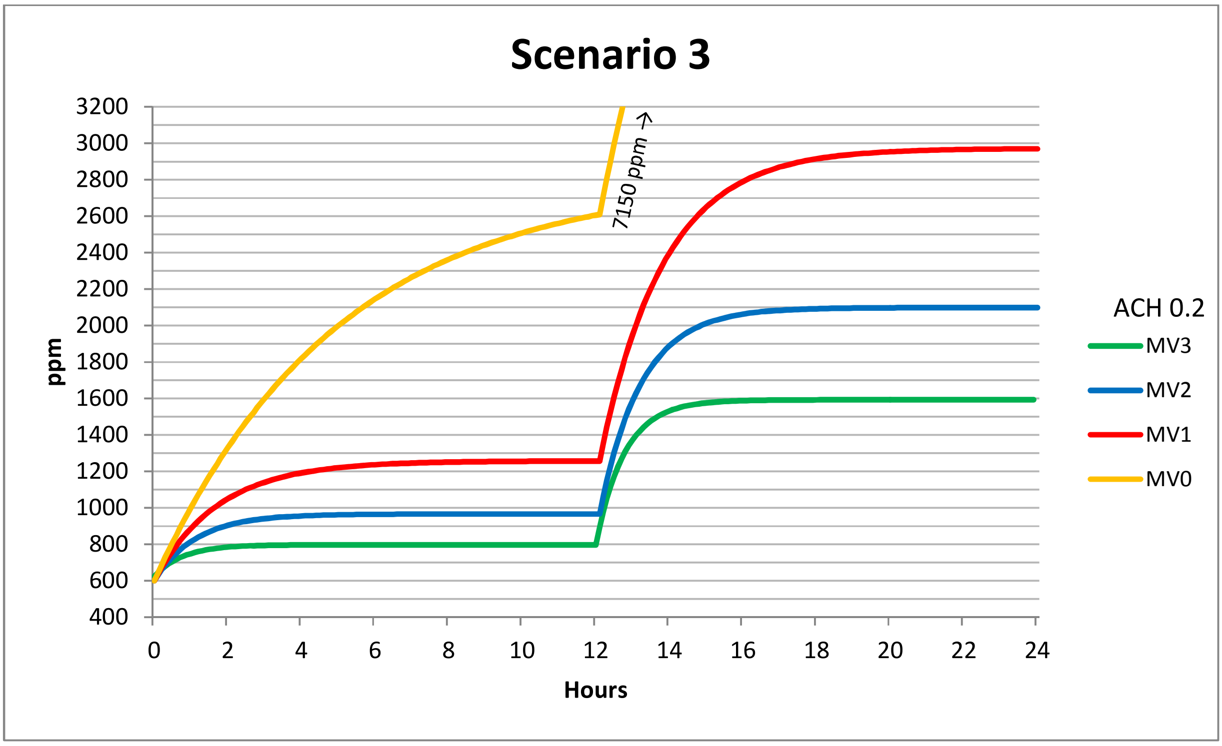

Figure 21 – CO_2-concentration with air supply rates for MV system control settings 3, 2, 1 and off with an envelope leakage of 0.2 ACH and no window ventilation.

Other results

As described in chapter 2, the building envelopes of European houses are becoming more airtight. Insulation improvements keep decreasing the ‘unwanted’ air leakages in houses. Building contractors must adhere to the building laws concerning the building envelope and other parts of the construction. Minimal ventilation rates are also described in the building codes, but are often not controlled on their functioning. Furthermore, the interactions of the residents with installed mechanical ventilation systems in houses are not taken into account at all.

The effect of increasing the building envelope without changing the ventilation rates has been modeled and can be seen in figure 22. The ventilation rate has been set at MV2, which is the prescribed level in normal situations. Literature research suggests a healthy baseline of 700 ppm, since higher concentrations are reported to cause health effects. Within houses with an ACH of 0.8, MV2 provides enough refreshed air in order to keep CO_2-concentration slightly above 700 ppm. Recently-increased building envelopes to ACH 0.5 results in increased indoor air CO_2-concentrations up to 800 ppm. If houses are built with a building envelope leakage of 0.2 ACH, installed MV systems cannot control CO_2-concentration anymore. In normal situations, the concentration will increase to almost 1000 ppm. Changes in the activity of resident will further increase the concentrations.

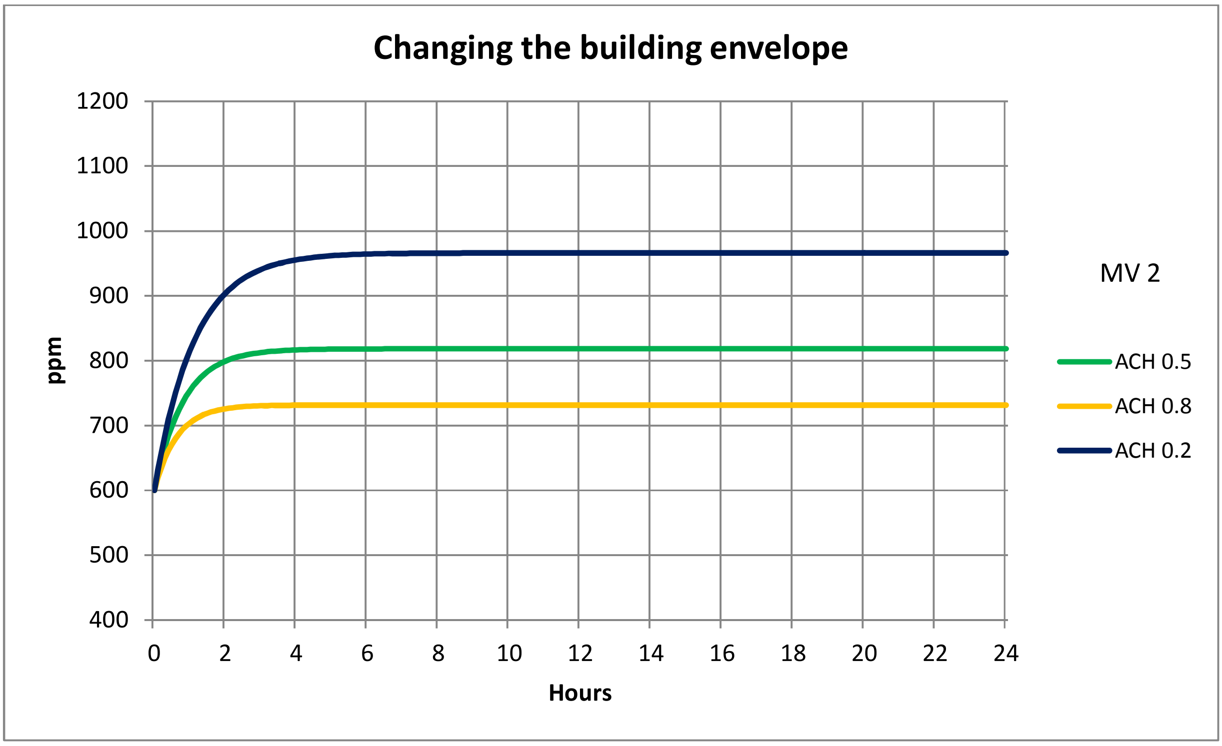

Figure 22 – the effect of decreasing the building envelope without changing the ventilation rate.

Increasing the insulation capacity of the building envelopes cause increased CO_2-concentrations in the inside air. The actual provided ventilation rate of the highest power level (MV3) should, theoretically, be much higher. Power level MV3 has an actual provided ventilation rate of the theoretically calculated power level of MV2. Power level MV2 is prescribed to be used in normal living situations. If the goal for highly energy-efficient houses (0.2 ACH) will be to avoid an indoor air CO_2-concentration above 700 ppm, than the actual MV2 supply rate must increase a lot. The proposed change in supply rates can be seen in figure 23. The model shows that an increase of 200%, compared to the actual supply rates from this power level, is needed in order to reach CO_2-concentrations of 700 ppm. It is recommended to pursue the healthy baseline value of 700 ppm because multiple health problems are described in different studies of houses with indoor air CO_2-concentrations above 800 ppm. Furthermore, if the value already reaches 700 ppm within these normal-living situations, CO_2-concentrations will be much higher in active-living situations.

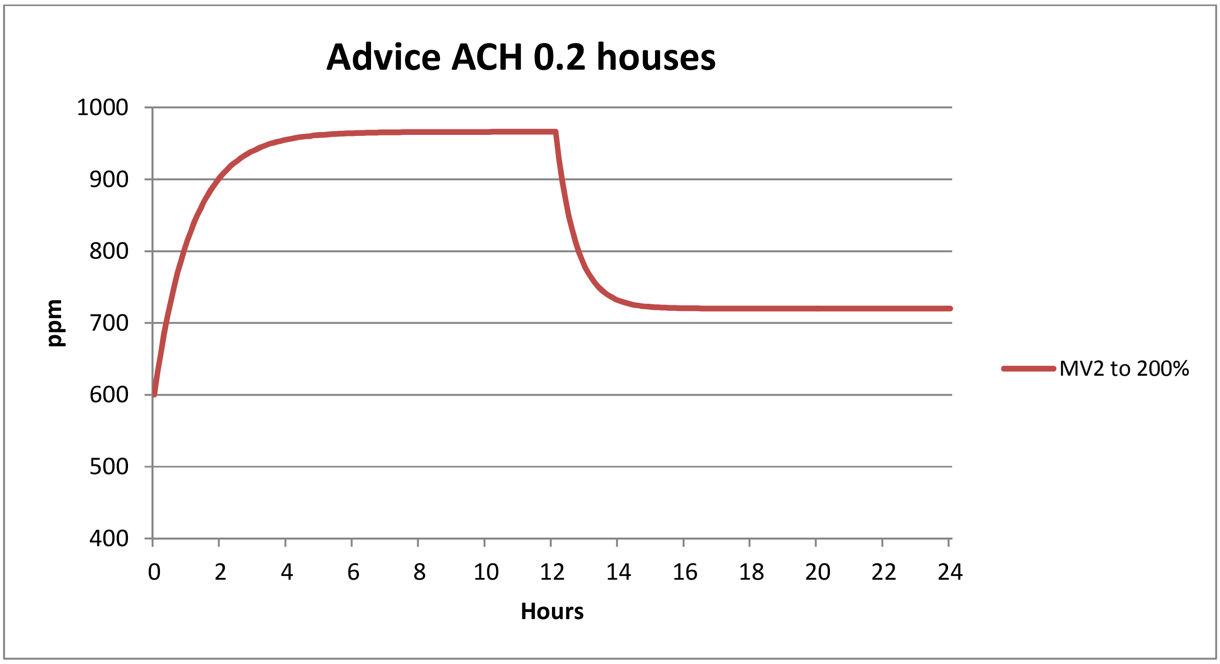

Figure 23 – The necessary airflow within highly energy efficient houses

In this thesis, CO_2 has been used as indicator for the IAQ. The idea of qualifying the IAQ based on CO_2-concentrations works if more is known about the relation between CO_2-concentrations and other indoor air pollutants. CO_2 depends on human activity by respiration and on the outdoor air concentrations. The indoor air humidity concentration is also mainly depended on human activity (respiration) and the outdoor air concentrations. Therefore, more residents results in more humidity production. Maier *et al.* (2009) compared the physical performances of the ventilation systems in low-energy houses. They presented a strong correlation between the number of residents and the relative humidity (figure 24). So, both CO_2 and humidity concentrations are correlated with the number of residents. The model showed high CO_2-concentrations in multiple scenarios. This means that in these scenarios the humidity levels may also be too high.

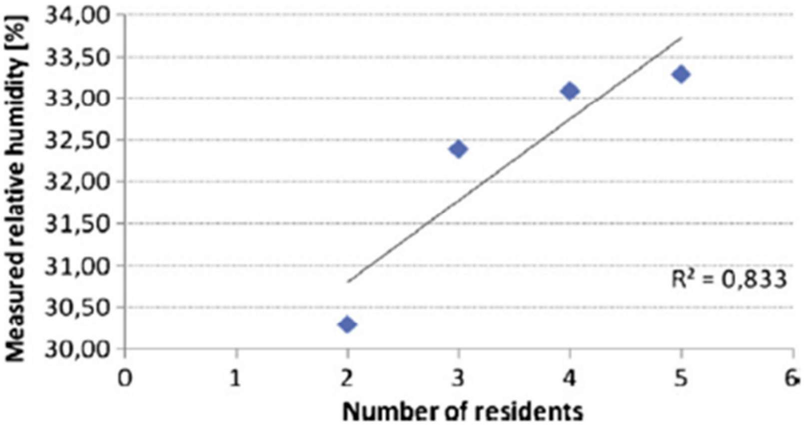

Figure 24 – The relationship between the number of residents and relative humidity (Maier *et al.*, 2009)

The relationship between indoor air CO_2-concentrations and other indoor pollutants, such as VOC and PM, has not been determined yet. These pollutants are not connected to human activity in the way CO_2 and humidity are. The rate of release depends on other conditions, such as the type of building materials or the frequency of use of certain equipment. Almost every house is different which results in other rates and amounts of produced indoor air pollutants. Therefore, it will be really difficult to generalize the model for other indoor air pollutants than CO_2-concentrations and humidity levels. Nevertheless, VOC and PM concentrations probably will increase due to decreased ventilation inside houses. In my model, the production of CO_2 by human respiration is stable. Therefore, the increase in indoor air CO_2-concentrations is caused by a decrease in ventilation.

The developed model can only be used to predict the concentrations of other indoor air pollutants if the rate and amount of releases is known. Predicting the IAQ is more difficult. This is due to the fact that different indoor air pollutants cause different health problems at different concentrations.

More research must be executed on the correlation between CO_2-concentrations and the concentrations of different air pollutants. For example, a linear relationship between CO_2-concentration between 600 ppm and 1200 ppm and the total number of measured bacteria in classroom air has been found (Liu *et al.*, 2000). If the correlation between CO_2-concentrations and specific air pollutants is more clarified, guidelines can be adjusted to the knowledge. Furthermore, a distinction should be made about the severity of different pollutants and if the problem could be solved at the source.

7. Human health problems due to poor indoor air quality

The Dutch National institute for human health and environment presented an increase in asthma patients over the last years (figure 25). The increase started shortly after the oil crisis of 1973. As a response to the oil crisis, people tried to save energy is multiple ways. One way to reduce the household energy consumption is by improving the insulation of the building envelope. At the moment, a lot of research is being performed on the question whether increasing the airtightness of the building envelope, combined with a lack of adequate ventilation, could be the reason for the rapid increase of asthmatic diseases.

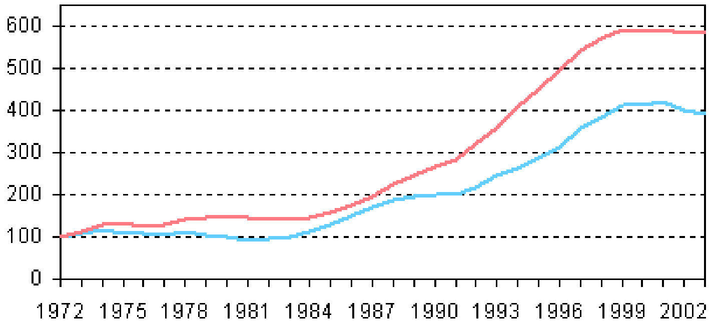

Figure 25 – Annual prevalence of Asthma from 1972-2004, red line for women and blue line for men (RIVM, 2012).

Asthma

Within developed countries, asthma and related allergic disorders have become some of the most common chronic diseases. Biologically, asthma is an excessive response of the immune system to allergens which are harmless to healthy people. It manifests as an inflammatory response in the airways. Asthma has a genetic base, but this cannot explain the rapid increase during the last decades. Therefore, exposure to air pollutants may play an important role in the development of this respiratory disease.

The change to energy-efficient houses also changed the common indoor environment of humans. Indoor environments include schools, offices, daycares, entertainment venues and many more. However, homes are by far the most important indoor environments, since people spend about 70% of their time at home. Results of this thesis showed that energy-efficient houses have higher CO_2-concentrations in everyday situations than less energy-efficient houses. The possibility that ventilation rates are too low at energy-efficient houses is higher. Therefore, there is also a chance that air pollutants are present in higher concentrations in the indoor environment of energy-efficient houses. Modern living conditions with high indoor temperatures and high humidity levels possibly increase the levels of indoor pollutants. Indoor air pollution has been quantified as the number ten of important risk factors for human health which could be prevented. It is estimated to being responsible for 1.5-2 million deaths each year (Viegi *et al.*, 2004). Research on all kinds of air pollutants associated with respiratory health problems has been done. Air pollutants can be divided in chemical and biological air pollutants. Examples of chemical air pollutants are volatile organic compounds (VOCs), formaldehyde, particulate matter (PM), dioxide nitrogen (NO_2) and phthalates. The most common biological air pollutants are allergens, molds and endotoxins. Endotoxins are basically the major constituent of the outer cell membrane of bacteria.

Health effects of molds

As mentioned before, energy-efficient houses may cope with high indoor humidity levels. High indoor humidity levels often cause moisture accumulation in building structures or materials. Moisture triggers the growth of microbial compounds. Research on microbial growth in buildings with moisture problems associated this with an increased risk on all kinds of health problems. Unfortunately, there is no such thing as a 'moldy building disease'. Moldy buildings are rather linked to multiple non-specific symptoms. There are some diagnosable diseases which have been associated with moldy buildings in clinical studies, as is the case for asthma. However, this does not automatically mean that molds or humid houses cause the disease to develop. It only implies that one of the determining factors to develop such a disease is associated with moisture or mold in houses. Assuming this, mold inside houses can be used as an indicator for the exposure and the risk for human health. If indoor microbial growth appears to be harmful to human health, it should be avoided. Research suggests that particles from molds and bacterial contaminants could likely be the cause for the observed health effects (Nevalainen and Seuri, 2005). However, the specific agents that cause the health effects are still being researched. Some fungi and bacteria produce toxic compounds, which could be one of the reasons why residents complain about respiratory problems. Altogether, there is an enormous amount of reports with evidence to strengthen the idea that mold is harmful to human health. These reports show an association between dampness or moisture damage in buildings, mold, microbial growth and adverse health effects. Some mentioned symptoms are irritations and recurrent respiration infections.

Within the literature, the current discussion is about the question if moisture directly causes respiratory health problems or exacerbates the already existing problems, such as sensitization. This thesis will not further elaborate on this discussion. Although this discussion is interesting, one thing is already certain; a high moisture level inside houses is bad for human health.

Health effects of allergens

Allergens in the indoor air and its effect on respiratory diseases are studied a lot. The most common producers of allergens are indoor molds and house dust mites. Especially house dust mites are strongly associated with respiratory diseases. A common allergen-producing species of house dust mites is *Dermatophagoides pteronyssinus*. This species causes 20% of the adult population in Europe to be sensitized to it (Arshad, 2010). Allergens produced by dust mites are usually found in dust from carpets, mattresses, soft furnishes and many more 'dust-collecting' materials. Research shows that there is a clear relation between indoor allergens such as dust mites and asthma. A lot of research has been done on the development and severity of asthma in children. For example Gent *et al.* (2009) showed clearly that there is a relation between the level of exposure to dust mite allergens and asthma severity in children. Another research performed with children is that of the Childhood Asthma Management Program. They published a ninefold increased risk of sensitization to dust mites in asthmatic children who were exposed to these allergens at home compared to children without asthma (Huss *et al.*, 2001). A follow up study from Sporik *et al.* (1990) concluded mite allergen exposure in infancy to be directly related to the development of asthma and other allergies in children of 11 years of age.

Sensitization

The association between sensitization to allergens in the air and asthma has been shown in all kinds of research. For example, Korppi *et al.* (2008) researched the association between cat and dog sensitizations and the increased risk of developing asthma in children. They found a sixfold and ninefold increased risk for future asthma in children who were sensitized to respectively cat and dog allergens. Overall, there are a lot of studies supporting a positive and linear relationship between sensitization and the development of asthma and allergic symptoms.

Still, there remain some doubts about this relation. The problem is that it has been shown that increased levels of indoor allergens cause asthma and allergy, but the symptoms are not reduced by lowering the concentration of indoor allergens. This way, skeptics keep doubting the relationship between allergens and asthma. More research is necessary to clarify this relationship. Also, the time of exposure and development of sensitization is under debate.

Health effects of PM

PM is a common air pollutant outdoors. Acute health effects of high PM concentrations in the outside air are coughing, stuffiness and exacerbation of respiratory symptoms, hospital admission and increase in daily mortality (RIVM, 2012). It is less known that PM concentrations can also occur in high concentrations indoors. Indoor PM concentrations are mainly produced by tobacco smoke and the use of gas-running devices. Gas-running devices are often present in houses as they are used a lot for cooking in the Netherlands. The presence of tobacco smoke inside houses depends on the behavior of the residents. According to the RIVM, within 50% of the households tobacco smoke is present (RIVM, 2012). PM2.5 is a product from tobacco smoke. Therefore, especially PM2.5, which is possibly worse than PM10, has been found inside these houses.

People with already existing respiratory disorders or heart diseases are more sensitive for high PM concentrations. Besides the already mentioned short term exposures to relatively high PM concentrations, long term exposures to average concentrations may also cause severe health problems. This applies especially to indoor air concentration. Symptoms caused due to long term exposures are lasting health problems, such as a decreased function of the lungs, aggravation of respiratory symptoms and premature mortality (RIVM, 2012).

Health effects of VOCs and formaldehyde

Besides the earlier mentioned mild irritation of the eyes and odor nuisance by Formaldehyde, VOCs in general can cause some real health problems. Headaches, fatigues and annoying irritations of the nose, throat and eyes have been reported (RIVM, 2012). The extent to which it affects humans depends on their personal sensitivity to the compound.

Health effects of phthalates

Phthalates are esters of phthalic acid, which are often added to plastic materials. Phthalates improve the quality of the material, such as the flexibility. They are used a lot in polyvinylchloride (PVC), which is the third-most widely produced plastic. PVC is used for construction in houses. Besides a source in PVC, phthalates are also present in vinyl flooring within a lot of houses. It is estimated that about 3.5 million metric tons of phthalates is produced each year on a global scale. One important type of phthalates, di(2-ethylhexyl)-phthalate (DEPH) will be discussed in this paragraph. DEPH contributes for about 50% to the total production, whereas 95% of it is used for the production of PVC (Bornehag *et al.*, 2004). Phthalates can become airborne and nestle in house dust, causing high indoor concentrations if not ventilated properly. Especially industrialized countries cope with relatively large daily exposures to phthalates. It is suggested that phthalate esters act as allergens, which would mean that they could also contribute to the rapid increase of asthmatic diseases in the world. Besides the increase of airtightness of the building envelope, exposures to phthalates also increased because of the increase of plasticized products since the end of World War II (Bornehag *et al.*, 2004).

8. Conclusion

The aim of this thesis is to answer the main research question: *"What is the effect of mechanical ventilation systems on the indoor air quality in highly energy-efficient houses and how does this affect human health?"*.

Most energy-efficient houses are implemented with MVHR systems. Literature research showed that the actual working of MVHR systems is far lower than prescribed. The MVHR systems provide houses with lower ventilation rates than needed in every possible power setting of the system. Experimental studies showed that in most cases almost half of the researched houses do not meet the minimal supply (and exhaust) rates.

Occupant behavior exacerbates this problem. Residents are changing the power levels in order to gain a good perceived IAQ, based on human comfort. Comfort is the first human need for residents, followed by safety in the home. Both needs are conflicting because perceived IAQ is not based on the same quality as the actual IAQ. Comfort is influenced by more complex psychological factors, while safety is based on the concentration of harmful pollutants in the indoor air. Residents act from a perceived quality perspective. Noise and drafts can motivate residents to lower or turn off their MV system. This effect became clear during a large experimental study in the Netherlands. In almost all the houses the MV system was used at a lower power setting than recommended for proper ventilation.

Besides the influence of occupants' behavior, the physical working of the MVHR system is also a problem. Sharp bends and dust accumulation in the pipes cause noise nuisance. This will further increase the interference of residents with the system. Furthermore, incorrect installation and poorly tuned supply and exhaust rates are causing pressure differences within the house which results in undesired drafts. Pressure differences may also cause an increase of the release of air pollutants from the building structures.

The model showed that the current MVHR systems are not capable of sustaining a healthy IAQ within the energy-efficient houses with a building envelope leakage of 0.5 ACH. Improving the building envelope leakage to 0.2 ACH results in lower ventilation rates. Therefore, the IAQ in highly energy-efficient houses will be very low. Decreasing the building envelope leakage from ACH 0.8 to ACH 0.5 resulted in a CO_2-concentration increase of 12% for the prescribed MV power level MV2. An increase from ACH 0.5 to ACH 0.2 resulted in a further increase in CO_2-concentration of 18%.
Within the model, the CO_2-concentrations of highly energy-efficient houses are increased up to 800 ppm, 960 ppm and 1260 ppm for MV system settings 3, 2 and 1 respectively. The power level MV1 is being used most often. Literature recommends indoor air CO_2-concentrations to stay below 700 ppm. Highly energy-efficient houses with the current MVHR systems will not meet this goal.
The model showed that window ventilation can (temporally) restore the indoor air CO_2-concentrations within 2-3 hours (W1), or within 1 hour (W4). However, during the winter months, window ventilation is almost not being used.
Changes in the living situation resulted in more insufficient supply rates. Increasing the number of residents resulted in extremely high CO_2-concentrations. Humidity levels are also correlated with the number of residents inside the house. Therefore, this scenario also showed that insufficient ventilation rates can increase the chance of molds within energy-efficient houses.

The degree of increase of other indoor air pollutants is still unknown. However, literature studies claim that indoor air CO_2-concentrations can be a good reflection of the overall indoor air quality.
The most common indoor air pollutants have been presented. A decreased IAQ is associated with multiple health problems, mostly problems with the respiratory system. Asthma is an increasing health disease, especially in western countries. At the moment, it cannot be concluded that asthma and other respiratory health diseases are caused by one or more specific indoor air pollutants. However, the increase of respiratory health diseases is very clear. The outcome of this thesis will add to the concern about the IAQ and adverse health effects in highly energy-efficient houses.

The working of MVHR systems must increase in the current energy-efficient residential sector. As for upcoming highly energy-efficient houses, the occurrence of respiratory health effects will probably increase tremendously if no improvements of the MVHR systems are made. The used model within this thesis predicts that it necessary that the current MVHR system doubles its capacity to supply air into houses in order to reach a healthy indoor air.

9. Discussion

Several assumptions were made during this research which will be discussed in this chapter. First of all, the modeled ventilation rates for MV1, 2, and 3 are based on only one large experimental study. If more experimental studies will be performed on this topic, the actual ventilation rates of MVHR systems will become more certain.
Secondly, within this thesis, average behavior patterns were used. However, literature presents a wide range of possible human behaviors in the residential sector. The underlying reasons for the behaviors vary a lot. For this research, average behaviors are used which reflect the situations for the majority of the residential sector.

One option in the model was to turn off the MVHR system. Turning off the MVHR system showed unhealthy high CO_2 levels in both ACH 0.5 and ACH 0.2 houses. In practice, it is difficult to completely turn off the MVHR systems. However, the results also show that a broken or badly working MVHR system should be taken seriously and must be fixed as soon as possible. Furthermore, the model reflected a perfectly balanced system to predict the indoor air CO_2-concentrations. CO_2-concentrations were directly influenced by changes in the air supply and exhaust rates. However, reaching a CO_2-concentration equilibrium within a certain space takes some time and can easily be disrupted. Therefore, dynamically modeled CO_2-concentration may give some biased values.

This research used the decreased ventilation rates from an experimental study and expectations according to the literature. However, literature also discusses the actual working of the airtightness of the building envelope. It has been suspected that houses are often not that airtight as theoretically calculated. Within this thesis, theoretically prescribed envelope leakages are used.

This thesis described the most common indoor air pollutants and their presence in the indoor air. Different health effects from these indoor air pollutants have also been mentioned. However, nothing has been said about the possible effects of combined exposures to pollutants. At this moment, no research has been done on these effect. The National Institute for Human Health and Environment also mentions this and concluded that too little is known about the effect of combined indoor air pollutants (RIVM, 2012). This is an important aspect with a large shortcoming in the research on human health problems caused by a poor IAQ.

10. Recommendations

During this research, multiple ideas for further research have emerged. This thesis investigated the effect of ventilation on the IAQ. Ventilation can be effective in diluting the concentration of indoor air pollutants; however, the removal of pollution sources is a more effective way to control the IAQ. This does not apply for CO_2 as a pollutant because the increase is merely due to human respiration. As for other indoor air pollutants, it would be very helpful if project developers would choose low-emission materials. For example, by using materials which release less VOCs. This way, the same amount of ventilation would result in a better IAQ. So, in order to prevent indoor air pollutants to build up inside houses, it would be best to prevent them from becoming airborne. The use of low-emission materials can contribute to this solution. An example of a development in this area is M1 classification labels for materials or products, such as paint. The M1 classification shows that materials are qualified as low-emission materials. More research should be done on this, and it should become more popular to build houses with low-emission materials. One way to promote this in the Netherlands is by using a green label for indoor air quality next to the already used green label for insulation qualities.
According to this thesis, human behavior is an important aspect in reaching healthy indoor air qualities. One way to affect human behaviors is by educating residents about the purpose and about the effects of certain actions. Therefore, a green label can also be a recommendation to increase the knowledge about the importance of the IAQ.
In the future, houses and buildings will cost a gradually decreasing amount of money in the use stage. Therefore, the building stage will become a larger part of the total energy use. Energy for materials and resources will become more important and research on the possible options will increase. In order to create houses with low-emission materials, research on low-energy materials and the corresponding emissions should start as soon as possible.

The RIVM concluded that smoke was present in the house in about 50% of the houses they researched. Smoke inside houses will become a larger problem in the future if insulation performances keep improving. PM2.5 is a severe indoor air pollutant and is very bad for human health. Overall, smoking inside houses should be discouraged more. It should be made clear to residents that smoke consists of severe pollutants which decrease the IAQ extremely. This is not only increasingly bad for the smoker, but also for other residents present in the house. A recommendation is to provide airtight energy-efficient houses above a certain level with a mark which warns the residents about smoking inside their extremely airtight house.

The model showed that in some scenarios the MV system could not sustain a good IAQ. In these cases, additional ventilation is necessary by window ventilation. Follow up research should be directed at the differences in air changes between opening a hanged window for quite some time or occasional and transfer ventilation for a few minutes. The energy losses should be taken into account and the information should be presented to the residents.

At last, this thesis used ventilation rates which were based on recently built energy-efficient houses with relatively new MVHR systems. It would be interesting to look at the working of MVHR systems when they become older. Dust contamination in the piping and malfunctioning of the valves is prospected to even further decrease the working of the MV system.

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12. References

AGPO FERROLI, 2002. Werking en bediening van het warmteterugwinningsysteem. Stichting HR ventilatie.

Andersen, R.V., Toftum, J., Andersen, K.K., Olesen, B.W., 2009. Survey of occupant behaviour and control of indoor environment in Danish dwellings. Energy and Buildings 41, 11-16.

Arshad, S.H., 2010. Does exposure to indoor allergens contribute to the development of asthma and allergy? Current allergy and asthma reports 10, 49-55.

Balaras, C., Droutsa, K., Argiriou, A., Asimakopoulos, D., 2000. Potential for energy conservation in apartment buildings. Energy and Buildings 31, 143-154.

Balvers, J., Bogers, R., Jongeneel, R., van Kamp, I., Boerstra, A., van Dijken, F., 2012. Mechanical ventilation in recently built Dutch homes: technical shortcomings, possibilities for improvement, perceived indoor environment and health effects. Architectural Science Review 55, 4-14.

Bornehag, C.G., Sundell, J., Weschler, C.J., Sigsgaard, T., Lundgren, B., Hasselgren, M., Hägerhed-Engman, L., 2004. The association between asthma and allergic symptoms in children and phthalates in house dust: a nested case–control study. Environmental health perspectives 112, 1393-1397.

BPIE, 2010. Energy Performance Certificate across Europe.

Duijm, F., 2006. Toetswaarden voor ventilatie in scholen en kindercentra. GGD Nederland, werkgroep binnenmilieu.

Dyrbol, S., Thomsen, K.E., Alboek, T., 2010. European Directive on the Energy Performance of Buildings: Energy Policies in Europe - Examples of Best Practice. ACEEE Summer study on Energy Efficiency in Buildings, 126-140.

Ekerschot van, F. and Heinemans, M., 2008. Implementation of the EPBD in The Netherlands: Status and planning in June 2008. EPBD Buildings Platform, P131.

Emenius, G., Svartengren, M., Korsgaard, J., Nordvall, L., Pershagen, G., Wickman, M., 2003. Building characteristics, indoor air quality and recurrent wheezing in very young children (BAMSE). Indoor air 14, 34-42.

EPA, 2013. EPA's revised particulate matter standards. http://www.epa.gov/ttn/oarpg/naaqsfin/pmfact.html Retrieved: 01-21-2013.

European Commission, 2002. Towards a European strategy for the security of energy supply. 769.

European Communities, 2002. DIRECTIVE 2002/91/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 2002 on the energy performance of buildings.

European Union, 2010. DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings.

Fabi, V., Andersen, R.V., Corgnati, S., Olesen, B.W., 2012. Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. Building and Environment 58, 188-189.

Fanger, P.O., 2007. Wat is IAQ? TVVL Magzine 36, 14-20.

Gent, J.F., Belanger, K., Triche, E.W., Bracken, M.B., Beckett, W.S., Leaderer, B.P., 2009. Association of pediatric asthma severity with exposure to common household dust allergens. Environmental research 109, 768-774.

Guerra Santin, O., 2012. Occupant behaviour in energy efficient dwellings: evidence of a rebound effect. Journal of Housing and the Built Environment, 1-17.

Habets, T., van Ass, M., Duijm, F., Geleen, L., Haans, L., van Brederode, N., 2008. GGD-Richtlijn Ventilatie Scholen. LCM landelijk centrum, 69-72.

Huss, K., Adkinson, N.F., Eggleston, P.A., Dawson, C., Van Natta, M.L., Hamilton, R.G., 2001. House dust mite and cockroach exposure are strong risk factors for positive allergy skin test responses in the Childhood Asthma Management Program. Journal of allergy and clinical immunology 107, 48-54.

Jongeneel, W.P., van Balen, E.C., Koudijs, E.A., Staatsten, B.A.M., Houweling, D.A., 2009. Recente wetenschappelijke ontwikkelingen en beleid op een rij. RIVM Binnenmilieu briefrapport 630789003.

Jongeneel, W., Bogers, R., van Kamp, I., 2011. Kwaliteit van mechanische ventilatiesystemen in nieuwbouw eensgezinswoningen en bewonersklachten. RIVM rapport 630789006.

Koistinen, K., Kotzias, D., Kephalopoulos, S., Schlitt, C., Carrer, P., Jantunen, M., Kirchner, S., McLaughlin, J., Mølhave, L., Fernandes, E., 2008. The INDEX project: executive summary of a European Union project on indoor air pollutants. Allergy 63, 810-819.

Koivula, M., Kymäläinen, H.R., Virta, J., Hakkarainen, H., Hussein, T., Komulainen, J., Koponen, H., Hautala, M., Hämeri, K., Kanerva, P., 2005. Emissions from thermal insulations—part 2: evaluation of emissions from organic and inorganic insulations. Building and Environment 40, 803-814.

Korppi, M., Hyvärinen, M., Kotaniemi-Syrjänen, A., Piippo-Savolainen, E., Reijonen, T., 2008. Early exposure and sensitization to cat and dog: different effects on asthma risk after wheezing in infancy. Pediatric allergy and Immunology 19, 696-701.

Leidelmeijer, K., Menkveld, M., Cozijnsen, E., Heemskerk, H., 2009. Mechanische ventilatie in nieuwbouwwoningen: ervaringen en oordelen van bewoners over de kwaliteit van ventilatie en de eigen gezondheid. Amsterdam, RIGO Research en Advies BV report number P10700.

Liu, L.S., Krahmer, M., Fox, A., Feigley, C.E., Featherstone, A., Saraf, A., Larsson, L., 2000. Investigation of the concentration of bacteria and their cell envelope components in indoor air in two elementary schools. Journal of the Air & Waste Management Association 50, 1957-1967.

Lucht, F.v.d., Meijer, G., Duijm, F., Broer, J., Nijman, R., 1995. Binnenmilieu-LuchtwegOnderzoek. GGD Groningen.

Maier, T., Krzaczek, M., Tejchman, J., 2009. Comparison of physical performances of the ventilation systems in low-energy residential houses. Energy and Buildings 41, 337-353.

Maslow, A.H., 1943. A theory of human motivation. Psychological review 50, 370-396.

Nevalainen, A. and Seuri, M., 2005. Of microbes and men. Indoor air 15, 58-64.

Nicol, J.F., 2001. Characterising occupant behaviour in buildings: towards a stochastic model of occupant use of windows, lights, blinds, heaters and fans. 2, 1073-1078.

NKC-Advies, 2013. Waarom ventileren. http://www.nkc-advies.nl/campertechniek/waarom-ventileren/index.html Retrieved: 01-06-2013.

NYCOSH, 2013. Methods for Evaluation of Indoor Mold Growth. http://nycosh.org/index.php?page=Biological Retrieved: 01-18-2013.

Riezen van, M.M.C., 2013. MVR Installaties. Personal contact, 01-28-2013.

Rijksoverheid, 2011. Bouwbesluit 2012. Staatsblad van het Koninkrijk der Nederlanden, 416.

RIVM, 2012. Rijksinstituut voor Volksgezondheid en Milieu. www.rivm.nl. Retrieved: September - March 2012/2013.

Roetzel, A., Tsangrassoulis, A., Dietrich, U., Busching, S., 2010. A review of occupant control on natural ventilation. Renewable and sustainable energy reviews 14, 1001-1013.

Seinen, H., 2013. Seinen Projectontwikkeling. Personal contact, 01-24-2013.

Seppänen, O. and Fisk, W.J., 2004. Summary of human responses to ventilation. Indoor air 14, 102-118.

Sporik, R., Holgate, S.T., Platts-Mills, T.A.E., Cogswell, J.J., 1990. Exposure to house-dust mite allergen (Der p I) and the development of asthma in childhood. New England Journal of Medicine 323, 502-507.

Stevenson, F., 2011. Evaluating usability for the design of low carbon homes. AECB 2011 Annual Conference http://www.aecb.net/conference2011.php.

Twardella, D., Matzen, W., Lahrz, T., Burghardt, R., Spegel, H., Hendrowarsito, L., Frenzel, A.C., Fromme, H., 2012. Effect of classroom air quality on students' concentration: results of a cluster-randomized cross-over experimental study. Indoor air 22, 378-387.

Viegi, G., Simoni, M., Scognamiglio, A., Baldacci, S., Pistelli, F., Carrozzi, L., Annesi-Maesano, I., 2004. Indoor air pollution and airway disease State of the Art. The International Journal of Tuberculosis and Lung Disease 8, 1401-1415.