MASTER

Keeping cool in heat waves
ventilative cooling potential in low-energy dwellings (HoTT)

Bouwens, E.P.M.

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Keeping cool in heat waves

Ventilative cooling potential in low-energy dwellings (HoTT)

Graduation project
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Abstract

Former research has claimed that low-energy dwellings are more sensitive to overheating than regular dwellings. In this research, the ventilative cooling potential of low-energy dwellings is considered. A low-energy dwelling, based on the Active House concept, “House of Tomorrow Today” (HoTT) has been investigated as representative for low-energy dwellings in general. A computational model of the house was created with the software Trnsys and this model has been calibrated according to measurements in the house.

The potential of creating or maintaining thermal comfort in the house with natural ventilation has been considered. The simulation results showed that ventilative cooling is able to reduce the temperature when the building is overheated to 26°C. Higher indoor temperatures can also be cooled down with natural ventilation, but this is dependent on temperature differences between inside and outside, and the cooling periods are longer. It turned out that the ventilative cooling effect in HoTT could be increased, if higher air change rates are attained by increasing the atrium window openings or by a favourable wind direction.

Furthermore, this report describes how overheating can be mitigated and thermal comfort can be maintained. The house will heat up too much in free floating conditions when daily ambient temperatures are 26°C or larger. The research has shown that a combination of natural ventilation during the night and external shadings significantly reduce the indoor temperatures. Next to that, it has been concluded that a heavyweight building is more effective to prevent overheating. HoTT is a lightweight building, but therefore the ventilative cooling effect is larger than for a heavyweight building.
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1. Introduction

The energy consumption in buildings has become of major interest in The Netherlands because of requirements imposed by the government. This has led to an evolution in reducing the energy consumption in both residential and office buildings in the past decade.

Much research has been done to low-energy dwellings and passive houses (Audenaert et al., 2008; Pineau et al, 2013). Designs have been optimized in order to improve the energy performance. However, this optimization often causes thermally uncomfortable indoor climates (Larsen et al., 2011; McLeod et al., 2013).

It turned out that well insulated low-energy dwellings are more sensitive to overheating than regular dwellings (Karlsson et al., 2006; Isaksson et al., 2006; Rodrigues et al., 2013). Hamdy et al. (2014), showed that natural cooling will be more beneficial in the future when there is much more overheating to be eliminated in Dutch dwellings due to climate change. Many existing Dutch dwellings have no mechanical ventilation nor mechanical cooling. Natural ventilation might be both an inexpensive replacement for cooling systems and a sustainable solution for overheating. In addition, natural cooling is in line with the low-energy concept, as mechanical cooling loads are reduced.

In this research, the “House of Tomorrow Today” (HoTT) (Lichtenberg, 2012) was investigated as representative for low-energy houses. This house is an experiment and a living lab based on the concept of Active House (http://www.activehousenl.info/) and the ‘Slimbouwen’ concept (http://www.slimbouwen.nl/). Ventilative cooling is defined in this research as cooling by natural ventilation.

The research objective and research questions are defined in chapter 2. Literature study has been conducted in order to find answers to sub questions prior to performing the computational research. This literature study is included in chapter 3. Chapter 4 describes the methodology of this investigation, and results and discussion of elaborated case studies are presented in chapter 5. Chapter 6 provides a conclusion about the ventilative cooling potential in HoTT and a recommendation for ventilative cooling in low-energy dwellings in general.
2. **Research objective**

The objective of this research is to provide guidance for the House of Tomorrow Today how to create thermal comfort by using ventilative cooling. This guidance relates to natural ventilation and can aid in overheating improvement for similar low-energy dwellings. The main research question is:

*How is thermal comfort created in the House of Tomorrow Today with ventilative cooling?*

The following sub questions have been defined:

1) What are the indicators for thermal comfort?
2) Which parameters are involved in ventilative cooling and how are these applied in the House of Tomorrow Today?
3) How sensitive is the House of Tomorrow Today to overheating?
4) How can overheating be prevented in the House of Tomorrow Today?
5) How is the House of Tomorrow Today cooled down with natural ventilation?
6) To what extent ventilative cooling is able to limit overheating in the HoTT-case as a representative for a solution of low-energy dwellings?

The indicators for thermal comfort and the parameters for ventilative cooling are discussed in the literature study in chapter 3. Section 4.2 considers the application of these parameters in HoTT. The sensitivity study that has been conducted is described in section 4.1. Sub questions 4 and 5 are answered in the elaborated case study. The results are shown and discussed in chapter 5. HoTT as representative for the ventilative cooling potential in low-energy dwellings is considered in the recommendation section of chapter 6.
3. Literature study

3.1 Introduction

This research was initiated in response to the appearance of low-energy dwellings to be more sensitive to overheating than conventional dwellings. The answer that has been obtained from literature is to what extent low-energy dwellings are vulnerable to overheating.

The research objective is to create thermal comfort with ventilative cooling. Sub questions 1 and 2 relate to thermal comfort and ventilative cooling, respectively. The indicators for thermal comfort and the involved parameters for ventilative cooling been obtained from literature as well.

3.2 Literature research method

Google Scholar was initially used to search for the main concepts stated in section 3.1, divided into several keywords. The concepts and keywords are shown in table 3.1. Articles have been obtained from the online databases of ‘Science Direct’, ‘Taylor and Francis Online’ and ‘Sage Journals’. The included reference list in each article provided a source of more useful literature. Google Scholar was used again to obtain the referred articles. Additional literature has been obtained by recommendation from the supervisors of this research.

<table>
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<tr>
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3.3 Literature review

3.3.1 Thermal performance of low-energy dwellings

Before the question could be answered to what extent low-energy dwellings are sensitive to overheating according to literature, it was important to know how low-energy dwellings have been defined in literature. Audenaert et al. (2008) divided low-energy dwellings into two types: active houses and passive houses. The operating energy of the building systems of active houses is reduced due to the application of energy efficient systems, which subsequently reduces the energy consumption. A passive house is a house which is designed and built to optimally utilize passive technologies. According to Stephan et al. (2013), a passive house can be seen as a highly insulated and airtight building with only a mechanical ventilation system for heating delivery. Figure 3.1 shows an overview of low-energy building systems for passive and active designs. (Rodriguez-Ubinas et al., 2014).

Multiple reports highlighted that while the energy performance of low-energy dwellings was continuously improving, the performance of the indoor climate significantly decreased for both active houses (Karlsson et al., 2006; Isaksson et al., 2006; Rodrigues et al., 2013) and passive houses (Larsen et al., 2011; Mlakar et al., 2011; McLeod et al., 2013; Rohdin et al., 2013).

Karlsson et al. (2006) investigated the indoor climate behaviour of a Swedish active low-energy house. The results of their simulations in comparison with measurements of two different rooms are shown in figure 3.2. The authors demonstrated that this low-energy house is overheated in summer months, with indoor air temperatures fluctuating around 35°C while the ambient temperatures is ±20°C. A different case of an active house was used in a simulation study of Rodrigues et al. (2013). They investigated a low-energy steel frame house and concluded that mitigation strategies were necessary in order to prevent intense overheating.
The energy efficient design of passive houses often results in inadequate indoor thermal performances as well. Larsen et al. (2011) compared measured and calculated results of the indoor temperature of a Danish passive house. The measured results of this research are shown in Figure 3.3. The authors claimed that the indoor climate must carefully be considered at the beginning of a design process of a passive house. Otherwise, the focus is only on energy savings and the house will become in risk of overheating.

Figure 3.2 – Simulated and measured temperatures of a Swedish low-energy house (Karlsson et al.).

Figure 3.3 – Measured temperatures of a Danish passive house in June (Larsen et al.).
In an investigation of Rohdin et al. (2013), nine Swedish passive houses were compared to conventional houses. In this investigation, it is shown that there are much complaints related to high temperatures and varying temperatures in the passive houses. The complaint overview from the report of Rohdin et al. is shown in Figure 3.4.

3.3.2 Prevention of overheating

The different reports in the former section indicated that low-energy dwellings are more sensitive to overheating than ordinary dwellings. Many studies investigated mitigation strategies to prevent dwellings from overheating. For ordinary (existing) dwellings, exterior solar shading and additional natural ventilation were concluded to be most effective against overheating (Porritt et al., 2012; Gupta et al., 2013; Taleghani et al., 2014; Van Hooff et al., 2014). Mlakar et al. (2011) and McLeod et al. (2013) stated that the thermal behaviour of low-energy dwellings is sensitive to the solar transmission in combination with the glazing to wall ratio on the south façade. Next to that, the authors claimed that the thermal capacity of a building has a large effect on the indoor temperature. Because thermal capacity, next to ventilative cooling, is stated to effectively prevent dwellings overheating, it is thoroughly discussed in the next section.
**Thermal capacity**

**Thermal mass**
According to several authors (Braun, 2003; Henze et al., 2004), the thermal mass of a building implies the ability of its construction to absorb and store heat. A heavyweight construction has a high thermal mass. Henze et al. stated that high thermal mass materials take a long time to heat up and cool down again, while the temperature of materials with a low thermal mass rapidly fluctuates with the surrounding temperature.

**Time constant**
The heating and cooling period of a structure is determined by its thermal inertia. The building time constant characterizes the internal thermal inertia of a conditioned building (Reddy, 2015). It indicates to what extent a structure is resistant to temperature changes. According to Béla et al. (2003), the time constant is defined as the time it takes for the indoor temperature to heat up with a value 63.2% of the initial difference or for the temperature to cool down to 36.8% of the initial difference. Reddy stated that buildings with a high thermal mass have a high time constant. Based on his work, Figure 3.5 shows an example of the cooling time (in days) for heavyweight buildings and lightweight buildings. As can be seen, the time constant of this lightweight building is 3-4 days, while the time constant of the heavyweight variant 10-11 days (as the count started at day 5). Reddy states that a higher time constant results into reduced temperature fluctuations, which improves thermal comfort.

![Figure 3.5 – Example of time constants obtained from cooling time heavyweight and lightweight buildings (Reddy)](image-url)
Ventilative cooling

Liddament (1996) provided a review of ventilation in the context of both energy efficiency and the achievement of a good indoor air quality. According to Liddament, natural ventilation is used to replace hot air in the building with fresh air and to cool the building fabric. Methods for natural ventilation include window opening, wind towers, solar chimneys and atria. These methods are designed in such a way that the system optimally uses driving forces like thermal buoyancy. Many studies have been done to investigate how passive cooling techniques are able to reduce the cooling loads in hot climates (Hirano et al., 2006; Haase et al., 2009; Reyes et al., 2013; Ezzeldin et al., 2013; Taleb, 2014). These researches mainly focused on office buildings or educational buildings where the yearly energy costs for air conditioning are very high.

Artmann et al. (2008) showed that night-time ventilative cooling in buildings in Europe can also reduce the cooling loads. Their results are shown in Figure 3.6. The graph clearly shows that the overheating degree hours above 26°C ($ODH_{26}$) are significantly decreased with night ventilation, especially in heavy weight buildings. According to Artmann et al., the thermal mass of the building is used as a heat sink that provides sufficient cooling during the occupant period.

Air conditioning systems are usually not applied in Dutch dwellings. For these dwellings, it is important to know what natural ventilation can accomplish for thermal comfort in case of a hot period, in order to reduce cooling energy loads. However, Larsen (2006) stated that ventilation through window openings is a complicated process and that the amount of air going through a window opening depends on weather conditions and geometric conditions. The wind speed near the building, the temperature difference between inside and outside the room, the wind direction, turbulence characteristics in the wind and the pressure variations influence the air flow according to Larsen. It also depends on the size, type and location of the opening or openings.

---

*Figure 3.6 – Overheating degree hours above 26°C in a building in Zürich, exposed to increasing air change rates of night ventilation. Different building weight types are provided, as well as different heat transfer coefficients ($h$) (Artmann et al.).*
3.3.3 Thermal comfort indicators

Adaptive temperature limits – office buildings

In 2004 a new Dutch guideline was introduced as a practical tool for design, simulation and assessment of thermal comfort in buildings (Van der Linden et al., 2004). This Adaptive Temperature Limits guideline (ATG) was developed as an alternative for the former guideline, the Weighted Temperature Exceeding Hours method (GTO) which was based on the analytical PMV model (Fanger, 1970).

De Dear et al. (1997) made a distinction in buildings with air conditioning and minimal opportunities for adaptations, and buildings that are naturally ventilated and have a large possibility for adaptation ( operable windows or fans). This distinction was expressed by De Dear et al. as ‘Alpha-buildings’ and ‘Bèta-buildings’, respectively. The main advantage of this thermal comfort model is that it takes the dynamic ambient temperatures into account.

Adaptive temperature limits – residential buildings

Peeters et al. (2009) considered the existing approaches (Van der Linden, et al., 2004) for thermal comfort in the context of residential buildings. They stated that when focusing on residential buildings, conditions are not comparable to conditions with the PMV and PPD indicators (Fanger). These indicators focus on steady state conditions in office buildings. Domestic areas cannot be considered as steady state: both the activity level and the clothing value can vary within small periods of time. Internal gains and the occupancy of residential scenes are also likely to fluctuate. These fluctuations affect the indoor temperature and the required air flow rates on short notice. The indoor comfort temperature is stated to be the most important environmental parameter of a residential building, so the effects of changing conditions were considered. Peeters et al. specified three different thermal zones in residential buildings: bathroom, bedroom and others.

Bathrooms

People experience thermal comfort differently in bathrooms within small periods of time because a nude, wet body will desire a higher temperature than when the person is dried and dressed. Peeters et al. compared the considerations of bathroom comfort from literature with the adaptive temperature limits (Appendix A) and they have derived the following neutral temperatures \( T_n \) (°C) for a bathroom:

\[
T_n = 0.112 \cdot T_{e,ref} + 22.65 \text{ °C} \quad \text{for} \quad T_{e,ref} < 11 \text{ °C} \\
T_n = 0.306 \cdot T_{e,ref} + 20.32 \text{ °C} \quad \text{for} \quad T_{e,ref} \geq 11 \text{ °C}
\]

The temperature ranges were distributed asymmetrically around the neutral temperature according to Humphreys et al. (2007). They found an asymmetric relation between the desired thermal sensation and the actual sensation. This resulting comfort band has a width of 5°C in case of a 90% acceptability.
Thus, the temperature limits creating the comfort upper and lower threshold of the comfort band are as follows:

\[
\begin{align*}
T_{\text{upper}} & = T_n + 3.5^\circ C \\
T_{\text{lower}} & = T_n - 1.5^\circ C
\end{align*}
\] (3.3)

Additional restrictions have been taken into account. For bathrooms and other rooms the minimum temperature is 18°C, but the maximum temperatures are less strict. There is an 80% acceptability level for temperatures up to 31°C. The comfort band for bathrooms is shown in Figure 3.7.

![Figure 3.7 – Comfort band bathrooms as a function of the ambient temperature (Peeters et al.)](image)

**Bedrooms**

According to Peeters et al., bedroom conditions are very dependent on ambient conditions. The neutral temperatures vary due to the fluctuating temperatures during the different seasons. In the case of no elevated air velocity in summer, the derived equations for bedroom temperatures are:

\[
\begin{align*}
T_n & = 16 ^\circ C & \text{for } & T_{e,ref} < 0 ^\circ C \\
T_n & = 0.23 \cdot T_{e,ref} + 16 ^\circ C & \text{for } & 0 ^\circ C \leq T_{e,ref} < 12.6 ^\circ C \\
T_n & = 0.77 \cdot T_{e,ref} + 9.18 ^\circ C & \text{for } & 12.6 ^\circ C \leq T_{e,ref} < 21.8 ^\circ C \\
T_n & = 26 ^\circ C & \text{for } & T_{e,ref} \geq 21.8 ^\circ C
\end{align*}
\] (3.4, 3.5, 3.6, 3.7)

Additional limitations for temperatures in bedrooms are a minimum of 16°C and a maximum of 26°C. The comfort band for bedrooms is shown in Figure 3.8.
Other rooms
The third category defined by Peeters et al. are the kitchen, living room and study room, which have physical activity levels comparable to those in offices. More adaptive options, however, are available (changing activity, going to another room, drinking cold or warm drinks, etc.). The neutral temperature can therefore be more dependent on the outside climate than what is generally accepted in offices. It is defined by:

\[
T_n = 20.4 \, ^\circ C + 0.06 \cdot T_{e,ref} \quad \text{for} \quad T_{e,ref} < 12.5 \, ^\circ C
\]

\[
T_n = 16.63 \, ^\circ C + 0.36 \cdot T_{e,ref} \quad \text{for} \quad T_{e,ref} \geq 12.5 \, ^\circ C
\]

With the additional restrictions taken into consideration, the comfort band for other rooms is shown in Figure 3.9.
3.3.4 Air flow measurement

**Tracer gas method**

Several authors (Flourentzou et al., 1998; Shen et al., 2012; Belleri et al., 2014) have used the tracer gas method to measure ventilation flow rates. According to Liddament (2006), an inert gas is released into a room for the purpose of the tracer gas method. Incoming air will mix with the tracer gas and after a certain period of time the concentration of the tracer gas can be considered. Liddament states that the air flow rate can then be measured in two ways: the decay of the tracer gas concentration over time can be measured; or the rate at which the tracer gas needs to be supplied in the room to maintain the target concentration can be measured. Liddament also states that exhaust air locations must be well defined and the air flow rate needs to be constant in order to measure this value accurately with this method.

The calculation of the air flow rate using the decay of the tracer gas concentration is described in equation 3.10. Figure 3.10 illustrates the concentration decay over time.

\[
\text{Air flow rate} = \frac{\ln C(0) - \ln C(t)}{t} \quad (3.10)
\]

- C(0) = tracer gas concentration at t=0 (ppm)
- C(t) = tracer gas concentration at t=t (ppm)
- t = time (sec)

**Air flow calculation**

Larsen (2006) discussed natural ventilation driven by wind and temperature difference. Based on Heiselberg et al. (2005), Larsen considered the calculation of airflows by wind and/or thermal buoyancy for both single-sided and cross ventilation ventilation. In a real-life situation, wind and thermal buoyancy are both involved in ventilative cooling. Methods for calculating air flow rates can be found in Appendix B.
3.4 Conclusions literature review

The extent to which low-energy dwellings are sensitive to overheating has been derived from literature. Housing designs are being optimized in order to reduce energy consumption. However, it turned out that this often results into poor indoor environments. Measurements in low-energy dwellings indicated overheating in summer months and residents of passive houses complained about temperatures being too hot. Exterior shadings, natural ventilation and beneficial influence of the thermal mass were recommended as mitigation or prevention strategies for overheating.

The indicators for thermal comfort (sub question 1) that have been used in this research, are the adaptive temperature limits defined by Peeters et al. The temperatures in the investigated rooms had to meet the corresponding comfort bands in order to acknowledge these rooms to be thermally comfortable.

The involved parameters of ventilative cooling (sub question 2) were stated by Larsen (2006). Based on his work, it was assumed that temperature differences between inside and outside, window opening properties (surface, height, type) and wind properties (speed, direction) had to be taken into account for a ventilative cooling analysis. The second part of sub question 2 – how these parameters are applied in HoTT – has been established by a computational analysis of ventilative cooling.

The remaining sub questions have also been answered with a computational analysis of ventilative cooling in HoTT. Possible methods were a computational fluid dynamics (CFD) analysis or the application of building energy software (BES) tool such as Trnsys or IES.
4. **Methodology**

In order to answer the main research question of how thermal comfort is created with ventilative cooling, information was needed about the ability of natural ventilation to cool down the building or to prevent the building from overheating. As concluded in the literature study of chapter 3, this information had to be obtained with a building energy simulation tool. For this research, the software Trnsys (Trnsys 17 documentation, 2012) has been selected. This tool offers the possibility to implement overheating prevention strategies in the model. In addition, Trnsys contains the possibility of including air flows with the TRNFlow tool.

The first step of the method has been used to provide insight in the overheating sensitivity of the House of Tomorrow Today. This preliminary case study indicated which areas of the house were in need of ventilative cooling or different overheating mitigation strategies. In order to simulate reliable results, the preliminary model has been calibrated in the second step. A set of measurements were performed in the house to obtain information about the actual physical behaviour. The goal of this calibration process has been to optimize the accuracy and reliability of the simulation results. This has been attained by fitting the model in such a way that the simulation results corresponded to the measured results. Subsequently, the calibrated model has been applied in elaborated cases in order to investigate the prevention of overheating and the ability of ventilative cooling (sub questions 4 and 5). Figure 4.1 provides a schematic overview of the methodology.

---

**Figure 4.1 – Schematic overview methodology**
4.1 Preliminary case study

To investigate the ventilative cooling potential in low-energy dwellings, the active house “House of Tomorrow Today” (HoTT) has been used as a representative case. Additional information about HoTT can be found in Appendix C. The goal of this section has been to create an energy model of HoTT that was able to indicate which rooms were vulnerable to overheating and therefore in need of ventilative cooling. This analysis consists of two parts: the first part contains the sensitivity study, and the second part considers the required ventilative cooling in the determined rooms.

4.1.1 Method preliminary case study

The block scheme of Figure 4.2 summarizes the methodology of the preliminary case study. First, the model has been created. Secondly, the important parameters have been specified, based on comparable data from literature. Finally the energy model has been simulated under free floating conditions in order to obtain results of the sensitivity study.

![Figure 4.2 - Schematic overview preliminary case study](image-url)
Create model

The geometry of the house has been modelled by using the Sketchup tool from Trnsys. The information has been obtained by personal communication with the architect and owner of the house prof. dr. ir. J.J.N. Lichtenberg.

The zone division has been based on differences in functions, ventilation and/or heating systems between the rooms. The room specifications can be found in Appendix C. Figures 4.3 and 4.4 show floorplans of the building with an indication of the zone division. (Note that the top of the figures represent south).

Building specifications

Construction specifications

Additional building model information has been specified in the TRNBuild tool from Trnsys. Tables C2 to C5 in Appendix C show the construction properties of the external wall, the internal wall, the ground floor and the roof respectively.

Thermal capacity

The thermal mass of the building has been defined by the specification of the construction properties. However, according to literature (Bradley, 2011; Dipasquale et al., 2013), the zone capacitance must be reconsidered because furniture is not taken into account in this parameter. Furnishing has thermal capacity as well, and can significantly influence the thermal behaviour. The authors recommended that the value of the zone capacitance in Trnsys is multiplied by a factor 5 to 10. Therefore, in the preliminary model, the air capacitance of each zone has been multiplied by a factor 5.

Ventilation

In the description of HoTT (Lichtenberg, 2012), it is stated that the building is equipped with a hybrid ventilation system with natural air inlet and mechanical air exhaust (Appendix C). When the CO₂ rate is lower than 800 ppm, the air flow rate is 15 m³/h. In the combined area of the living room, atrium and kitchen, this equates to an air change rate per hour of ACH=0.05 (h⁻¹) (considering the entire volume). Thus, this value for ventilation has been applied in the model.

Air is also being refreshed in buildings due to infiltration. In the investigation of Artmann et al. (2008), air change rates of 1-2 (h⁻¹) were present in the case of almost no natural ventilation. Because this investigation considered an office building, and HoTT is a newly built low-energy dwelling, the amount of basic ventilation in HoTT is assumed to be slightly lower. Therefore, the basic ventilation in the model has been set at an air change rate of ACH(basic)=0.5 (h⁻¹).

Convective heat transfer coefficient

According to literature (Delcroix et al., 2012), the convective heat transfer coefficient (CHTC) is dependent on temperature differences and air velocity. This value was recommended to be carefully considered in building energy simulation tools. The value of the CHTC was kept at the default value until elaborating research was performed that provided additional information about the temperature difference and air velocity. The default value of the CHTC in TRNBuild is 11 kJ/h · m² · K (=3.055 W/m² · K).
Assumption gives a more realistic temperature fluctuation. Measurements should later on provide a clear reference to set the right heat capacitance in the model.

Appendix D contains a table with all the rooms of the house and their characteristics. Although natural ventilation is considered, basic ventilation is included in this model with the air change rate per hour, ACH = 1.

3D modelling (geometry and zones)
- Wall specifications
  - Convective heat transfer coefficient
  - Thermal capacity
- Ventilation (basic and hybrid)
- Apply weather file
- Simulate energy model
- Determine vulnerable zones

Figure 4.3 – Zone division ground floor House of Tomorrow Today

Figure 4.4 – Zone division first floor House of Tomorrow Today
Simulation specifications

The model has been finished by application of the weather file. This file contained hourly data of the Dutch climate in De Bilt. The energy model was simulated for two weeks in moderate Dutch climate. Maximum temperatures were fluctuating around 20°C and minimum temperatures were fluctuating around 10°C.

4.1.2 Sensitivity study

Figure 4.5 shows the temperature behaviour in each zone during the two simulated weeks. The boxplots show the maximum/minimum temperatures, as well as the mean temperatures and the deviations. A small box indicates a more constant temperature. The same room ‘codes’ are applied as in Figures 4.3 and 4.4.

From Figure 4.5 it can be stated that the bathrooms in the house are relatively vulnerable to overheating, especially bathroom A. Figure 4.6 shows the actual temperature fluctuations of the bathrooms during the two simulated weeks. The tendency of the bathrooms to heat up quickly can be explained by the fact that they are all relatively small rooms which have large surfaces of south oriented windows.
To prevent the bathrooms from overheating, external shadings have been added. Figure 4.7 shows the effect of external shadings on the air temperature curves. In this variant, all windows in the bathrooms are provided with external shadings between 8:00 AM and 9:00 PM. The windows are for 70% covered with shadings, so the bathrooms are not completely darkened. Figure 4.7 shows that external shadings have a significant effect on the temperature curve. Bathroom A no longer reaches air temperatures over 30°C.

4.1.3 Air flow study

The results of the sensitivity study indicated that the living room and the atrium are more vulnerable for overheating than other zones and thus in need of ventilative cooling. Severe overheating in the bathrooms has been avoided with external shadings. The air flow has been defined in the living room with the TRNFlow tool of Trnsys. The air flow path is indicated in Figure 4.8.
The included air flow path was expected to have influence on the temperature in the living room. However, no significant air flow rates due to thermal buoyancy were shown in the simulation results, and therefore no temperature changes. Also inclusion of wind in the model had no effect on the temperature curves. It turned out that the TRNFlow tool was not adequate. The air flow simulation result with a comparing basic calculation are presented in Appendix D.

4.1.4 Conclusions preliminary case study

The sensitivity study showed that the bathrooms, the living room and the atrium are most vulnerable for overheating. Ventilative cooling has not been applied in the bathrooms, because the results indicated that exterior shading significantly reduces the overheating risk. It can be concluded that shadings might be applied in combination with natural ventilation to avoid overheating.

The living room and atrium, together with the kitchen and office, are in reality one large open space with clear boundary conditions. Modelling air flows with strict boundary conditions instead of non-physical boundaries will improve the accuracy of the results. In addition, the hybrid ventilation system in the house is operable for this entire area (new large zone) and combinations of windows in the different rooms have been applied for natural ventilation in the entire new zone. Thus, it has been concluded that one large zone (Figure 4.9) is more beneficial for the investigation of ventilative cooling than different zones in the living area at the ground floor.

Because the air flow created with the TRNFlow tool provided an insufficient amount of ventilation, a different tool, CONTAM, has been used. “CONTAM is a multizone ventilation analysis computer program designed to determine airflows” (Dols, 2012). It is an external tool which can be implemented in Trnsys. This tool has been providing more realistic simulation results (chapter 5).
4.2  Model calibration

In order to use the model for ventilative cooling in elaborated cases, the accuracy and reliability have been optimized by calibrating the model. This section describes the calibration process and the measurements that have been used to optimize the model by making the simulation results and measurement results correspond. The main parameters that have been adapted are the (basic) ventilation value and the thermal capacity. This analysis has answered how the involved parameters in ventilative cooling are applied in HoTT (sub question 2).

4.2.1  Calibration method

In order to compare the simulation results with the measured results, measurements have been done under reproducible circumstances for the model. Three measurement sessions have been performed in this analysis where different ventilation types have been considered:

The red boxes show which variables were measured in the real-life situation for each measurement step. The green boxes indicate which parameters were verified in the model according to the measured results.
4.2.2 Measurement set-ups

1. Basic ventilation

Description
In the first step, resulting temperatures exposed to free floating conditions (no mechanical heating, cooling or ventilation) have been obtained. Measured temperatures during the free floating period had to correspond to simulated temperatures of the energy model.

Various temperatures and the CO$_2$ rate were measured in the house for two weeks. Air temperatures were measured in the atrium, office, kitchen and living room. For the purpose of obtaining information about the heat capacity and CHTC, wall and floor temperatures were also measured in the living room. The set-up is shown in Figure 4.10 and the measurement schedule is shown in Figure 4.11. Additional equipment information is presented in Appendix E.

Set-up

![Figure 4.10 – Measurement set-up session 1](image)

Table 4.1 – Legend set-up 1

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Measuring</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Red Circle]</td>
<td>T$_{air}$</td>
</tr>
<tr>
<td>![Purple Circle]</td>
<td>T$_{ambient}$</td>
</tr>
<tr>
<td>![Green Circle]</td>
<td>T$_{wall}$</td>
</tr>
<tr>
<td>![Blue Circle]</td>
<td>T$_{floor}$</td>
</tr>
<tr>
<td>![Gray Circle]</td>
<td>CO$_2$</td>
</tr>
</tbody>
</table>

Schedule

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Residents absent</td>
<td></td>
<td></td>
<td><strong>Blue</strong></td>
<td><strong>Green</strong></td>
</tr>
<tr>
<td>Heating system off</td>
<td></td>
<td><strong>Blue</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 4.11 – Measurement schedule session 1](image)
2. Hybrid ventilation

Description
In the second step of this analysis, air temperature curves have been obtained as a result of the application of the hybrid ventilation system. This automatic, CO₂ controlled system can be overruled and specific air flow values can be set (Appendix C). The same air flow value for ventilation was applied in the model for the purpose of calibration.

Air temperatures in the atrium, office, kitchen and living room were measured as well as the CO₂ rate. Furthermore, the ambient air temperature was measured for the purpose of simulating it in the model. Besides, ambient air is entering the building when this hybrid ventilation system is applied. The ventilation system was overruled and set at its highest position (Figure 4.12). The highest position provides an air flow of ACH = 0.5 (h⁻¹) (https://www.duco.eu). A flow finder was used during these measurements to measure the actual air extraction. At the end of the session, one atrium window was opened for 30 minutes to verify the influence on the temperature and CO₂ rates. The set-up is shown in Figure 4.13 and the measurement schedule is shown in Figure 4.14. Additional equipment information is presented in Appendix E.

Set-up

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Measuring</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T&lt;sub&gt;air&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>T&lt;sub&gt;ambient&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>CO₂</td>
</tr>
<tr>
<td></td>
<td>Air inlet vents</td>
</tr>
<tr>
<td></td>
<td>Air exhaust</td>
</tr>
</tbody>
</table>

Schedule

<table>
<thead>
<tr>
<th>Time</th>
<th>Measurement period</th>
<th>ACH=0.5</th>
<th>ACH=0.05 (automatic)</th>
<th>Atrium window open</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11:00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11:30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12:00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.12 – Overruled ventilation panel

Figure 4.13 – Measurement set-up session 2

Figure 4.14 – Measurement schedule session 2
3. Natural ventilation

Description
In the third session, air temperatures have been obtained as a result of opened windows. Figures 4.15 and 4.16 show the living room door and the atrium windows respectively, which were used for these measurements to create an air flow. In Contam, the same window heights and surfaces have been applied in order to simulate the same temperatures and air flows as measured. Air temperature, ambient temperature and CO₂ rates were measured as can be seen in Figure 4.17. Additional equipment information is presented in Appendix E.

![Opened living room door](image)
![Opened atrium windows](image)

Figure 4.15 – Opened living room door  Figure 4.16 – Opened atrium windows

Set-up

![Measurement set-up session 3](image)

Table 4.3 – Legend set-up 3

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Measuring</th>
</tr>
</thead>
<tbody>
<tr>
<td>⬜️</td>
<td>$T_{air}$</td>
</tr>
<tr>
<td>⬜️</td>
<td>$T_{ambient}$</td>
</tr>
<tr>
<td>⬜️</td>
<td>CO₂</td>
</tr>
<tr>
<td>⬜️</td>
<td>Window/door openings</td>
</tr>
<tr>
<td>⬜️</td>
<td>Air flow path</td>
</tr>
</tbody>
</table>

Figure 4.17 – Measurement set-up session 3
Schedule
Because temperature difference, height difference and window surfaces all have influence on the amount of air flow due to thermal buoyancy according to literature, various situations have been investigated. Figure 4.18 indicates the height difference between the atrium windows and the living room door, as well as the applied surfaces of openings in the façade. Each row of the atrium windows contains three Velux windows that can open ±10cm.

Measurements were performed with both upper and lower atrium windows, as well as measurements with all six atrium windows opened. The measurement with six opened windows was repeated with a different ambient temperature and thus a different temperature difference (ΔT). Each time, the windows were opened for 10 minutes. During the measurements, the wind speed was 1-2 m/s (source: KNMI). Wind speed influences the air flow, but the direction of the wind determines whether this is a positive or a negative effect. Besides, wind speed and direction can vary within small periods of time. In order to accurately fit the model to the measurements, only air flow due to thermal buoyancy has initially been considered in the model and the wind speed has been set at 0 m/s. The effect of the wind is discussed in section 5.2. Figure 4.19 shows the timeline of the opened windows.

<table>
<thead>
<tr>
<th>29-04-2015</th>
<th>9:00</th>
<th>9:30</th>
<th>10:00</th>
<th>10:30</th>
<th>11:00</th>
<th>11:30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement period</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All 6 atrium windows</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower 3 atrium windows</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper 3 atrium windows</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Situation 1: \( T_e = 10.2°C \)
- Situation 2: \( T_e = 12.5°C \)
- Situation 3: \( T_e = 13.4°C \)
- Situation 4: \( T_e = 14.5°C \)

4.2.3 Measurement results and model fitting
This section contains the most important measurement results from each measurement step. Additional results are shown in Appendix F. In the graphs, simulation results are included from the preliminary model (with revision to one large zone and application of Contam). These simulations have been performed under similar circumstances as in the measurements (e.g. same ambient temperatures, mechanical ventilation rates, window openings). In this way it was possible to compare the simulation results with the measured results.
Results session 1: basic ventilation

The measured air temperatures and CO₂ rate for the entire measurement period are shown in Figure 6.10. The green area indicates the period where the heating system was turned off. The blue area indicates the period where the residents were absent.

![Figure 4.20 – Measured temperature curves and CO₂ rate during two weeks of the first measurement session.](image)

Ventilation indication by CO₂ decay

An indication of the ventilation rate in the house has been obtained by considering the CO₂ concentration decay during the period with free floating conditions (green area), using equation 3.10. The CO₂ concentration was decreasing during the night between 0:00 and 8:00, while the residents were in the adjacent bedroom. Figure 4.21 shows the decay of the CO₂ concentration during this night.

From equation 3.10 (Liddament, 2006) follows:

Air change rate = (6.6 - 6.39) / (8 hours) = 0.026 (h⁻¹)

Because the CO₂ concentration was lower than 800 ppm during the considered period, air was extracted by the hybrid ventilation system with a value of at least ACH=0.05 (h⁻¹). Because the calculated air flow rate indicates an even lower value, the outcome is not reliable. However, it indicates that the additional basic ventilation is less than the preliminary assumed ACH(basic)=0.5 (h⁻¹).
Air temperature

To compare the simulated and the measured air temperatures, the different measured air temperatures have been averaged to gain knowledge about the temperature in the entire zone, because Trnsys simulates the averaged air temperature of the entire zone. The averaged air temperature curve of the entire measurement period is shown in Appendix F. The solid red line in Figure 4.22 shows this averaged air temperature during the free floating conditions.

Figure 4.22 – Measured and simulated air temperature curves. Simulated temperature curves are corrected with an adapted ventilation rate and an adapted thermal mass.
Initial assumptions
The dashed lines in Figure 4.2 indicate simulated air temperature curves. The dashed red line presents the simulated air temperature in free floating conditions. The curve is dependent on the initial assumed values for ventilation and thermal capacity (section 4.1.1).

Adapted ventilation
The simulated air temperature with the initial assumptions decreases more than the measured air temperature. Based on this outcome and on the CO₂ concentration decay method of Figure 4.2, the value for basic ventilation has been adapted to a lower value. Instead of an additional basic ventilation of ACH\textsubscript{basic}=0.5 (h\textsuperscript{-1}), the value of ACH\textsubscript{basic}=0.2 (h\textsuperscript{-1}) has been applied. This simulation result is shown by the green line. Due to this lower ventilation rate, the temperature decreases significantly less than in the result of the initial assumption (broken red line). With a value of ACH\textsubscript{basic}=0.2 (h\textsuperscript{-1}), the slope of the simulated temperature is similar to the slope of the measured temperature (apart from the first hours, which can be explained by significant heat storage in the construction).

Adapted heat capacity
The zone capacitance was multiplied by a factor 5 in the preliminary model to include the influence of furniture (Bradley, 2011; Dipasquale et al., 2013). This theory has been verified in this section by considering the furniture in the entire zone. The specific heat values and the masses of the tables, cabinets and chairs have been estimated to determine a total additional heat capacitance in the zone. The heat capacitance of the air in the zone is applied as default value and calculated by V\textsubscript{zone} * ρ\textsubscript{air} * C\textsubscript{air} (Bradley, 2011). This value has been added to the additional heat capacitance for furniture. The estimated additional heat capacitance for each piece of furniture is presented in Table 4.4.

<table>
<thead>
<tr>
<th>Furniture</th>
<th>Average specific heat (kJ/kg K)</th>
<th>Mass (kg)</th>
<th>Heat capacitance (kJ/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Couch</td>
<td>1.3</td>
<td>100</td>
<td>130</td>
</tr>
<tr>
<td>Dinner table</td>
<td>1.88</td>
<td>100</td>
<td>188</td>
</tr>
<tr>
<td>Chairs (x6)</td>
<td>1.2</td>
<td>60</td>
<td>72</td>
</tr>
<tr>
<td>Coffee table</td>
<td>2</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>Dressoir</td>
<td>1.88</td>
<td>300</td>
<td>564</td>
</tr>
<tr>
<td>Cabinets (x2)</td>
<td>1.6</td>
<td>200</td>
<td>640</td>
</tr>
<tr>
<td>Desk</td>
<td>1.88</td>
<td>100</td>
<td>188</td>
</tr>
<tr>
<td>Stairs</td>
<td>0.8</td>
<td>100</td>
<td>80</td>
</tr>
<tr>
<td>Office cabinet</td>
<td>1.6</td>
<td>200</td>
<td>320</td>
</tr>
<tr>
<td>Kitchen interior</td>
<td>1.5</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>2432</strong></td>
</tr>
</tbody>
</table>

Air capacitance = 326.502 * 1.2 * 1.007 = 394.55 kJ/K  
Additional capacitance = 2432 kJ/K  
Total = 2826.55 kJ/K

As literature describes, the default value (394.55 kJ/K) should be multiplied by a factor 5 to 10 to include the heat capacity of the furniture. The new value has a multiplication factor of 2862.55/394.55 = 7.2. So the theory in literature has been confirmed and the value for heat capacity
has been increased. This increased value for heat capacity was adapted in the model and the resulting simulation curve is shown in Figure 4.22 by the purple dashed line. It results in a slightly higher temperature. Overall it can be stated that with the adapted parameters taken into account, the simulation result approaches the measured result. Especially in the first hours of the simulation, the simulated temperature decreases more rapidly than in reality, resulting in a colder indoor environment. However, in the real situation heat is stored in the building due to long term heating. This initial stored heat is not considered by the model.

**Surface temperature**

Figure 4.23a shows the measured air and surface temperatures and Figure 4.23b shows the simulated air and surface temperatures. The measured surface temperatures of the entire measurement period are shown in Appendix F. In this simulations the default CHTC is applied, which has a value of 11 (kJ/h·m²·K). To determine what influence this value has on the surface temperatures, it was enlarged and diminished by a factor 5. The resulting temperature curves of these simulations are shown in Figures 4.23c and 4.23d.
From these graphs, it can be stated that the effect of the CHTC in the air temperature is limited. A lower value approaches the steepness of the measured surface temperatures, but this would result into lower air temperatures than they appear in reality. The figures indicate that the CHTC could be kept at the default value.

**Model fitting according to measurement session 1**

The adapted values, based on the comparison of the first measurement results with the preliminary model simulation results, are summarized in table 4.5.

**Table 4.5 – Summary adapted values based on measurement session 1**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Based on</th>
<th>Preliminary value</th>
<th>Adapted value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACH&lt;sub&gt;basic&lt;/sub&gt;</td>
<td>CO&lt;sub&gt;2&lt;/sub&gt; decay</td>
<td>0.5 (h&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>0.2 (h&lt;sup&gt;-1&lt;/sup&gt;)</td>
</tr>
<tr>
<td></td>
<td>Air temperature measurement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat capacity zone</td>
<td>Air temperature measurement</td>
<td>1972.75 kJ/K</td>
<td>2826.55 kJ/K</td>
</tr>
<tr>
<td>CHTC</td>
<td>Surface temperatures</td>
<td>11 kJ/h·m&lt;sup&gt;2&lt;/sup&gt;·K</td>
<td>-</td>
</tr>
</tbody>
</table>

**Results session 2: hybrid ventilation**

**Air temperature**

The individual air temperatures, as well as the ambient temperature and the CO<sub>2</sub> rate measured in session 2 are shown in Appendix F. The *average* air temperature is shown in Figure 4.24. For the simulated results, the model adaptions from the former section (table 4.5) were maintained. Furthermore, the ventilation rates in the model were set at the same values as the hybrid ventilation system in the real-life situation $ACH_{(hybrid, overruled)} = 0.5$ (h<sup>-1</sup>) and $ACH_{(hybrid, automatic)} = 0.05$ (h<sup>-1</sup>).

![Figure 4.24 – Measured and simulated air temperature curves, measured ambient temperature and CO<sub>2</sub> rate. The schedule of air flow amount is indicated with different coloured areas.](image-url)
Figure 4.24 clearly shows that the simulated air temperature corresponds to the measured air temperature. The increase of the ventilation rate during the first 30 minutes did not lead to a temperature drop. The simulated and measured temperature show a similar increasing curve due to an increasing ambient temperature during the full measurement period. Because of the corresponding development of both curves, this figure indicates that the model is correctly fitted with the presumed and adapted values in the building specifications.

**Ventilation flow rates**

As stated before, the adapting ventilation rate during the measurements with hybrid ventilation system did not influence the indoor air temperature. However, the measured CO₂ concentration, as shown in Figure 4.24, clearly indicates differences in air flow rates. The blue area indicates the first 30 minutes of the measurement where the system was overruled to ACH=0.5 (h⁻¹). This value was confirmed with a flow finder, as the extracted air was measured at an average rate of 153 m³/h. This corresponds for a volume of 326 m³ to the applied air change rate per hour. The green area indicates the second period where the system was set back at automatic (ACH=0.05 (h⁻¹) when CO₂<800 ppm). Finally, to verify the differences in air flow rates, one atrium window was opened (red area). The expected increase in air flow rate due to thermal buoyancy is clearly visible in Figure 4.24. The CO₂ concentration decreases most during this period. This implies that opened atrium windows have large potential in increasing air flow rates and therefore ventilative cooling.

**Results session 3: natural ventilation**

**Air temperature**

![Figure 4.25](image)

Figure 4.25 – Temperature difference curves between inside and outside in living room and atrium due to opened windows. Four situations describe different combinations of opened windows.
Figure 4.25 shows the temperature difference curves in the living room and the atrium of the entire measurement period of the third session. The blue areas indicate when atrium windows were opened. The absolute temperature curves, as well as the measured CO₂ rate, are shown in Appendix F. According to the results, most cooling effect is created with higher temperature differences and when all six atrium windows were opened.

The measured indoor air temperatures of the living room and the atrium have been averaged to consider the mean temperature of a larger area in the zone. Besides, in the simulated result, the mean indoor air temperature of the entire zone is modelled. Figure 4.26 shows temperature differences between inside and outside, and the air change rates per hour (ACH) caused by thermal buoyancy.

\[
\Delta T \text{ (measured)} = T_{i, \text{average measured}} - T_{\text{ambient}}
\]

\[
\Delta T \text{ (simulated)} = T_{i, \text{simulated}} - T_{\text{ambient}}
\]

Figure 4.26 contains the results of situation 1, where six atrium windows were opened. The measured results seem to indicate that in reality the house cools down more rapidly than according to the model. However, this can be explained by the fact that the indoor temperatures near the air flow path have been measured (as can be seen in Figure 4.17), instead of considering the average temperature of the entire zone (as the model does). This has to be taken into account in order to ascertain that the model is operable for elaborated case studies. The comparisons between the measured and simulated temperature differences in the other three situations are shown in Appendix F.
Verifying simulated cooling effect
The marked area in Figure 4.27 indicates the area where the temperature has been measured in the third session. As can be seen, the air flow path is located in this area and thus the temperature in this area is decreased more rapidly than in other parts of the zone. Other parts are the office and the kitchen (marked in Figure 4.28). During the measurement with an included air flow, the temperatures in these areas also decrease, although they are not measured. For the verification of the simulation results, two conditions have been considered. In the first condition, the air flow has no effect on the temperature in these areas (it remains 21°C); in the second condition, the temperatures in these areas decrease similarly as the area directly in the air flow path (hence, an optimal cooling effect). The simulated temperature decay should be in between these two boundaries.

Figure 4.27 – Area in which temperature is measured
Figure 4.28 – Remaining areas that must be included in verification of model

Figure 4.29 shows the boundary temperature curves with no cooling effect in the remaining rooms (red line) and with maximum cooling effect (purple line) for the situation with six opened atrium windows. As can be seen, the simulated temperature difference curve is located between both conditions, which indicated that the model was correct.

However, a simulated temperature curve between the two boundary conditions was not attained in each situation. Figure 4.30 shows again the situation with six opened atrium windows, this time with smaller temperature differences. It can be seen that the simulated temperature provided even less cooling in the (entire) zone than the minimal expected cooling effect (red line). This indicated that the model was not correctly calibrated. The cooling effect had to be increased by increasing the air change rate in the zone. As stated in section 4.2.2, the wind speed during the measurements was 1-2 m/s. Therefore, a wind speed of 2 m/s with the same direction as the consisting air flow has been included in the air flow model. The resulting temperature curve and the air change rates are also shown in Figure 4.30. The ACH value increased from ±4.5 (h⁻¹) to ±7.5 (h⁻¹) due to the wind, resulting in a simulated temperature curve within the expected region.
Figure 4.29 – Simulated temperature decrease in combination with averaged minimum and maximum cooling effect in the surrounding zone area.

Figure 4.30 – Simulated temperature decrease, in combination with averaged minimum and maximum cooling effect in the surrounding zone area, for lower temperature differences; compared with simulated temperature decrease and ACH with included wind speed of 2 m/s.
**CO₂ decay**

Figures 4.26 and 4.30 show the simulated air change rate per hour (dashed blue line). It can be seen that as soon as the windows are opened, an air change rate occurs. Because the temperature difference between inside and outside decreased during the measurement period, the resulting air change rate also shows a decreasing curve.

![Figure 4.31 – Decay CO₂ rate with 6 opened atrium windows](image)

In order to get an indication of the ventilation rate from the measurements, the CO₂ concentration decay has been considered in Figure 4.31 as was done in section 4.2.3. An indication of the ventilation rate has been obtained by considering the CO₂ concentration decay with equation 3.10.

From equation 3.10 (Liddament, 2006) follows:

\[
\text{Air change rate} = \frac{(6.55-6.11)}{(5.5 \text{ minutes})} = 0.08 \text{ (min}^{-1}) \quad \rightarrow \quad \text{ACH} = 4.8 \text{ (h}^{-1})
\]

The simulated air flow indicated ACH values of 5-6 (h⁻¹) and with the influence of wind 7-8 (h⁻¹). Basic calculation, based on the measured CO₂ concentration decay, resulted in a comparable value within order of magnitude.

**4.2.4 Conclusions calibration**

For the purpose of using it in elaborated cases, the model has been calibrated. The model has been fitted to make the simulated results correspond to the measured results. Table 4.6 presents a summary of the considered parameters of each measurement session in the calibration process. With the (iteratively) applied adoptions, the simulation results correspond sufficiently to the measured results to apply the model for the elaborated cases. Deviations in the comparison of the results have been accepted with limitations of the model taken into account.
Measurement session | Variable | Initial value | Adapted value
--- | --- | --- | ---
**Basic ventilation** | $\text{ACH}_{(\text{hybrid})}$ | 0.05 ($h^{-1}$) | -
 | $\text{ACH}_{(\text{basic})}$ | 0.5 ($h^{-1}$) | 0.2 ($h^{-1}$)
 | Heat capacity | 1972.75 kJ/K | 2826.55 kJ/K
 | CHTC | 11 kJ/h·m²·K | -

**Hybrid ventilation**

 | $\text{ACH}_{(\text{hybrid, overruled})}$ | 0.5 ($h^{-1}$) | -
 | $\text{ACH}_{(\text{basic})}$ | 0.2 ($h^{-1}$) | -
 | Heat capacity | 2826.55 kJ/K | -

**Natural ventilation**

 | $\text{ACH}_{(\text{basic})}$ | 0.2 ($h^{-1}$) | -
 | Heat capacity | 2826.55 kJ/K | -
 | Wind speed | 0 m/s | 2 m/s
 | Wind direction | - | 90° (East)

**Limitations**

Creating a 100% accurate computational model of a dwelling in-use is hardly possible. Accuracy can merely be improved by detailed measurements and calibration. In this investigation, the simulated indoor temperatures, influenced by basic and hybrid ventilation, had the same slopes as the measured results after adapting several variables (Table 4.6). However, the simulated temperature curves showed an immediate decrease (Figure 4.22), while in reality, the temperature decreases more constantly. This is due to the limitation that in reality heat is stored in the building while in the simulation, the cooling starts at instant (no possibility of heat storage).

Instead of performing actual measurements for the air flow rates in HoTT, the tracer concentration decay method has been applied. The calculated and simulated ACH values corresponded within order of magnitude, but the accuracy of the calculation can be improved by measuring the CO$_2$ concentration at several places and by an artificial initial increase of the CO$_2$ rate.

Another limitation is the fact that the model considers the entire zone and mixed conditions, while the measurements were performed at a few points and local temperatures. This limitation has been resolved in the calibration of the air flow model, where two utmost conditions have been considered and the correctly simulated results have been expected in between those conditions.
### 4.3 Elaborated case study

From the former section, it has been stated that the model is properly calibrated. The model is assumed to be usable for elaborated cases. Two cases have been considered in this section, based on sub questions 4 and 5. It has been determined how overheating is prevented in HoTT and in the case overheating does occur, it has been determined how the house is cooled down again with natural ventilation in order to recreate a thermally comfortable environment.

#### 4.3.1 Overheating prevention

The overheating risk in HoTT according to the calibrated model has been investigated. This has been done by simulating the indoor temperatures during weekly periods with average Dutch weather conditions, as well as summer conditions. The adaptive temperature limits for residential buildings (Peeters et al.) have been applied as thermal comfort indicator. Overheating is prevented as long as the temperature does not exceed the upper temperature limit. For conditions in which overheating occurs, the following prevention measures have been applied in order to maintain thermal comfort:

1. **Natural ventilation**

In line with determining the ventilative cooling potential, natural ventilation has been applied to avoid that the house heats up too much. In this investigation, night ventilation was applied because ambient temperatures are significantly lower during night time and therefore night ventilation has a higher cooling potential. The applied air flow path (which has also been investigated in the calibration process) can be seen in Figure 4.32. Figure 4.33 presents the dimensions of the window heights and surfaces. The inlet air opening has been increased for the purpose of creating more air flow and therefore more cooling. The inlet surface has been set at 2m$^2$.

*Figure 4.32 – Three-dimensional air flow path*
All six atrium windows have been applied for this analysis, as well as the door in the living room. The Velux windows each have a maximum opening surface of approximately 0.1m² (three windows at each height). For the living room door, a surface of 2m² is assumed. The simulated air flow dimensions are schematically shown in Figure 7.2. Wind is not included in this analysis, because different wind directions can increase or decrease the air flow and thus the cooling potential. More accurate simulation results can be obtained by considering air flow only due to thermal buoyancy.

2. Exterior shading

Based on literature and the preliminary case study, exterior shadings have been applied in the model using the TRNBuild tool, to keep the temperature within the comfort zone.

3. Increased thermal mass

Literature stated that thermal mass can also reduce the overheating risk. The thermal mass cannot be changed in the house, but is has been investigated as mitigation strategy in general. The cooling time has been considered in order to obtain an indication of the time constant. This value can be used to investigate adaptions of the thermal mass.

4.3.2 Ventilative cooling

This section focusses on natural cooling in the House of Tomorrow Today. In the case that the overheating prevention has failed and the house is heated up too much during daytime, it has been investigated how thermal comfort is recreated with ventilative cooling. The air flow model from the calibration process has again been applied for this analysis (Figures 4.32 and 4.33). Different initial indoor temperatures have been considered in combination with various ambient temperatures. These different ambient temperatures correspond to different indoor comfort bands (adaptive temperature limits). In this way it has been possible to determine the cooling times. The cooling effect during one hour is considered. This research focusses on recreating a thermally comfortable indoor environment for the residents and if it is not possible to attain this environment with ventilative cooling as quickly as possible, it is not of interest for the residents. Furthermore, the ventilative cooling potential is investigated for varying air change rates due to different window openings, different thermal mass and inclusion of wind.
5. Results and discussion

5.1 Results over heating prevention

Figures 5.1 and 5.2 show weekly simulated temperature curves in free floating circumstances in average Dutch weather conditions and summer conditions, respectively, in order to indicate the overheating risk.

*Figure 5.1 – Free floating indoor air temperatures in average Dutch climate. The black lines are the upper and lower limit of the comfort zone and indicate whether overheating occurs.*

*Figure 5.2 – Free floating indoor air temperatures in Dutch summer period. The black lines are the upper and lower limit of the comfort zone and indicate whether overheating occurs.*
The indoor air temperature should be within the comfort band of the adapted temperature limits (Peeters et al.). It can be seen in Figure 5.2 that the indoor temperature (red line) exceeds the upper limit of the comfort band in a summer period. This outcome indicates overheating risk for daily peak temperatures of ±26°C and higher.

The first measure has been the implementation of ventilative night cooling in the model. This influence is shown in Figure 5.3. In the model, the condition is included that atrium windows (and door) are opened when $T_{\text{ambient}} < 20^\circ$C. The resulting air change rates when the windows are opened are also shown in Figure 5.3.

![Figure 5.3 – Improved indoor air temperature due to ventilative night cooling; with corresponding ACH values](image)

Despite the mitigation of overheating with ventilative cooling, the (improved) air temperature still exceeds the upper temperature limit. Therefore, a second mitigation strategy has been necessary. To ensure that the air temperature remains lower than the upper temperature limit, external shadings have been added to the living room windows and the atrium windows. An amount of 80% of the windows has been covered. In this way, solar gains have been diminished while daylight was still able to enter the building. The green line in Figure 5.4 represents the temperature curve with included night cooling and external shading. Although the indoor temperature exceeds the upper limit in free floating conditions, overheating is significantly reduced because of these measures.
**Time constant**

According to literature, another effective overheating mitigation strategy is increasing the thermal mass. The time constant (the reference value for the thermal mass) of the situation with an ambient temperature of 10°C and an indoor temperature of 30°C has been determined \((\text{ACH}=8-9 \text{ h}^{-1})\). The time constant is defined as the time it takes for the indoor temperature of this specific situation to cool down to 36.8% of the initial difference. This is \(10 + 0.368 \times (\Delta T) = 17.36°C\).

Figure 5.5 demonstrates that the time constant of the current situation with included air flow is 4 hours and 11 minutes. Thermal mass has been increased in the model by adding a layer of 200mm of concrete to the adjacent walls and the external walls. The red line in Figure 5.5 shows that the ventilative cooling effect is reduced due to increased thermal mass. The time constant has been increased to more than 18 hours. With this measure implemented in the model, it takes longer for the indoor temperature to increase in free floating conditions, which can be beneficial for occasional hot days. However, in case of a heat wave, it is possible that too much heat is stored in the building/construction. In that case, it would take longer for the zone to cool down again. The indoor air temperature as a result of an increased thermal mass is shown in Figure 5.6. Indoor peak temperatures are significantly reduced and less fluctuation occurs. Because it takes more time to cool down the house, overheating is more difficult to prevent after a long period of high temperatures. In this case, ventilative cooling provides opportunities to create thermal comfort.
Figure 5.5 – Time constant indication current situation and increased thermal mass

Figure 5.6 – Improved indoor air temperature due to increased thermal mass
5.2 Results ventilative cooling

Figures 5.7 – 5.10 show the cooling effect of the simulated air flow with ambient temperatures of respectively 5°C, 10°C, 15°C and 20°C. The temperature differences as a result of ventilative cooling are presented for a period of one hour. The ΔT values have been considered, so in fact, all the temperature curves could have been presented in one graph. However, they are presented in separate graphs with their reference ambient temperature. In this way it was possible to indicate the comfort zones and cooling times.

The comfort bands (Peeters, 2009) correspond to the reference ambient temperature and demonstrate the desired indoor temperature decrease. It can be seen for example (Figure 5.8) that with an initial indoor temperature of 26°C and an ambient temperature of 10°C, it takes ±33 minutes for the entire zone to become thermally comfortable again (21°C). Figure 5.10 shows that with an initial temperature of 30°C and an ambient temperature of 20°C, it is not possible to reach the thermal comfort boundary within one hour. When the ambient temperature is higher than 20°C, it would no longer be possible to cool down the building with natural ventilation.

![Figure 5.7 – Temperature difference curves between inside and outside for several initial indoor temperatures. The red area indicates the thermal comfort zone for an ambient temperature of 5°C.](image)

\[
T_e = 5°C
\]

\[
\begin{align*}
T_{(\text{initial})} &= 30°C \\
T_{(\text{initial})} &= 28°C \\
T_{(\text{initial})} &= 26°C \\
T_{(\text{initial})} &= 24°C
\end{align*}
\]
Figure 5.8 – Temperature difference curves between inside and outside for several initial indoor temperatures. The red area indicates the thermal comfort zone for an ambient temperature of 10°C.

Figure 5.9 – Temperature difference curves between inside and outside for several initial indoor temperatures. The red area indicates the thermal comfort zone for an ambient temperature of 15°C.
Adapted air flow rates

The applied temperature differences between inside and outside in combination with opened windows (Figures 4.32 and 4.33) resulted into an air change rate caused by thermal buoyancy. The maximum air change rates of the current situation in HoTT are presented in Figure 5.11 (blue line) as a function of the temperature difference. It can be seen that the air change rates increase for an increasing ΔT. ACH values of nearly 10 (h⁻¹) are attained.

Figure 5.10 – Temperature difference curves between inside and outside for several initial indoor temperatures. The red area indicates the thermal comfort zone for an ambient temperature of 20°C.

Figure 5.11 – Simulated air change rates as a function of the temperature difference
If the air change rates increase, a larger cooling effect can be attained. Larger window openings or a beneficial contribution of wind are able to increase the air change rates. In HoTT, the Velux atrium windows each can only open ±10cm. Therefore, air outlet window surfaces of 0.1m² for each window have been applied. To determine the influence of larger window openings, a situation has been considered where each window can open 50cm. This results in air outlet surfaces of 0.5m² (three windows per height row, Figure 5.12). The red line in Figure 5.11 presents the increased air change rate as a function of the temperature difference. Figure 5.13 shows the cooling effect (in ΔT’s) of the house when windows are implemented that are able to open 50cm.

As can be seen in Figure 5.13, the cooling effect is larger when the window openings are increased. The steepness of the temperature curves indicate that the building is cooled down more rapidly than in the current situation with the limited possibility of window openings.

![Figure 5.12 – Schematic air flow path with increased air outlet window](image)

![Figure 5.13 – Cooling effect natural ventilation with increased air outlet surfaces, expressed in ΔT](image)
Section 5.1 discussed the increase of the thermal mass. This turned out to be an effective overheating prevention strategy. Figure 5.14 shows the cooling effect of the current situation with increased thermal mass. The results show that due to increased thermal mass, the cooling effect is reduced. It takes longer to cool down the building than with the present thermal mass. Thus, although this measure effectively prevents overheating, it reduces the ventilative cooling potential.

**Influence wind**

As stated in literature and in section 4.2.3, wind is able to increase the air change rates. However, wind can also have a negative effect on the air flow. If the wind direction is opposite to the air flow path due to thermal buoyancy, the air change rates will decrease.

The influence of the wind has been considered in the model. Wind speeds of 5m/s were included in two opposite directions. The inclusion of wind in the direction of the flow path (inlet through the door and outlet through the atrium windows) and in the direction against the flow path have been simulated. The resulting air change rates are shown in Figure 5.15. The graph shows that wind can have a negative effect in the air change rates, and because of the stochastic patterns, it is hard to include wind accurately in the model. Nevertheless, it can be stated that wind is able to improve the air flow caused by thermal buoyancy, as long as its direction is towards the lower window opening of the flow path (Figure 5.16).
Figure 5.15 – Air change rates with the influence of wind in opposite directions

Figure 5.16 – Influence wind in opposite directions
6. Conclusion and recommendation

6.1 Ventilative cooling potential

The main research question is how thermal comfort is created in HoTT with ventilative cooling. The results showed that with the opening of the living room door in combination with the opening of the atrium windows, an ambient temperature of 20°C is able to recreate thermal comfort within one hour from indoor temperatures up to 26°C. When the ambient temperature is 10°C, indoor temperatures up to 30°C can be remedied with ventilative cooling. Natural ventilation with air change rates up to ACH=10 (h⁻¹) can be attained in HoTT by using the atrium windows optimally. According to the results, wind is able to influence the air change rate. This value can be increased or decreased, dependent on the wind direction.

Nevertheless, indoor temperatures higher than 26°C should be prevented, otherwise the comfort zone cannot be reached within one hour for higher ambient temperatures. Figure 6.1 presents an overview of the cooling times for initial indoor temperatures and corresponding ambient temperatures. In order to prevent the temperature in HoTT to exceed 26°C, the results showed that ventilative night cooling and exterior shading during the day significantly reduce the daily indoor temperatures. Overheating prevention turned out to be necessary when the daily ambient temperatures rise up to 26°C and higher.

![Figure 6.1](image_url)  
*Figure 6.1 – Summary of the ventilative cooling time of various initial indoor temperatures and corresponding ambient temperatures.*
6.2 Recommendation ventilative cooling

In HoTT, for temperature differences of $\Delta T=6^\circ\text{C}$ or larger, natural ventilation can create thermal comfort within one hour. Ventilative cooling with shorter cooling times and with smaller temperature differences can be attained in low-energy dwellings if the air flow rates are increased. Larger window openings or positive contribution of the wind can increase air flow rates. Therefore, it is recommended that surfaces of the air inlet and outlet are large enough to create natural ventilation with air change rates up to 20 ($\text{h}^{-1}$). The improved cooling effect of larger window openings has been discussed in section 5.2. The cooling times of this improved situation are shown in Figure 6.2. Comparison with Figure 6.1 demonstrates that in this improved variant with larger air flow rates, also indoor temperatures of 28°C and 30°C can be remedied within one hour for ambient temperatures up to 20°C.

![Figure 6.2 – Summary of the ventilative cooling time of various initial indoor temperatures and corresponding ambient temperatures for increased air outlet surfaces](image)

The overall conclusion for ventilative cooling in HoTT is that cooling down the building with natural ventilation is limitedly possible. If natural ventilation is aspired to be the only cooling system in the house, it is recommended that the atrium windows are adapted in order to attain larger opening surfaces and therefore larger air flow rates. Furthermore, a smart system is proposed that continuously measures the wind direction. If the wind direction is towards the living room door (east), the office room door (south) or the kitchen window (west), it can be opened in combination with the atrium windows to attain an increased air flow rate with optimal utilization of the wind.
The final question is to what extent the results from HoTT are representative for low-energy dwellings in general. First of all, the investigated case is an active house. Therefore, this guidance for ventilative cooling is representative for this type of low-energy dwelling. This research showed that overheating in low-energy dwellings can be mitigated with natural ventilation during the night and exterior shading during the day. This has been considered for HoTT as a representative case, which can be categorized as a lightweight building where most thermal mass is situated in the concrete floor. However, the investigation of an increased thermal mass and increased time constant demonstrated that a large thermal mass provides significant overheating mitigation.

It can be stated for low-energy dwellings in general, that for the prevention of overheating lightweight buildings are dissuaded. Heavyweight buildings have a high thermal mass and therefore a lower risk of overheating. In case of a heat wave, ventilative cooling can be applied to eliminate surplus heat in heavyweight buildings, but due to the higher time constant, the natural cooling potential is limited.

The advantage of a lightweight building is that ventilative cooling is more effective. A lightweight building has a higher risk of overheating, but in case of overheating, natural cooling can be applied to rapidly cool down the building to the comfort zone. This cooling time can be improved by the possibility of large window openings. Overheating can be prevented by the application of window shadings.

### 6.3 Follow-up research

The simulated air change rates have been verified with the tracer concentration decay method within order of magnitude. Measurements of the exact air change rates due to open windows in the house would provide more insight. In this way accurate ACH values can be obtained and the cooling effect they provide can be used as recommendation for similar low-energy dwellings.

From this research, it turned out that wind is able to influence the air flow for ventilative cooling. However wind has stochastic patterns, which make it hard to accurately include wind in the ventilative cooling investigation. An additional (CFD) study of the House of Tomorrow Today of the wind behaviour provides information about how wind should be included in the model.

Although difficult to investigate in a dwelling in-use, the time constant of HoTT without natural ventilation would characterize the thermal mass of this lightweight building. With this time constant in combination with validated air change rates, the ventilative cooling potential of low-energy dwellings with a similar thermal mass can be determined.
7. References


[22] Reddy, R. Building Time Constant (Verification) in LEB. Technical University Eindhoven, BPS Unit, Department of the built Environment. 2015.


Appendix

A. Overheating thresholds from standard

Figure A1 – Design values for the indoor operative temperature for buildings without mechanical cooling systems as a function of the exponentially-weighted running mean of the outdoor temperatures (NEN-EN 15252).

\[ \Theta_{\text{rm}} = \text{Outdoor Running mean temperature (°C)} \]

\( (\text{combination of current and mean ambient temperatures of the former days}) \)

\[ \Theta_o = \text{Operative temperature (°C)} \]
B. Air flow rate calculation methods

Single sided ventilation driven by thermal buoyancy

\[
Q_v = \frac{1}{3} \cdot C_D \cdot A \cdot \sqrt{\frac{(T_i - T_e) \cdot g \cdot (H_t - H_b)}{T}} \tag{1}
\]

- \(Q_v\) = air flow volume (m\(^3\)/s)
- \(C_D\) = discharge coefficient (between 0.6 and 0.75) (-)
- \(A\) = window surface (m\(^2\))
- \(T_i\) = internal temperature (K)
- \(T_e\) = external temperature (K)
- \(g\) = gravitational acceleration (m/s\(^2\))
- \(H_t\) = top window opening (m)
- \(H_b\) = bottom window opening (m)

Air flows driven by buoyancy through a single opening have a bidirectional flow pattern and can be calculated with equation 1. The direction of the velocity changes at the level of the neutral plane \(H_n\) (Figure B1) (Heiselberg et al. 2005).

Cross ventilation driven by thermal buoyancy

Buoyancy driven ventilation is caused by a pressure difference created by thermal buoyancy. It is obtained with equation 2. Air flow caused by thermal buoyancy through one of multiple window openings can be calculated with equation 3. The different window openings should be at different heights in the building (Figure B2).

\[
\Delta P_{\text{buoyancy}} = \rho_e \cdot g \cdot (H_0 - H_1) \cdot \frac{T_i - T_e}{T_i} \tag{2}
\]

\[
\Delta P_{\text{wind}} = \text{pressure difference caused by temperature difference (Pa)}
\]

- \(\rho_e\) = external density (kg/m\(^3\))
- \(T_i\) = internal temperature (K)
- \(T_e\) = external temperature (K)

\[
Q_v = \pm C_D \cdot A \cdot \frac{1}{\rho} \cdot \sqrt{\frac{2 \cdot \rho_e \cdot g \cdot (H_0 - H_1) \cdot (T_i - T_e)}{T_i}} \tag{3}
\]
Single sided ventilation driven by wind

Wind driven ventilation is caused by pressure differences, created by wind speed and direction. Overpressure will occur at the windward side of the building, and underpressure at the leeward side (Figure B3). Equation 4 describes how the pressure difference between inside and outside is calculated.

\[ \Delta P_{\text{wind}} = C_p \cdot \frac{1}{2} \cdot \rho_e \cdot U_{\text{ref}}^2 - P_i \]  

\( \Delta P_{\text{wind}} \) = pressure difference caused by wind (Pa)  
\( C_p \) = pressure coefficient (-)  
\( \rho_e \) = external density (kg/m\(^3\))  
\( U_{\text{ref}} \) = velocity at reference height (m/s)  
\( P_i \) = pressure inside (Pa)

Based on the pressure difference, the wind driven air flow can be calculated with equation 5:

\[ Q_v = \mp C_D \cdot A \cdot \sqrt{\frac{2 \cdot C_p \cdot \frac{1}{2} \cdot \rho_e \cdot U_{\text{ref}}^2 - P_i}{\rho}} \]  

\( Q_v \) = air flow volume (m\(^3\)/s)  
\( A \) = window surface (m\(^2\))  
\( H \) = window height (m)  
\( C_D \) = discharge coefficient (between 0.6 and 0.75) (-)  
\( C_p \) = pressure coefficient (-)  
\( \rho_i \) = internal density (kg/m\(^3\))  
\( \rho_e \) = external density (kg/m\(^3\))

Cross ventilation driven by thermal buoyancy and wind

Natural ventilation in reality is usually caused by both thermal buoyancy and wind. For this calculation, pressure differences of both buoyancy (eq. 2) and wind (eq. 4) are combined. The internal pressure \( P_i \) and the neutral plane \( H_0 \) must be derived from an iterative solution of the mass balance (Heiselberg et al., 2005). With equation 6, the air flow driven by buoyancy and wind can be calculated:

\[ Q_Y = Q_v \sum_{j=1}^{n} C_{D,j} \cdot A_{j} \cdot \left( \frac{\sqrt[\frac{1}{3}]{{\frac{2}{3}} \cdot C_{p,j} \cdot \rho_e \cdot U_{\text{ref}}^2 \cdot \frac{P_i + \frac{1}{2} \cdot \rho_e \cdot \Delta T}{T_i} - g \cdot (H_0 - H_j)}}{\frac{1}{2} \cdot \rho_{j}} \right)^{\frac{1}{3}} \]

\( Q_v \) = air flow volume (m\(^3\)/s)  
\( A \) = window surface (m\(^2\))  
\( H \) = window height (m)  
\( C_D \) = discharge coefficient (between 0.6 and 0.75) (-)  
\( C_p \) = pressure coefficient (-)  
\( \rho_i \) = internal density (kg/m\(^3\))  
\( \rho_e \) = external density (kg/m\(^3\))
C. House of Tomorrow Today

“The House of Tomorrow Today (HoTT) is a demonstration, experiment and a living lab with regard to three visions” (Lichtenberg, 2012). The first vision is the Active House concept. In this concept, a modern energy vision is applied that focusses on the comfort of the user. The second vision is the Slimbouwen concept. This is a concept based on an efficient process which focusses on the economical realisation of a high quality. The third vision is based on a circular economy that also contains the concept of Cradle to Cradle. This is specifically applied in the way in which materials are selected and how they are coped with. Figure C1 shows an impression of HoTT and Figure C2 shows the conceptual point of view.

**Figure C1 – Impression House of Tomorrow Today**

**Figure C2 – Concept House of Tomorrow Today (Lichtenberg, 2012)**
The project concerns a detached family dwelling. Characteristic is the high quality building envelope with a thermal resistance $R_c$ of ±6.5 m$^2$K/W. The orientation of the house and the location of the windows are designed to capture much daylight, but to prevent an excessive amount of sunlight. The southern roof is fully covered with PV and solar panels. The included air heat pump operates on the self-generated power. There is a connection to the grid however. Special HR++ glazing is applied. A central hallway that can be considered as an ‘aorta’, splits the house in two parts. In this aorta a floor heating system is realized.

Furthermore, a hybrid ventilation system with natural inlet and mechanical exhaust is applied. Fresh air enters the building through openings above the windows and air is mechanically extracted. It is an automatic, CO$_2$ controlled system that adjusts the air flow rate based on CO$_2$ rates between 800 and 900 ppm. This comes down to air flow rates varying from 15m$^3$/h to 150m$^3$/h (in the living room).
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<th>Zone</th>
<th>Volume (m$^3$)</th>
<th>Condition (°C)</th>
<th>Gains</th>
<th>Profile</th>
<th>Inlet air</th>
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<th>Window area (m$^2$)</th>
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<td>4.07+3.73</td>
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<td>Mechanically + Manual air extractor</td>
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<td>Hallway</td>
<td>36.68</td>
<td>20.0</td>
<td>Heat convector</td>
<td>5 Vents</td>
<td>Natural</td>
<td>5.53+5.48+4.43</td>
<td>N, E</td>
<td></td>
</tr>
<tr>
<td>0.13</td>
<td>Bed and breakfast</td>
<td>Bed_and_breakfast</td>
<td>76.80</td>
<td>15.0</td>
<td>Heat convector</td>
<td>2 Vents</td>
<td>Natural</td>
<td>4.56+7.79</td>
<td>N, S</td>
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</tr>
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<td>0.14</td>
<td>Bathroom 2</td>
<td>Bathroom_B</td>
<td>17.22</td>
<td>22.0</td>
<td>Heat convector</td>
<td>4 Window</td>
<td>Mechanically</td>
<td>1.88</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>1.01</td>
<td>Hall</td>
<td>Atrium</td>
<td>11.50</td>
<td>20.0</td>
<td></td>
<td>5 Window</td>
<td>Natural</td>
<td>Same as 0.04</td>
<td>N, S</td>
<td></td>
</tr>
<tr>
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<td>Bedroom_3</td>
<td>39.00</td>
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<td>Heat convector</td>
<td>2 Vents</td>
<td>Natural</td>
<td>1.41+2.60</td>
<td>E, S</td>
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<tr>
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<td>Mechanically</td>
<td>1.57</td>
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</tr>
<tr>
<td>1.04</td>
<td>Bedroom 2</td>
<td>Bedroom_2</td>
<td>54.15</td>
<td>15.0</td>
<td>Heat convector</td>
<td>2 Vents</td>
<td>Natural</td>
<td>1.41+2.85</td>
<td>W, S</td>
<td></td>
</tr>
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<td>1.05</td>
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<td>Tech_room_2</td>
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<td>6 -</td>
<td>Mechanically</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
Profiles

1. Occupied at daytime (living room)
2. Occupied at nighttime (bedroom)
3. 30-60 minutes per day in total (kitchen)
4. 10-30 minutes per day in total (bathroom)
5. Short visits 10-30 minutes a day in total (restroom/traffic room)
6. Once in a while (technical room)
### Wall specifications

#### Table C2 – Material properties external wall

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness d (m)</th>
<th>Conductivity λ (W/m K)</th>
<th>Capacity $C_p$ (kJ/kg K)</th>
<th>Density $\rho$ (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigidur gypsum</td>
<td>0.012</td>
<td>0.16</td>
<td>1.09</td>
<td>800</td>
</tr>
<tr>
<td>Rigidur prefab plasterboard</td>
<td>0.013</td>
<td>0.16</td>
<td>1.09</td>
<td>800</td>
</tr>
<tr>
<td>Mineral wool</td>
<td>0.173</td>
<td>0.04</td>
<td>0.84</td>
<td>30</td>
</tr>
<tr>
<td>Spano wood</td>
<td>0.018</td>
<td>0.15</td>
<td>1.88</td>
<td>800</td>
</tr>
<tr>
<td>Rockwool</td>
<td>0.090</td>
<td>0.035</td>
<td>1.4</td>
<td>25</td>
</tr>
<tr>
<td>Cavity</td>
<td>0.031</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Brick</td>
<td>0.065</td>
<td>0.89</td>
<td>0.79</td>
<td>1920</td>
</tr>
</tbody>
</table>

#### Table C3 – Material properties internal wall

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness d (m)</th>
<th>Conductivity λ (W/m K)</th>
<th>Capacity $C_p$ (kJ/kg K)</th>
<th>Density $\rho$ (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timber</td>
<td>0.017</td>
<td>0.14</td>
<td>1.2</td>
<td>650</td>
</tr>
<tr>
<td>Cavity</td>
<td>0.022</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mineral wool</td>
<td>0.128</td>
<td>0.04</td>
<td>0.84</td>
<td>30</td>
</tr>
<tr>
<td>Rigidur gypsum</td>
<td>0.012</td>
<td>0.16</td>
<td>1.09</td>
<td>800</td>
</tr>
</tbody>
</table>

#### Table C4 – Material properties ground floor

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness d (m)</th>
<th>Conductivity λ (W/m K)</th>
<th>Capacity $C_p$ (kJ/kg K)</th>
<th>Density $\rho$ (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>0.10</td>
<td>0.29</td>
<td>1.55</td>
<td>1100</td>
</tr>
<tr>
<td>EPS</td>
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<td>0.035</td>
<td>1.47</td>
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<td>Concrete</td>
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</table>

#### Table C5 – Material properties roof

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<th>Material</th>
<th>Thickness d (m)</th>
<th>Conductivity λ (W/m K)</th>
<th>Capacity $C_p$ (kJ/kg K)</th>
<th>Density $\rho$ (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigidur gypsum</td>
<td>0.012</td>
<td>0.16</td>
<td>1.09</td>
<td>800</td>
</tr>
<tr>
<td>Rockwool</td>
<td>0.22</td>
<td>0.035</td>
<td>1.4</td>
<td>25</td>
</tr>
<tr>
<td>Spano wood</td>
<td>0.018</td>
<td>0.15</td>
<td>1.88</td>
<td>800</td>
</tr>
<tr>
<td>Mineral wool</td>
<td>0.10</td>
<td>0.04</td>
<td>0.84</td>
<td>30</td>
</tr>
<tr>
<td>Alkor roof cover</td>
<td>0.002</td>
<td>205</td>
<td>0.91</td>
<td>2700</td>
</tr>
</tbody>
</table>
D. TRNFlow simulation result

Resulting simulation data

![Graph showing ACH [hr⁻¹] over time](image)

Figure D1 – TRNFlow ventilation results bedroom

**Basic calculation**

When two windows are opened in a room, it is expected that the air volume in that room is renewed by fresh air multiple times per hour. Based on the work of Larsen (2006), a basic calculation can be made for airflow due to thermal buoyancy using equation 3 from Appendix B:

\[
Q_v = \pm C_D \cdot A \cdot \sqrt{2 \cdot \rho_v \cdot g \cdot (H_0 - H_1) \cdot \frac{T_i - T_e}{T_i} / \rho}
\]

The estimated discharge coefficient \(C_D = 0.65\) and because \(H_1\) and \(H_2\) (figure B2) are at respectively 1.5m and 4m, the neutral line \(H_0\) is estimated at 2.5m. The window surface is set at 1m² and a temperature difference of \(\Delta T = T_i - T_e = 20 - 15 = 5^\circ C\) is assumed.

For the assumed values, the airflow \(Q_v\) becomes 1.44 m³/s. With a room volume of 128 m³ (living room), the air change rate per hour becomes ACH=40. Although this is a basic calculation based on estimations, it implies that the air change rate should be more than the TRNFlow tool simulates.
E. Measurement equipment

**Basic ventilation**

Table E1 – Measurement equipment session 1

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Parameter</th>
<th>Location</th>
<th>Accuracy</th>
<th>Unit</th>
<th>Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID-1568</td>
<td>T&lt;sub&gt;air&lt;/sub&gt;</td>
<td>Living room</td>
<td>-40.0 to 70.0 °C</td>
<td>°C</td>
<td>00:10:00</td>
</tr>
<tr>
<td>ID-1801</td>
<td></td>
<td>Atrium</td>
<td>-40.0 to 70.0 °C</td>
<td>°C</td>
<td>00:10:00</td>
</tr>
<tr>
<td>ID-1797</td>
<td></td>
<td>Kitchen</td>
<td>-40.0 to 70.0 °C</td>
<td>°C</td>
<td>00:10:00</td>
</tr>
<tr>
<td>ID-1569</td>
<td></td>
<td>Office</td>
<td>-40.0 to 70.0 °C</td>
<td>°C</td>
<td>00:10:00</td>
</tr>
<tr>
<td>ID-1436</td>
<td>T&lt;sub&gt;wall&lt;/sub&gt;</td>
<td>Living room</td>
<td>-30.0 to 65.0 °C</td>
<td>°C</td>
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</tr>
<tr>
<td>ID-0972</td>
<td>T&lt;sub&gt;floor&lt;/sub&gt;</td>
<td>Living room</td>
<td>-30.0 to 65.0 °C</td>
<td>°C</td>
<td>00:10:00</td>
</tr>
<tr>
<td>ID-1430</td>
<td>T&lt;sub&gt;ambient&lt;/sub&gt;</td>
<td>Outside</td>
<td>-40.0 to 70.0 °C</td>
<td>°C</td>
<td>00:10:00</td>
</tr>
<tr>
<td>h100-18714</td>
<td>CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Atrium</td>
<td>0 to 5000 ppm</td>
<td>ppm</td>
<td>00:10:00</td>
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</table>

**Hybrid ventilation**

Table E2 – Measurement equipment session 2

<table>
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<tr>
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<th>Accuracy</th>
<th>Unit</th>
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<tbody>
<tr>
<td>ID-1568</td>
<td>T&lt;sub&gt;air&lt;/sub&gt;</td>
<td>Living room</td>
<td>-40.0 to 70.0 °C</td>
<td>°C</td>
<td>00:00:10</td>
</tr>
<tr>
<td>ID-1801</td>
<td></td>
<td>Atrium</td>
<td>-40.0 to 70.0 °C</td>
<td>°C</td>
<td>00:00:10</td>
</tr>
<tr>
<td>ID-1797</td>
<td></td>
<td>Kitchen</td>
<td>-40.0 to 70.0 °C</td>
<td>°C</td>
<td>00:00:10</td>
</tr>
<tr>
<td>ID-1569</td>
<td></td>
<td>Office</td>
<td>-40.0 to 70.0 °C</td>
<td>°C</td>
<td>00:00:10</td>
</tr>
<tr>
<td>ID-1430</td>
<td>T&lt;sub&gt;ambient&lt;/sub&gt;</td>
<td>Outside</td>
<td>-40.0 to 70.0 °C</td>
<td>°C</td>
<td>00:00:10</td>
</tr>
<tr>
<td>h100-18714</td>
<td>CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Atrium</td>
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<td>ppm</td>
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<tr>
<td>ID 2289</td>
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<td>m&lt;sup&gt;3&lt;/sup&gt;/h</td>
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**Natural ventilation**

Table E3 – Measurement equipment session 3

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<th>Accuracy</th>
<th>Unit</th>
<th>Interval</th>
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</thead>
<tbody>
<tr>
<td>ID-1568</td>
<td>T&lt;sub&gt;air&lt;/sub&gt;</td>
<td>Living room</td>
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<td>°C</td>
<td>00:00:10</td>
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<tr>
<td>ID-1801</td>
<td></td>
<td>Atrium</td>
<td>-40.0 to 70.0 °C</td>
<td>°C</td>
<td>00:00:10</td>
</tr>
<tr>
<td>ID-1430</td>
<td>T&lt;sub&gt;ambient&lt;/sub&gt;</td>
<td>Outside</td>
<td>-40.0 to 70.0 °C</td>
<td>°C</td>
<td>00:00:10</td>
</tr>
<tr>
<td>h100-18714</td>
<td>CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Living room</td>
<td>0 to 5000 ppm</td>
<td>ppm</td>
<td>00:00:10</td>
</tr>
</tbody>
</table>
F. Additional measurement results

Session 1: Basic ventilation

Figure F1 – Average air temperature and CO₂ rate during two weeks of the first measurement step.

Figure F2 – Measured air and surface temperatures entire period of the first measurement step.
Session 2: Hybrid ventilation

Figure F3 – Measured temperatures and CO₂ rate of second measurement session.

Session 3: Natural ventilation

Figure F4 – Measured temperature curves with opened windows. The blue areas represent what times atrium windows were opened.
Figure F5 – Temperature difference between average indoor air temperature and ambient temperature; temperature difference between simulated air temperature and ambient temperature; ACH, situation 2

Figure F6 – Temperature difference between average indoor air temperature and ambient temperature; temperature difference between simulated air temperature and ambient temperature; ACH, situation 3
Figure F7 – Temperature difference between average indoor air temperature and ambient temperature; temperature difference between simulated air temperature and ambient temperature; ACH, situation 4