Climate change and heat stress in residential buildings

Evaluation of adaptation measures

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Abstract

Climate is changing and this result, amongst others, in a rise in temperature in the Netherlands (Klein Tank & Lenderink, 2009). It is assumed that this rise in temperature will decrease the thermal comfort in dwellings, especially in summer periods. Therefore, the focus of this research is on how dwellings could be adapted, by applying passive climate adaptive measures, to reduce the decrease in thermal comfort in future summer situations. Passive measures are defined, in this research, as measures which do not use energy when they are applied. The summer situation that is created is composed of climate data of the summer of 2003, because it is predicted that this summer will become an average summer during the 2040s (Scott et al., 2004). Four different dwelling typologies, which vary in the amount of insulation which is present in the construction of the roof and walls, are simulated. The following measures are applied to the different dwelling types: increasing the amount of insulation, increasing the thermal mass, increasing the albedo, implementing an overhang above vertical windows, opening the windows above a certain temperature and implementing a vegetated façade or roof. The effects that these measures have on the indoor thermal comfort of the different dwelling types are evaluated by counting the number of hours above the so-called adjusted adaptive temperature limit (overheating hours).

Different dwelling types have been defined in this research; dwelling types 1 represents a dwelling built before 1974, dwelling type 2 represents a dwelling built between 1974 and 1991, dwelling type 3 represents a dwelling built between 1992 and 2011 and dwelling type 4 represents a dwelling built after 2011. When renovating, it depends on the dwelling type which measures could be applied best to obtain the largest reduction in overheating hours. For dwelling type 1, the measure ‘albedo’ shows the largest reduction in overheating hours, while the measure ‘thermal mass’ shows the smallest reduction in overheating hours. The measure ‘opening of windows’ shows the largest reduction in overheating hours for dwelling type 2. The smallest reduction in overheating hours for this dwelling type is obtained by the measure ‘thermal mass’. For dwelling type 3, the largest reduction can be obtained by applying the measure ‘overhang’ or ‘opening windows’. The degree of reduction in overheating hours for this dwelling type depends on the orientation of the dwelling. For the newest dwelling (type 4), the largest reduction can be obtained by applying the measure ‘overhang’ or ‘opening windows’. This order depends on the orientation of the dwelling.
# Table of content

1. **ACKNOWLEDGEMENTS**

2. **INTRODUCTION**
   2.1 **MOTIVATION FOR RESEARCH**
      2.1.1 Consortium ‘Climate Proof Cities’
   2.2 **BACKGROUND INFORMATION**
      2.2.1 Climate change
      2.2.2 Influence on humans
      2.2.3 Buildings
      2.2.4 Passive climate adaptive measures
   2.3 **RESEARCH OBJECTIVE**
      2.3.1 Research question
      2.3.2 Sub-questions
   2.4 **OUTLINE REPORT**

3. **METHODS**
   3.1 **SIMULATION INPUT PARAMETERS**
      3.1.1 Typical Dutch dwelling
      3.1.2 User profiles
      3.1.3 Ventilation and infiltration rate
      3.1.4 Simulation period
      3.1.5 Climate data
      3.1.6 Ground properties
      3.1.7 Orientations
   3.2 **PASSIVE CLIMATE ADAPTIVE MEASURES**
      3.2.1 Increasing amount of insulation
      3.2.2 Increasing thermal mass
      3.2.3 Increasing the albedo value
      3.2.4 Implementing an overhang
      3.2.5 Opening of windows
      3.2.6 Implementing a vegetated facade and/or roof
   3.3 **OVERVIEW SIMULATIONS**
   3.4 **REFERENCE DWELLING TYPES**
   3.5 **PERFORMANCE INDICATOR**
      3.5.1 Predicted Mean Vote
      3.5.2 Overheating hours
      3.5.3 Weighted overheating hours
      3.5.4 Adaptive Temperature Limit
      3.5.5 Adjusted adaptive temperature limit
      3.5.6 Performance indicator applied
   3.6 **PROGRAMS USED**
      3.6.1 Building energy simulation
4. RESULTS

4.1 BASE CASE DWELLING
   4.1.1 Ambient temperatures
   4.1.2 Operative indoor temperatures
   4.1.3 Adjusted adaptive temperature limit
   4.1.4 Indication older dwellings

4.2 PASSIVE CLIMATE ADAPTIVE MEASURES
   4.2.1 Increasing amount of insulation
   4.2.2 Increasing thermal mass
   4.2.3 Increasing the albedo value
   4.2.4 Implementing an overhang
   4.2.5 Opening windows
   4.2.6 Implementing a vegetated facade and/or roof

5. DISCUSSION

5.1 REFERENCE DWELLING TYPE BUILT BEFORE 1974
5.2 REFERENCE DWELLING TYPE 1974 - 1991
5.3 REFERENCE DWELLING TYPE 1992 – 2011
5.4 REFERENCE DWELLING TYPE BUILT AFTER 2011

6. CONCLUSIONS

6.1 SUB-QUESTIONS
6.2 RESEARCH QUESTION
6.3 RECOMMENDATIONS

7. REFERENCES

8. APPENDICES

I. Floor maps and facades of analysed dwelling
II. Material properties of analysed dwelling
III. Simulated ambient indoor temperatures
IV. Simulated operative indoor temperatures
V. Overheating hours per measure
VI. Overheating hours per dwelling type
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Variable</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>DuBois surface area of the naked body</td>
<td>m²</td>
</tr>
<tr>
<td>ACH</td>
<td>Air changes per hour</td>
<td>1/h</td>
</tr>
<tr>
<td>C</td>
<td>Convective heat flux</td>
<td>W/m²</td>
</tr>
<tr>
<td>Cₚ</td>
<td>Wind pressure coefficient</td>
<td>-</td>
</tr>
<tr>
<td>d</td>
<td>Thickness</td>
<td>m</td>
</tr>
<tr>
<td>Eₜ</td>
<td>Heat loss by water vapour diffusion through the skin</td>
<td>W/m²</td>
</tr>
<tr>
<td>Eₑₑ½</td>
<td>Latent heat loss due to respiration</td>
<td>W/m²</td>
</tr>
<tr>
<td>Eₑₑ½</td>
<td>Evaporation heat loss due to sweating</td>
<td>W/m²</td>
</tr>
<tr>
<td>hᵣ</td>
<td>Heat transfer coefficient for radiation</td>
<td>W/m²K</td>
</tr>
<tr>
<td>hₖ</td>
<td>Heat transfer coefficient for convection</td>
<td>W/m²K</td>
</tr>
<tr>
<td>IR</td>
<td>Infiltration rate</td>
<td>m³/s</td>
</tr>
<tr>
<td>L</td>
<td>Sensible heat loss due to respiration</td>
<td>W/m²</td>
</tr>
<tr>
<td>LAI</td>
<td>Leaf Area Index</td>
<td>-</td>
</tr>
<tr>
<td>M</td>
<td>Metabolic flux</td>
<td>W/m²</td>
</tr>
<tr>
<td>P</td>
<td>Power</td>
<td>W</td>
</tr>
<tr>
<td>P₀</td>
<td>Static reference pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>P₃</td>
<td>Dynamic pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>PMV</td>
<td>Predicted Mean Vote</td>
<td>-</td>
</tr>
<tr>
<td>PPD</td>
<td>Predicted Percentage Dissatisfied</td>
<td>-</td>
</tr>
<tr>
<td>Pₓ</td>
<td>Static pressure at a given point on the building façade</td>
<td>Pa</td>
</tr>
<tr>
<td>Qₑₑ condemn梭</td>
<td>Conductive heat flux</td>
<td>W/m²</td>
</tr>
<tr>
<td>Qₑₑ ET</td>
<td>Evapotranspiration heat flux</td>
<td>W/m²</td>
</tr>
<tr>
<td>Qₑₑ sensible</td>
<td>Sensible heat flux</td>
<td>W/m²</td>
</tr>
<tr>
<td>Qₑₑ thermal</td>
<td>Thermal heat flux</td>
<td>W/m²</td>
</tr>
<tr>
<td>R</td>
<td>Thermal resistance</td>
<td>m²K/W</td>
</tr>
<tr>
<td>Rₑₑ½</td>
<td>Heat loss by radiation</td>
<td>W/m²</td>
</tr>
<tr>
<td>Rₖ</td>
<td>Thermal resistance of the construction</td>
<td>m²K/W</td>
</tr>
<tr>
<td>RH</td>
<td>Relative humidity</td>
<td>%</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
<td>-</td>
</tr>
<tr>
<td>Rₑₑ½</td>
<td>Net radiative flux</td>
<td>W/m²</td>
</tr>
<tr>
<td>S</td>
<td>Solar intensity</td>
<td>W/m²</td>
</tr>
<tr>
<td>U</td>
<td>Transmission coefficient</td>
<td>W/m²K</td>
</tr>
<tr>
<td>V</td>
<td>Volume</td>
<td>m³</td>
</tr>
<tr>
<td>VR</td>
<td>Ventilation rate</td>
<td>m³/s</td>
</tr>
<tr>
<td>W</td>
<td>Wind velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>w</td>
<td>Width comfort band</td>
<td>°C</td>
</tr>
<tr>
<td>α</td>
<td>Constant</td>
<td>-</td>
</tr>
<tr>
<td>λ</td>
<td>Thermal conductivity</td>
<td>W/mK</td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
<td>kg/m³</td>
</tr>
<tr>
<td>θ</td>
<td>Temperature</td>
<td>°C</td>
</tr>
<tr>
<td>θₐ</td>
<td>Ambient air temperature</td>
<td>°C</td>
</tr>
<tr>
<td>θₑₑ½</td>
<td>Mean radiant temperature</td>
<td>°C</td>
</tr>
<tr>
<td>θₒ</td>
<td>Operative temperature</td>
<td>°C</td>
</tr>
</tbody>
</table>
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Anika Haak
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2. Introduction

2.1 Motivation for research

Climate is changing in the Netherlands which results in a rise of temperature (Klein Tank & Lenderink, 2009). It can be expected that these higher temperatures have an influence on the thermal comfort in dwellings. Therefore, this research focuses on thermal comfort in dwellings in a changing climate.

Different research efforts focused on the adaptation of buildings to a changing climate (Groot et al., 2008, Rahola et al., 2009, Porrit et al., 2011, Ren et al., 2011, Porrit et al., 2012). Research of Groot et al., (2008) and Rahola et al., (2009) showed measures that could be used to adapt buildings to climate change; however, they did not provide an analysis based on calculations or simulations. This differs in the research efforts by Porrit et al., (2011), Ren et al., (2011) and Porrit et al., (2012). These research efforts show similarities with the research presented in this report. However, the countries on which these research efforts focused (England and Australia) differ from the country which is focused on in this research effort; i.e. the Netherlands.

To our knowledge, this type of study has not yet been performed for the Netherlands. However, it is necessary, because the Dutch situation is different from the situation in other countries, because of differences in changes in climate and dwelling typologies.

2.1.1 Consortium ‘Climate Proof Cities’

A research program (‘Knowledge for Climate’) has been established to perform research on investigating climate change and its effect on city level in the Netherlands. This research project is part of the research program ‘Knowledge for climate’, which develops knowledge to climate proof the Netherlands (Knowledge for Climate, 2012). Part of this research program is the consortium ‘Climate Proof Cities’. The objective of this consortium is to “strengthen the adaptive capacity and reduce the vulnerability of the urban system against climate change and to develop strategies and policy instruments for adapting our cities and buildings” (Knowledge for Climate, 2012). This consortium is divided in five work packages, which consider different aspects of climate change and its effect on cities. The work packages perform research on different spatial scales and therefore, the work packages are divided in four cases, namely, building and street, neighbourhoods, integrated water management and region. The structure of the consortium is shown in Figure 2.1. The research described in this report is part of work package 3 (adaptation measures), case building and street.
2.2 Background information

2.2.1 Climate change

Research shows that there is a gap between the knowledge of the general public and scientists (Lowe et al., 2006). There are misconceptions about the causes and consequences of climate change. This can be explained by the mixed messages from the media, academic controversy and the political attitude (Seacrest et al., 2000). Most people acquire their knowledge of climate change from mass media (Wilson, 1995). However, there is a difference between scientific reports and how these are translated into newspapers and other media, due to the complexity of the subject climate change (Lowe et al., 2006). Another confusing aspect which is present in the media is the discussion of the actual existence of climate change. This discussion tends to be shown by the media as if there is an equal amount of scientists on each side of this discussion (Moser & Dilling, 2004). However, this does not show the actual balance of scientific agreement on climate change. Research of Bray (2010) shows that there are a significant amount of climate scientists (96.2%) who agree upon the global temperature rise, compared to temperatures before 1800.

The Intergovernmental Panel on Climate Change (IPCC) performs research on the causes and consequences of global climate change. In the Fourth Assessment Report of the IPCC, it is stated that climate change is unmistakably happening and is already shown in some direct observations in the recent climate (Pachauri & Reisinger, 2007). The global temperature increased with 0.56 to 0.92 °C in the last century. Since 1970, the temperature increased with an average of 0.2 °C per decade. It is shown that the hottest twelve years between 1850 and 2007 took place in the last thirteen years before 2007. This has its effect on the sea level, which has globally risen with 17 centimetres in the twentieth century. Another effect of the climate change is the decrease of the ice cover with 2.1 – 3.3 % per decade since 1978 (Pachauri & Reisinger, 2007).

Human contribution

Pachauri and Reisinger (2007) mentioned that the temperatures of the last 50 years were the highest in at least the last 1300 years. They also showed that the increase in yearly temperatures of the past decade(s) is very likely to be caused by human contribution and not due to natural fluctuations. Figure 2.2 shows the

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**Figure 2.1: Structure consortium ‘Climate Proof Cities’**
observed increase in temperatures with and without human contribution. This shows that the increase in temperatures could not be explained without taking the influence of human activity into account.

![Figure 2.2: Changes in temperatures during 1906-2005 per content (blue: uncertainty margins without human influences, red: uncertainty margins with human influences, black: observed temperatures)](Pachauri & Reisinger, 2007)

Human activity has changed, compared to 1750, which has caused an increase in the use of fossil fuels and changes in the use of land (Scott et al., 2004). This increased emission of carbon dioxide, methane and nitrous oxide, which are the most important gases that cause the greenhouse effect, indicates the contribution of humans to global warming (Scott et al., 2004). There is namely 97% consensus among climate scientists that humans are the main cause of the climate change, due to the increase in greenhouse gasses (Bray, 2010).

**Future expectations**

If the emission of greenhouse gases would stabilize this year, climate change will still continue for centuries due to the human contribution of the past (Dorland et al., 2007). This indicates that the yearly average temperatures will keep rising in the following decades ((Dorland & Jansen, 2007), (Klein Tank & Lenderink, 2009)). There is an uncertainty in how the amount of emissions, due to human activity will change in the future, and therefore there is an uncertainty in the total increase of temperatures in the future (Scott et al., 2004). Until the end of this century, a temperature increase between 1.1 and 6.4 °C is predicted when compared to temperatures in 1990 (Scott et al., 2004).

**Situation in the Netherlands**

The predicted climate change differs per continent, country and even per region (Dorland & Jansen, 2007). The Royal Dutch Meteorological Institute (KNMI) performs meteorological research and also focuses its research on climate change in The Netherlands. The KNMI defines a heat wave when there are at least five days with a maximum ambient air temperature of 25 °C or above. These five days must include at least three days with a maximum ambient air temperature higher than 30 °C (Garssen et al., 2005). In the period
between 1901 and 2009, 38 heat waves have been recorded in The Netherlands. Seven of these heat waves took place in the last decade (Rahola et al., 2009).

Research of Klein Tank & Lenderink (2009) shows that four changes are likely to occur in the Dutch climate. The magnitude of these effects are uncertain, however there is confidence that the following changes will happen:

- Temperatures will continue to rise; mild winters and hot summers will become more common;
- On average, winters will become wetter and extreme precipitation amounts will increase;
- The intensity of extreme rain showers in summer will increase, however the number of rainy days in summer will decrease;
- The sea level will continue to rise.

The KNMI created four weather scenarios which are based on the change of two parameters; air temperature and atmospheric circulation patterns. This is graphically shown in Figure 2.3. The predicted influence that these four weather scenarios have on the average air temperatures in the summer period, in the Netherlands, is shown in Figure 2.4.

### 2.2.2 Influence on humans

Climate change can have significant effects on the human body. As shown in paragraph 2.2.1, average temperatures are rising and heat waves will occur more frequently in the future. Research of Beniston (2004) showed that the summer of 2003 was the warmest summer since 1540 in the whole of Europe. Research has been performed in 16 European countries and concluded that the 70,000 additional deaths that occurred in 2003 were caused by heat (Robine et al.,...
After this hot summer, no “harvesting” effect was observed (Robine et al., 2007). This “harvesting” effect is a brief temporal decrease of death rates among persons who are already ill or frail and have a high risk of dying (Basu & Samet, 2002). Therefore, it could be concluded that these high temperatures affected the death rates of relatively healthy people and not only the death rates of the vulnerable people. The average temperatures in August 2003, in the Netherlands, were 8.3 °C higher than average (Garssen et al., 2005). There were 1400 – 2200 heath-related deaths measured during this summer (Garssen et al., 2005). Figure 2.5 shows the relation between the temperatures and the death rates for the Netherlands in the summer of 2003.

It was found that increased mortality rates during hot weather occur mostly among the elderly (Garssen et al., 2005). However, this is not restricted to this age group. This is shown in the death rates of the people in the age group 40 – 59 years, in the summer of 2003, which show an increase of 11% compared to expected death rates based on the period 1995 – 2002 (Garssen et al., 2005). An increased mortality rate did not occur in younger age groups (Garssen et al., 2005).

**Effects on human body**

People cool down by transpiration, breathing, conduction, radiation and convection. When the human body senses that the temperatures that the body experiences are too high, it cools itself down by sweating. This process is terminated when a person is exposed to heat for too long (Harmon, 2010). This results in a further increase of the core temperature and this eventually will affect the brain (Harmon, 2010). In a worst-case scenario when people cannot cool down they will eventually die of a heatstroke (Harmon, 2010). For people who are older or already sick, this process can be accelerated. Other causes of death by heat are malignant neoplasm (cancer), respiratory (breathing difficulties) and cardiovascular (problems with heart or blood vessels) related diseases (Huynen et al., 2001).

High temperatures during a heat wave, do not only affect death rates, they also have an effect on the functioning of the human body. High temperatures in the direct environment of a person have a negative influence on the sleeping behaviour of that person. People sleep shorter and wake up more frequently. The sleep stadia are less intense and there are less (intense) Rapid Eye Movement (REM) periods. When people cannot sleep well during the night, this also reduces the alertness and the cognitive functioning during the day (Daanen et al., 2010).

**2.2.3 Buildings**

People spend 80 - 90% of their time indoors (Boerstra et al, 2005) and therefore changing and adapting buildings to the predicted coming climate change could be a solution to protect people against heat. Dwellings in the Netherlands are typically not very well protected against climate change, mostly because in this type of building it is not common to have an air-conditioning system. Research shows that the share of sales of air-conditioning systems for dwellings is only 1 – 5% of the total air-conditioning market (Kempen, 2000). The penetration grade of air-conditioning systems in dwellings in 2000 is 0 – 2%. The expectation that this research gave for 2010 is that this will increase to 2.6 – 4.3%; meaning that only a relatively small amount of dwellings will be equipped with an air-conditioning system. This shows that dwellings in the Netherlands might be a risk group for heat waves. Research also indicates that it is likely that the use of air-conditioning systems will rise in the future when temperatures will rise (Kempen, 2000). Air-conditioning systems use energy and this leads to higher emissions of greenhouse gasses. These emissions intensify climate change and global warming (Li et al., 2012). Therefore, the penetration rate of air-conditioning systems in dwellings should be kept low.
2.2.4 Passive climate adaptive measures

In this research, applying an air-conditioning system is not used as a measure to create a climate proof dwelling. Therefore, other measures, which are passive and adapt a typical Dutch dwelling to future climate, will be applied. A passive measure is defined as a measure which does not use energy once it is applied. Recent research efforts show an overview of possible adaptation options on city or building scale (Groot et al., 2008, Aries & Bluyssen, 2009, Rahola et al, 2009, Coley & Kershaw, 2010). Aries & Bluyssen proposed three ways of reactions to climate change: (1) take away or adjust the source of climate change effects (mitigation), (2) adjust buildings to changing climate (adaptation) and (3) involve and inform people (Aries & Bluyssen, 2009). When people are involved and know what to do in case of a heat wave (open windows or change clothing level), they can protect themselves to some extent. This research focuses on the adaptation to climate change by adjusting buildings. Four different strategies which could be used to reach this goal are proposed by Aries & Bluyssen: (1) switch off (reduction of heat gains indoor), (2) absorb (increase thermal mass of a building), (3) blow away (use an intelligent ventilation strategy, like night ventilation) and (4) cool (use a cooling system) (Holmes & Hacker, 2007)

Other research efforts show measures that could be used to adapt buildings to climate change; however, they do not provide an analysis based on calculations or simulations (Groot et al., 2008, Rahola et al., 2009). This differs in the research efforts of Porrit et al., (2011) and Porrit et al., (2012). The measures which are studied in these publications can also be applied to the dwelling used in this research project.

2.3 Research objective

2.3.1 Research question

The aim of this research is to investigate the potential of different passive climate adaptation measures, applied to dwellings in a future climate. To reach this aim, different passive climate adaptation measures will be applied to dwellings to investigate the effects that these measures have. The effects will be evaluated by a performance indicator for indoor comfort. This results in the following research question:

*What are the effects of different passive climate adaptation measures, applied to a typical Dutch dwelling?*

2.3.2 Sub-questions

To answer this research question, different sub-questions should be answered:

- What climate data or scenarios should be used for the evaluation of different measures applied on dwellings?
- What is a typical Dutch dwelling which can be used for evaluation of the adaptive measures?
- Which performance indicator should be used to evaluate and quantify the adaptive measures?

2.4 Outline report

The third chapter of this report describes the method which is used to answer the research question. This chapter consists of the description of the simulation input parameters used, the passive adaptation measures, the performance indicators which were considered and it finishes with the programs used. Chapter four will show and describe the results which are obtained by the performed simulations. The fifth
chapter describes the discussion, with an analysis of the results. This report finishes with chapter six, in which the conclusions of this research will be described.
3. Methods

3.1 Simulation input parameters

In this research, building energy simulation (BES) is used for the analysis of the performance of a dwelling during a heat wave. Input data is needed to define the boundary conditions and parameters for these simulations. This paragraph describes the input parameters and assumptions that are made for these boundary conditions and parameters.

3.1.1 Typical Dutch dwelling

The first sub-question, as addressed in paragraph 2.3.2, focuses on which dwelling should be used for this research. Ideally, the dwelling chosen should meet the description of a typical Dutch dwelling. An overview of the Dutch dwelling stock is gathered in a database (Monitor nieuwe woningen, 2012) which includes a variety of data about the Dutch dwelling stock. Agentschap NL (an organization of the Dutch government) created six dwelling typologies, by using this database, which are based on the requirements for dwellings in 2006 and function as guidance for newly built dwellings (Senternovem, 2006). Figure 3.1 shows these dwelling types, whereby the gallery flats and apartments are combined.

As shown in Figure 3.1, the terraced house represents the largest part (36.5%) of the dwelling construction in the Netherlands. Therefore, this is the type of dwelling that will be used for the simulations in this research.

Geometry

The publication (Senternovem, 2006) not only provides an overview of the different dwelling typologies, it also provides the geometry and other properties of these different dwellings. The floor plans and facades of the terraced house are shown in Figure 3.2. More detailed floor plans and facades used in this research are
shown in appendix 1. The length and depth of the dwelling used in the simulation is the distance between the two opposite walls increased with half of the thickness of both walls, which is in line with the Dutch ISSO 32 guideline (ISSO, 2011). The same method is used for the distance between the floors and ceilings.

The simulation model is divided into three separate floors (shown in Figure 3.2). The separation walls are not taken into account, because the research will focus on the building as a whole and not on individual rooms. The dwelling, however, is divided in individual floors to take the mass of the floors into account. The floors are not connected to each other by openings for the stairs, because this would have the consequence that all the floors should be simulated as one zone in the model.

**Construction**

The publication (Senternovem, 2006) also provides properties of the construction of the dwelling. These include $R_c$-values for the construction of the walls, floor and roof. The materials and properties of individual layers of the construction of the walls, floor and roof are not provided. Therefore, assumptions on the materials are made, which give the construction properties as described in the reference buildings of SenterNovem (2006). Detailed information of the used constructions is shown in appendix 2.

The $R_c$-value of the walls is 3.0 m$^2$K/W. This value is obtained with the layers and properties shown in Table 3.1. The walls that separate the dwelling from the adjacent dwelling have different layers and properties and are shown in appendix 2.

**Table 3.1: Construction walls**

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity [W/mK]</th>
<th>Thickness [m]</th>
<th>$R$ [m$^2$K/W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer brick leafs</td>
<td>0.96</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Air</td>
<td>-</td>
<td>0.05</td>
<td>0.17</td>
</tr>
<tr>
<td>Insulation</td>
<td>0.04</td>
<td>0.10</td>
<td>2.58</td>
</tr>
<tr>
<td>Inner brick leafs</td>
<td>0.62</td>
<td>0.10</td>
<td>0.16</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>3.0</strong></td>
</tr>
</tbody>
</table>

The requirement for the $R_c$-value of the roof is 4.0 m$^2$K/W. The roof consists of tiles with an insulated layer underneath. The layers and properties are shown in Table 3.2.

**Table 3.2: Construction roof**

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity [W/mK]</th>
<th>Thickness [m]</th>
<th>$R$ [m$^2$K/W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer tile</td>
<td>0.85</td>
<td>0.02</td>
<td>0.02</td>
</tr>
</tbody>
</table>
The ground floor consists of a concrete and an insulation layer with air underneath. This whole construction has a R-value of 3.0 m²K/W. Table 3.3 shows the layers and properties which are used for the floor.

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity [W/mK]</th>
<th>Thickness [m]</th>
<th>R [m²K/W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>1.40</td>
<td>0.20</td>
<td>0.14</td>
</tr>
<tr>
<td>Insulation</td>
<td>0.03</td>
<td>0.08</td>
<td>2.70</td>
</tr>
<tr>
<td>Air</td>
<td>-</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>3.0</strong></td>
</tr>
</tbody>
</table>

The windows have a U-value of 1.8 m²K/W. The properties of the windows used in this research are based on data of manufacturer Saint Gobain. The window properties are shown in Appendix 2.

### 3.1.2 User profiles

For the model a user profile is created which represents the internal heat gains. Another profile is created for the heating of the dwelling when temperatures are lower than a certain temperature. These profiles will be introduced in the following paragraphs.

**Internal loads**

Internal loads are a form of heat gains which are not intended for the purpose of heating. Every human or equipment releases this heat from its body to the environment. Due to these internal loads users influence certain indoor climate parameters; for example: temperatures, relative humidity or air velocity. Research (Porrit et al., 2010) shows that these influences of users can be significant.

The internal gains which are used in this research represent a family with two parents and two children. They are not at home during the day, but present in the evening and night. During the evening they spend their time on the ground floor and during the night they are in their bedrooms on the first floor. Every day of the year, including weekends and holidays, has the same user profile.

The user profile which is used in this model needs different input parameters and is therefore composed of different sources (ISSO, 2011), (CIBSE, 2006), (ASHRAE, 2009), (Ministerie van VROM, 2010). The time periods which are used are based on the time periods of the heating profile (Ministerie van VROM, 2010). The internal loads of the equipment, kitchen and lighting are based on the publication of ISSO (2011). The internal loads of people are based on publications of ASHRAE (2009) and CIBSE (2006). These publications provide internal loads of a grown man for different activity levels. ASHRAE (2009) describes how these can be translated for women (85% of heat gain grown man) and children (75% of heat gain grown man). The internal loads are shown in Table 3.4.
### Internal loads

<table>
<thead>
<tr>
<th>Zone</th>
<th>Heat source</th>
<th>06:00 - 18:00</th>
<th>18:00 - 19:00</th>
<th>19:00 - 23:00</th>
<th>23:00 - 06:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor 0</td>
<td>Equipment$^2$ [W]</td>
<td>25</td>
<td>100</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>Kitchen$^2$ [W]</td>
<td>250</td>
<td>600</td>
<td>250</td>
<td>280</td>
<td></td>
</tr>
<tr>
<td>People$^{3,4}$ [W]</td>
<td>0</td>
<td>385</td>
<td>385</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Lighting$^2$ [W]</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Floor 1</td>
<td>People$^4$ [W]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>146</td>
</tr>
</tbody>
</table>

### Heating

Research has been performed to investigate which profiles are used for heating in dwellings (Ministerie van VROM, 2010). Residents were asked to report their user profile of the heating system in a typical heating week. From this research six heating profiles were created, which represent a certain part of all the profiles; standard (48%), low and morning-peak (19%), incidental heating (8%), high temperatures (8%), very low and morning-peak (6%) and large amplitude (6%) (Ministerie van VROM, 2010). The heating profile which is implemented in this simulation model is the standard profile, because this profile represents the largest part (48%) of the heating profiles. The profile is shown in Figure 3.3.

### Cooling

No air-conditioning system for cooling is implemented in the Building Energy Simulations, since it is uncommon in Dutch dwellings to have an air-conditioning system (Kempen, 2000) (see paragraph 2.2.3 for more information).

#### 3.1.3 Ventilation and infiltration rate

The Dutch building code describes the amount of ventilation which is required in buildings (Article 3.29 (BRIS Bouwbesluit Online, 2012)). This amount is 1 dm$^3$/s/m$^2$ for dwellings and for this situation this means a ventilation rate per floor of 49 dm$^3$/s. The infiltration rate for dwellings, with extra care for crack- and joint-sealing, can be assumed to be 0.1 m$^3$/m$^2$h (ISSO, 2011). Floors 0 and 1 both have a volume of 140 m$^3$, which means an infiltration rate of 7.8 dm$^3$/s per floor. Floor 2 has a volume of 120 m$^3$ which means an infiltration rate of 6.7 dm$^3$/s. These values are summarized in Table 3.5.

---

$^1$ Based on Ministerie van VROM (2010)
$^2$ Based on ISSO (2011)
$^3$ Based on CIBSE (2006)
$^4$ Based on ASHRAE (2009)
### Table 3.5: Infiltration and ventilation rates

<table>
<thead>
<tr>
<th></th>
<th>Floor 0</th>
<th>Floor 1</th>
<th>Floor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation rate [dm$^3$/s]</td>
<td>49</td>
<td>49</td>
<td>49</td>
</tr>
<tr>
<td>Air changes per hour [1/h]</td>
<td>1.26</td>
<td>1.26</td>
<td>1.47</td>
</tr>
<tr>
<td>Infiltration rate [dm$^3$/s]</td>
<td>7.8</td>
<td>7.8</td>
<td>6.7</td>
</tr>
</tbody>
</table>

#### 3.1.4 Simulation period

The period that will be simulated in this research is from 1$^{st}$ of January until 31$^{st}$ of December. The summer of 2003 officially started at 21$^{st}$ of June and ended at the 22$^{nd}$ of September (KNMI, 2012). For this research it is chosen to work with a longer summer period, because high temperatures already occurred in May and there were large peak temperatures in September. The actual period that will be shown in the results is from 1$^{st}$ of May until 30$^{th}$ of September.

The time step which should be used to create accurate results is investigated. The base case dwelling, which is simulated for this purpose is oriented to the North with the front facade. This means that the back facade, with the largest glass surface, is oriented to the South direction. The simulations are performed with different time steps per hour. Figure 3.4 shows that a time step of 2 times per hour is sufficient, because a smaller time step does not influence the results significantly. In this research a time step of 6 times per hour is used, because the simulation program (EnergyPlus) indicates that a time step of 6 is sufficient to create accurate results.

![Figure 3.4: Overheating hours depending on timesteps per hour (EnergyPlus)](image-url)
However, when simulating the measure ‘vegetation’ a time step of 60 times per hour is needed to create accurate results and to improve the numerical solution of the zone heat balance model (EnergyPlus, 2011). There is not much difference between the overheating hours with a time step of 6 or 60 for the base case situation. Another reason not to use 60 times per hour as the time step is the large computational time which would be needed to perform the simulations. Therefore, for the simulations a time step of 6 times per hour is used, with an exception for the measure ‘vegetation’, which uses a time step of 60 times per hour.

3.1.5 Climate data

Simulations require climate data. For this research, hourly climate data are needed which represent future climate. Different options for this climate data are proposed in different research efforts (Gaterall et al., 2005, Wilde et al., 2008, Klein Tank & Lenderink, 2009, Scott et al., 2004).

Similar research efforts (Gaterall et al., 2005, Wilde et al., 2008) used climate data from southern cities in Europe, like Rome or Milan. These cities have different latitudes compared to Dutch cities. This has its effect on the position of the sun and therefore on the solar radiation and shading. Humidity and wind speed would also differ from the Dutch situation when compared to these values in Rome or Milan.

Another option for climate data is the use of the climate scenario’s produced by the KNMI (Klein Tank & Lenderink, 2009), which can be translated into in hourly data. They show four different scenarios with different temperatures and atmospheric circulation patterns. These scenarios provide possible future average temperatures and chances on extreme weather events rather than weather predictions for a specific date. They come with a range of uncertainties about socio-economic developments, solar activity, volcanic eruptions, model uncertainties or possible chaotic behaviour of the climate system (Klein Tank & Lenderink, 2009).

Given the complexity and uncertainty in the future climate projections and lack of high-resolution data it was decided in this study to use a third option, namely using historical weather data. As described in paragraph 2.2.2 the summer of 2003 was an extreme summer regarding temperatures. Research of Scott et al. (2004) shows that the summer of 2003 is predicted to become an average summer in the 2040s. The biggest advantage of using these data is that they have certain accuracy, due to the fact that they actually happened. Similar research efforts also used these historical climate data (Porrit et al., 2005). The use of these climate data has, however, a disadvantage. This disadvantage would occur by all the options considered. The climate data which is used in this research is data measured in De Bilt in open field. This means that the Urban Heat Island effect is not taken into consideration. The Urban Heat Island effect is the tendency for a city to become warmer during the day than the surrounding areas and have larger problems to cool down during the night (Steeneveld et al., 2011). This results in higher average temperatures and is mostly caused through more paved and built areas instead of water or vegetation (Steeneveld et al., 2011). Accurate measured climate data of a city centre is not present, because this differs per city centre and even in this city centre. Therefore, in this research, is is chosen to work with climate data measured in De Bilt. However, it must be taken into consideration that average temperatures in city centres could be higher than the data used in this research (Steeneveld et al., 2011). Figure 3.5 shows the most important climate data that are used in this research.
3.1.6 Ground properties

There are two properties of the ground which need to be defined in the model; ground temperatures and shortwave ground reflectance (albedo). The temperature of the ground has a constant value of 10 °C at a depth of approximately 1 meter (KNMI, 2005). This temperature is not influenced by daily or monthly fluctuations, in contrast to the ground temperatures near the surface. Ground modelling is not very well implemented in most building energy simulation programs (Judkoff & Neymark, 1995). To avoid the problems which are related to this and create realistic assumptions for these temperature fluctuations, a layer of sand is assumed with a depth of 1 meter underneath the normal construction. A constant temperature of 10 °C is assumed underneath this layer. The shortwave reflectance of the ground is assumed to be 0.2 (default value).

3.1.7 Orientations

The simulations will be performed taking into account four different orientations. Figure 3.6 shows the orientation of the dwelling to different directions. When the orientation is mentioned in this report this means that the front façade of the dwelling is oriented in that direction.
3.2 Passive climate adaptive measures

As explained in paragraph 2.2.1, active measures will increase the exhaust of greenhouse gases, which amplify the greenhouse effect and thereby global warming (Scott et al., 2004). Therefore, this research will focus on passive measures. The amount of newly built dwellings each year is very small (91% of existing dwellings was built before 2000 (Rijksoverheid, 2011) compared to the existing amount of dwellings in the Netherlands. Therefore, it is considered important to adapt these older dwellings as well. When developing and implementing adaptive measures, they must ideally be applicable for existing dwellings as well as new dwellings.

The following paragraphs explain which climate adaptive measures will be applied on the base case dwelling used in this research. Every measure has five different theoretical variants, whereby variant 5 is the theoretical maximum of that measure. Furthermore, every measure has a value which is the maximum value that would be used in practice (feasible value for practice). The feasible values for practice of all the measures will be compared to one another and these results will provide a ranking of the performance of the measures.

3.2.1 Increasing amount of insulation

The properties of the reference dwelling were defined by (Senternovem, 2006). The \( R_c \)-value used for the walls is 3.0 \( m^2K/W \) and for the roof an \( R_c \)-value of 4.0 \( m^2K/W \) is used. This value will be increased in the roof and the walls when applying this measure. Research by Porrit et al. (2011) shows that changing the \( R_c \)-value of a construction can have a positive effect on the reduction of the amount of overheating hours in a dwelling. They changed the \( R_c \)-values of the walls from 0.45 and 0.75 \( m^2K/W \) to a value of 2.85 \( m^2K/W \). This decreased the amount of overheating hours with 30 to 45% in the period between June and September.

The theoretical maximum value that will be used in this research is a doubled \( R_c \)-value of the walls. The different variants will be created in increasing steps of 20%. The actual value which will be changed in the simulations is the thickness of the insulation material. The \( R_c \)-values which will be created by changing the thickness of the material are shown in Table 3.6.

Not all the values shown in Table 3.6 are representative for the \( R_c \)-values which are commonly used in practice. However, they are all used in this research to create a situation which might be present in the future. Documentation of an insulation manufacturer (Rockwool) shows that the highest \( R_c \)-value of insulation material that they can deliver is 5.1 \( m^2K/W \). Therefore, the properties of this insulation material will be used in this research as the feasible value for practice. When applying this type of insulation material in the walls and roof, a certain \( R_c \)-value for the construction arises. This value is shown in the last column of Table 3.6.
Table 3.6: Variants measure insulation

<table>
<thead>
<tr>
<th>Variant</th>
<th>Base case</th>
<th>Variant 1</th>
<th>Variant 2</th>
<th>Variant 3</th>
<th>Variant 4</th>
<th>Variant 5</th>
<th>Feasible value for practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased ( R_c )-value relative to base case [%]</td>
<td>-</td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>80</td>
<td>100</td>
<td>85</td>
</tr>
<tr>
<td>( R_c )-value construction ([m^2K/W])</td>
<td>Wall</td>
<td>3.0</td>
<td>3.6</td>
<td>4.2</td>
<td>4.8</td>
<td>5.4</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>Roof</td>
<td>4.0</td>
<td>4.8</td>
<td>5.6</td>
<td>6.4</td>
<td>7.2</td>
<td>8.0</td>
</tr>
<tr>
<td>Thickness insulation material ([m])</td>
<td>Wall</td>
<td>0.10</td>
<td>0.13</td>
<td>0.15</td>
<td>0.18</td>
<td>0.20</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>Roof</td>
<td>0.11</td>
<td>0.14</td>
<td>0.16</td>
<td>0.19</td>
<td>0.21</td>
<td>0.23</td>
</tr>
</tbody>
</table>

### 3.2.2 Increasing thermal mass

The indoor comfort is, among others, influenced by solar radiation, external temperatures and internal loads (Balaras, 1996). Thermal mass affects the level of influence that these factors have on the indoor comfort. The thermal mass of a construction can store energy (heat) when this construction is cooler than its direct environment and it can release this heat when the direct environment is cooler than the construction (Balaras, 1996). The effect of this process is that temperature fluctuations during the day can be reduced (Al-Sanae et al., 2012). This effect can even be more increased by increasing the thermal mass of a construction (Al-Sanae et al., 2012).

The thermal mass of a construction material is determined by the density and the specific heat (Balaras, 1996). However, the amount of thermal mass can also be increased by increasing the thickness of the material. By changing the thickness of the material, no properties (density or specific heat) of the material are changed.

The location of the thermal mass also influences the effect of the thermal mass on heat flow (Balaras, 1996). Balaras (1996) describes two thermal storage methods, namely a direct and an indirect method. Direct storage happens when the storage material receives energy by solar radiation. This happens at the outer surface of a facade or roof when it is exposed to solar radiation or at the inner surface when solar radiation is transferred through an open window. Indirect heat storage is experienced at indoor surfaces by infrared radiation, convection and conductivity. This is called indirect because the solar radiation does not fall directly on this surface. This form of storage is less effective than direct thermal storage (Balaras, 1996).

In this research it is chosen to work with both the direct and the indirect thermal storage. Both the thickness of the indoor brick surfaces and the external brick surfaces of the walls will be increased. The thermal mass of the roof is kept constant, because increasing the thermal mass of the roof would mean an increase in the weight of the roof, which results in an extra weight on the further construction. When renovating a dwelling, this would probably not be possible and when building a new dwelling this is unwanted because of higher expenses (Balaras, 1996). Table 3.7 shows the amount of increase of the thickness of the walls.
### Table 3.7: Variants measure thermal mass

<table>
<thead>
<tr>
<th>Variant</th>
<th>Base case</th>
<th>Variant 1</th>
<th>Variant 2</th>
<th>Variant 3</th>
<th>Variant 4</th>
<th>Variant 5</th>
<th>Feasible value for practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased thickness relative to base case [%]</td>
<td>-</td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>80</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Thickness wall</td>
<td>0.1</td>
<td>0.12</td>
<td>0.14</td>
<td>0.16</td>
<td>0.18</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

#### 3.2.3 Increasing the albedo value

The definition of the term albedo is: reflectance to solar radiation of the ground or the earth and/or its atmosphere (Iqbal, 1983). Normally, the term is used for the reflection of the ground or earth, but different research efforts use the word when referring to the shortwave reflection of surfaces of a building (walls or roof) (Akbari et al., 1997, Berdahl et al., 1997, Bretz et al., 1997). When reducing the reflectance of a building, less heat is absorbed by the outer surfaces. The effect of this process is that the heat flow through the building envelope is reduced. This causes lower temperatures in the indoor environment.

In countries with a hot climate, it is quite common to paint external surfaces white. Figure 3.8 shows an example of this in a small village in Greece. Another example is the white rooftops of the houses on the Island of Bermuda (Figure 3.7).

Several research efforts showed that changing the albedo value of the roof of different types of buildings resulted in a reduction of the temperatures indoor during the summer period (Akbari et al., 1997, Berdahl et al., 1997, Bretz et al., 1997). Akbari et al. showed savings of 80% on the cooling load in a dwelling with a high-albedo coating on external surfaces (Akbari et al. 1997). They also showed a delay in the peak cooling of two hours and a reduction of this peak cooling. Another research effort showed energy savings of 10 to 70% with the application of high-albedo coatings on a residential building in California (Bretz et al., 1997). This wide range of values is caused by different factors; material properties, different albedo values in the base situation, pollution of the external surfaces, amount of insulation and the location of the building.

The value of the albedo in the base case situation has an influence on the results of this measure. The Dutch dwelling in this research has walls with an external surface made of bricks. The external surface of the roof exists of red tiles. The albedo value, which will be used in this research in the base case situation, for red bricks (external surfaces walls) is 0.30 while the used albedo value for the red tiles (external surface roof) is 0.33 (Guberaff et al., 1960).
Akbari et al., (1997) performed measurements on the effect of the albedo value on the amount of peak heating and cooling. They experienced different albedo values after painting the roof and the walls with a high albedo coating. After painting the surfaces the measured value of the albedo was 0.79, however, after a while this value was reduced to 0.6, due to pollution. After restoring the paint, the albedo value was set back to 0.73. Research of Berdahl et al. (1997) focused on the solar reflectance of roofing materials and they measured an albedo value of 0.8. Researchers also discovered a decrease of this value over time, when the material got dirty. Bretz & Akbari (1997) performed research on the value of the albedo after degradation. They discovered that the degradation of the albedo value is highest in the first year after appliance. They showed measurements on one roof, where they discovered a degradation of 70% in the first two months. They measured albedo values between 0.4 – 0.6 on dirty roofs. After restoring the paints of these roofs the albedo value was increased to values between 0.5 and 0.76.

The values used in this research effort are shown in Table 3.8. The theoretical maximum value, as well as the feasible value for practice is 0.8. This measure will be applied on the external surfaces of the roof and walls of the dwelling by painting the facade in another colour. This changes the albedo value without altering the material properties of the underlying construction.

<table>
<thead>
<tr>
<th>Variant</th>
<th>Base case</th>
<th>Variant 1</th>
<th>Variant 2</th>
<th>Variant 3</th>
<th>Variant 4</th>
<th>Variant 5</th>
<th>Feasible value for practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albedo value</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walls</td>
<td>0.30</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Roof</td>
<td>0.33</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2.4 Implementing an overhang

The basic idea of the overhang above windows is that the sun is blocked from entering a building through the windows. Due to this blocking of the sun, less solar energy will enter a building. Therefore, the temperatures in this building will be reduced when compared to a situation without solar shading.

The overhang used in this research represents a horizontally placed screen above a window (for an example see Figure 3.9). This screen may be flexible; however it could also be a permanent overhang. The value that will be changed when applying the overhang to the dwelling is the depth of the overhang. The theoretical maximum depth of this overhang should be the depth of the overhang that completely blocks the sun from coming in. When this theory is applied, the overhang should have a depth which is over 10 meters (shown in Figure 3.10). This figure shows that even with an overhang of 10 meter, still solar radiation enters the dwelling (orientation East, on 28 July, 19:13). Thereby, this value is quite unrealistic. Therefore, another maximum is chosen which is based on Dutch regulation for extensions to dwellings. Extensions (like an overhang) may be built without having a license when it meets certain requirements. One important requirement, for this research, is that an extension may have a maximum depth of 2.5 meters (Figure 3.11).
Therefore, this value will be used in this research as the theoretical maximum value. The feasible value for practice is assumed to be 2 meter. The different variants are shown in Table 3.9.

<table>
<thead>
<tr>
<th>Variant</th>
<th>Base case</th>
<th>Variant 1</th>
<th>Variant 2</th>
<th>Variant 3</th>
<th>Variant 4</th>
<th>Variant 5</th>
<th>Feasible value for practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth overhang [m]</td>
<td>0.0</td>
<td>0.5</td>
<td>1.0</td>
<td>1.5</td>
<td>2.0</td>
<td>2.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>

### 3.2.5 Opening of windows

When people do not feel comfortable, they will react and try to change a factor which will restore their comfort again (Humphreys & Nicol, 1998). One factor which can easily be changed by people to control the indoor comfort is the opening of the windows (Rijal et al., 2007). This control device is easy to use and the effect can be immediately noticeable.

The windows in the base case model cannot be opened. However, the opening of windows is used as a measure in this research. The value which changes in this research is the indoor temperature at which the windows are opened. The starting temperature at which the user will open the windows is 24 °C (JISO, 2011). The fraction of opening of the windows is shown in Figure 3.12 with a red colour. Table 3.10 shows the opening fraction of the window relative to the whole window area.

<table>
<thead>
<tr>
<th>Window</th>
<th>Floor</th>
<th>Opening fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0.35</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0.50</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0.35</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0.35</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0.35</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>0.35</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>1.00</td>
</tr>
</tbody>
</table>
An important factor which defines the amount of flow through the windows is the wind pressure coefficient (Cp-value). This wind pressure coefficient is influenced by a large set of parameters; i.e. building geometry, façade detailing, position on the façade, degree of exposure/sheltering, wind speed and wind direction (Cóstola et al., 2009). The wind pressure coefficient can be calculated by using the following equations:

\[ C_p = \frac{P_x - P_0}{P_d} \]  
\[ P_d = \frac{\rho \cdot u_h^2}{2} \]

\( C_p \) = Wind pressure coefficient  
\( P_x \) = Static pressure at a given point on the building façade  
\( P_0 \) = Static reference pressure  
\( P_d \) = Dynamic pressure  
\( \rho \) = Air density  
\( U_h \) = Wind speed at building height h  
\([\text{Pa}]\)  
\([\text{kg/m}^3]\)  
\([\text{m/s}]\)

The values of the wind pressure coefficient used in this research are provided by a database for simple geometries of the Air Infiltration and Ventilation Centre (AIVC). These values can be used if no wind tunnel experiments or other measurements are present for the case study used. The \( C_p \)-values given in this database depend on wind direction and the degree of exposure of the building used. The categories that are used for the degree of exposure are: exposed, semi-sheltered (surrounding obstacles with half of the building height) and sheltered (surrounding obstacles with the same height as the building). The values are also divided in different type of walls. There are short walls with a width to height ratio of 1:2. Normal walls have a width to height ratio of 1:1. The long walls have a width to height ratio of 2:1. The last categories which are defined are the differing tilt angles for the roof; lower than 10°, between 11° and 30° and higher than 30° (Cóstola et al., 2009).

This research focuses on a terraced house which is placed in between a row of dwellings. The dwelling is placed in an urban area which can be defined as sheltered. The tilt angle of the roof is 46°. The wind pressure coefficients used in this research are extracted from the database of the AIVC and are shown in Table 3.11.

<table>
<thead>
<tr>
<th>Angle relative to North orientation [°]</th>
<th>0</th>
<th>22.5 / 337.5</th>
<th>45 / 315</th>
<th>67.5 / 292.5</th>
<th>90 / 270</th>
<th>112.5 / 247.5</th>
<th>135 / 225</th>
<th>157.5 / 202.5</th>
<th>180</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cp-values sheltered long wall [-]</td>
<td>0.06</td>
<td>-0.03</td>
<td>-0.12</td>
<td>-0.16</td>
<td>-0.2</td>
<td>-0.29</td>
<td>-0.38</td>
<td>-0.34</td>
<td>-0.3</td>
</tr>
<tr>
<td>Cp-values sheltered roof &gt; 30° [-]</td>
<td>0.06</td>
<td>-0.045</td>
<td>-0.15</td>
<td>-0.19</td>
<td>-0.23</td>
<td>-0.42</td>
<td>-0.6</td>
<td>-0.51</td>
<td>-0.42</td>
</tr>
</tbody>
</table>

In this research two simulation programs are employed (see paragraph 3.5.1). The simulation programs have different rules for the opening of the windows and these cannot be changed. The program EnergyPlus works with a set point for the indoor temperature. When this temperature is reached, it is checked if the outdoor temperature is lower than the indoor temperature. If this is the case, the windows will open. If this is not the case, the windows will stay closed. The program ESP-r works with a set point temperature at
which the windows will be opened. When the windows open, the wind pressure coefficients will be used to calculate the flow rate through these windows. For the variants of the measure, see Table 3.12.

<table>
<thead>
<tr>
<th>Variant</th>
<th>Base case</th>
<th>Variant 1</th>
<th>Variant 2</th>
<th>Variant 3</th>
<th>Variant 4</th>
<th>Variant 5</th>
<th>Feasible value for practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature opening windows [°C]</td>
<td>-</td>
<td>28</td>
<td>27</td>
<td>26</td>
<td>25</td>
<td>24</td>
<td>24</td>
</tr>
</tbody>
</table>

### 3.2.6 Implementing a vegetated facade and/or roof

There are two types of vegetated roofs; extensive and intensive vegetated roofs (Gaffin et al., 2009). The essential difference between an intensive and extensive roof is the type of vegetation and therefore the height of the vegetation layer (Gaffin et al., 2009). It can be assumed that extensive roofs generally have vegetation lower than 15 centimetres and intensive roofs have vegetation higher than 15 centimetres (Gaffin et al., 2009). Intensive roofs have a larger effect on the heat flux through the roof. Using an intensive roof means more vegetation, but the roof also needs a different construction, because the whole vegetated roof weighs more than is the case for an extensive roof. In this research, the measures are applied on current building constructions; therefore, the vegetated roof cannot have too much effect on the existing construction of the dwelling. Another reason for the choice of an extensive roof in this research is that the dwelling has a tilted roof and therefore it is not possible to apply an intensive vegetated roof to this surface.

Sailor (2008) implemented a vegetated surface in the simulation program EnergyPlus. In this program, a nominal variant is used, which can be explained as the most default variant (Sailor, 2008). The vegetated roof has a structure that contains (from bottom to top) a protection layer, drainage layer, growing media (soil) and a vegetation layer (see Figure 3.13). The construction has a growing medium that delivers the nutrients. This growing medium typically has a depth between 10 and 30 centimetres. The drainage layer beneath the growing media stores the water that is received by rain. This layer stores this water and makes sure that the water does not run of the roof. The protection layer protects the construction of the roof for moisture and roots from the vegetation. This is also the way in which the vegetated roof is implemented in the Building Energy Simulation, with exception of the drainage and protection layers.

The advantages of vegetated roofs are storm water reduction, aesthetic appeal and lower indoor temperatures, the latter being the focus of this research (Sailor, 2008). The energy balance for a vegetated roof is represented by the following equation (Tabares-Velasco & Srebric, 2011):

\[
R_n = Q_{ET} + Q_{\text{sensible}} + Q_{\text{conduction}} + S_{\text{thermal}} + M
\]  

(Equation 3)

\[
R_n \quad \text{(Net radiative flux (represents total incoming/outgoing solar and long-wave radiation))} \quad [\text{W/m}^2]
\]
By implementing a vegetated roof, the heat flow through the roof can be reduced. Research has shown that this reduction in heat flux can vary between 18 and 75% (Tabares-Velasco & Srebric, 2011). The effect of this reduction in heat flux through the roof reduces the indoor temperatures. There are three effects on the heat flux through a roof caused by a vegetated roof. The albedo value of the façade changes. As described in paragraph 2.2.3, the albedo value of a surface can be an important factor for the heat flux through a surface. Another effect is the extra insulation layer that is provided by the soil that is used for the vegetation. This layer of soil, with a depth between 7.5 and 15 centimeters, can have an extra insulation value between 0.37 and 0.85 m$^2$K/W (Tabares-Velasco & Srebric, 2011). The most important vegetated roof effect that causes lower temperatures indoor is the process of evapotranspiration (Tabares-Velasco & Srebric, 2011). This process is caused by the vegetation that is planted in the growing medium. Evapotranspiration is a combined term which is extracted from evaporation and transpiration. The evaporation is caused by the soil, which evaporates water that has been gathered in this soil. The evaporation extracts heat from the surrounding air and therefore reduces the temperatures in the surrounding environment (Tabares-Velasco & Srebric, 2011). The part of transpiration is carried by the vegetation, which occurs when there is a vapour pressure differential between the plants and the surrounding air. Due to this vapour pressure difference, water vapour is transferred from the leaf of the plant into the air by diffusion and convection (Tabares-Velasco & Srebric, 2011). Research has shown that, due to evapotranspiration, the heat flux can be reduced with 12 – 25 % (respectively in dry and wet situation) (Tabares-Velasco & Srebric, 2011).

Research shows that indoor temperatures reduce significantly when applying vegetation to a roof (Niachou et al., 2001). They measured a decrease in the amount of hours that temperatures were above 30 °C and 32 °C. The other conclusion that could be drawn from their research is that this decrease in temperatures is highly dependent on the level of insulation of the surface where the vegetation is applied on. The temperatures and humidity also are aspects that influence the results that could be reached by applying a vegetated roof. Another research effort also shows these effects and adds some more aspects that have an influence on the effect of the vegetated roof on the indoor temperatures; foliage height, foliage density and wind speed (Theodosiou, 2003). To find out what influence a vegetated roof can have on a typical Dutch dwelling, a vegetated roof is used as a measure in this research.

It is shown that different factors, like foliage type (height and density), type of vegetated roof, insulation, relative humidity and wind speed, affect indoor temperatures in various ways (Theodosiou, 2003). The type of vegetated roof has been discussed; an extensive vegetated roof will be applied. The height of the vegetation is influenced by the type of vegetated roof and will be set to 10 centimeter. This value represents the height of sedum plants, used as extensive vegetation on a roof (Groendak, 2012). The only important factor that can be influenced is the foliage density, which is represented by the Leaf Area Index. Scurlock et al., defined the Leaf Area Index as the functional vegetated leaf area of the canopy (m$^2$) per area of ground (m$^2$) (Scurlock et al., 2001). This value can be varied between 0.001 and 5 in the program EnergyPlus. Figure
3.14, Figure 3.15 and Figure 3.16 show an indication of which Leaf Area Index represents what type of plant. This shows that a plant with a large Leaf Area Index does not immediately represent a large plant type.

The vegetation will be applied on the façades and the roof of the dwelling for the theoretical variants. For the feasible value for practice the vegetated surface will only be applied to the roof, because it is not common in the Netherlands to apply vegetated surfaces to the facades. The values which are used in this research are shown in Table 3.13.

![Figure 3.14: LAI 3.07 (Chen, 2006)](image1)
![Figure 3.15: LAI 6.66 (Chen, 2006)](image2)
![Figure 3.16: LAI 1.69 (Chen, 2006)](image3)

<table>
<thead>
<tr>
<th>Variant</th>
<th>Base case</th>
<th>Variant 1</th>
<th>Variant 2</th>
<th>Variant 3</th>
<th>Variant 4</th>
<th>Variant 5</th>
<th>Feasible value for practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaf Area Index [-]</td>
<td>Wall</td>
<td>-</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Roof</td>
<td>-</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3.13: Variants measure vegetated surface

3.3 Overview simulations

The previous paragraphs have described the measures which will be applied to the dwelling. Table 3.14 shows an overview of all the measures and the variants that will be simulated in this research.
3.4 Reference dwelling types

The shown $R_c$- and $U$-values, which are used in this research for the base case dwelling (see paragraph 3.1.1) are relatively high and represent dwelling properties for newly built dwellings. The minimum requirement, which is described in the Dutch building code, for the $R_c$-value of external surfaces, is currently $3.5 \, \text{m}^2 \text{K/W}$ (Article 5.3 in Bouwbesluit (2012)). However, from 1992 till 2011 this minimal value was $2.5 \, \text{m}^2 \text{K/W}$ (Article 5.2 in Bouwbesluit (2003)) and the minimal value from 1974 till 1991 was $1.3 \, \text{m}^2 \text{K/W}$ (Agentschap NL, 2011). The Dutch housing industry exists for 90.3 % of dwellings that were built before 2000 (Rijksoverheid, 2011) which therefore do not meet the requirement of $3.5 \, \text{m}^2 \text{K/W}$.

Older dwellings were built with less or no insulation in the facades and/or roof. The proposed dwelling does not represent these older types of dwellings. Therefore, three other dwelling types are also used, which provide an indication of older dwellings, with respect to the $R_c$-values of the surfaces and roof. The first dwelling is based on the period before 1974. This type of dwelling has no insulation in the walls and the roof. The second type of dwelling represents dwellings in the period between 1974 and 1991. This type of dwelling has an insulation layer in the construction, which provides the construction with an $R_c$-value of $1.3 \, \text{m}^2 \text{K/W}$. The third dwelling type gives an indication of dwellings built between 1992 and 2011 and has an insulation layer in the construction, which provides the construction with an $R_c$-value of $2.5 \, \text{m}^2 \text{K/W}$. The different dwelling types are summarized in Table 3.15.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Changing factor</th>
<th>Applied</th>
<th>Base case</th>
<th>Theoretical variants</th>
<th>Feasible value for practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulation</td>
<td>$R_c$-value walls $[\text{m}^2\text{K/W}]$</td>
<td>On walls</td>
<td>3.0</td>
<td>3.6 4.2 4.8 5.4 6.0 5.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_c$-value roof $[\text{m}^2\text{K/W}]$</td>
<td>On roof</td>
<td>4.0</td>
<td>4.8 5.6 6.4 7.2 8.0 5.3</td>
<td></td>
</tr>
<tr>
<td>Thermal mass</td>
<td>Thickness bricks walls $[\text{m}]$</td>
<td>On walls</td>
<td>0.1</td>
<td>0.12 0.14 0.16 0.18 0.2 0.2</td>
<td></td>
</tr>
<tr>
<td>Albedo</td>
<td>Short wave reflection $[-]$</td>
<td>On roof</td>
<td>0.3</td>
<td>0.4 0.5 0.6 0.7 0.8 0.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>On walls</td>
<td>0.33</td>
<td>0.4 0.5 0.6 0.7 0.8 0.8</td>
<td></td>
</tr>
<tr>
<td>Overhang Length</td>
<td>Length $[\text{m}]$</td>
<td>Above vertical windows</td>
<td>0.0 0.5 1.0 1.5 2 2.5 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opening windows</td>
<td>Setpoint temperature $[^\circ \text{C}]$</td>
<td>All windows</td>
<td>- 28 27 26 25 24 24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegetated roof</td>
<td>Roof leaf index $[-]$</td>
<td>On roof</td>
<td>- 1 2 3 4 5 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>On walls</td>
<td>- 1 2 3 4 5 -</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.14: Overview variants measures
The feasible values for practice of all the measures will be applied to the different dwelling typologies, shown in Table 3.15. These values will be applied to the three different dwelling types and subsequently the difference between the base case and the variant will be compared to each other. These results will be compared to the effect that measures have on the base case dwelling.

### Table 3.15: Properties other dwelling types

<table>
<thead>
<tr>
<th>Type of dwelling</th>
<th>Description</th>
<th>$R_c$-value walls and roof $[\text{m}^2\text{K/W}]$</th>
<th>Thickness insulation material $[\text{m}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Walls</td>
<td>Roof</td>
</tr>
<tr>
<td>Type 1</td>
<td>Reference dwelling built before 1974</td>
<td>0.435</td>
<td>0</td>
</tr>
<tr>
<td>Type 2</td>
<td>Reference dwelling 1974 - 1991</td>
<td>1.3</td>
<td>0.035</td>
</tr>
<tr>
<td>Type 3</td>
<td>Reference dwelling 1992 - 2011</td>
<td>2.5</td>
<td>0.083</td>
</tr>
<tr>
<td>Type 4</td>
<td>Reference dwelling built after 2011</td>
<td>3.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

The feasible values for practice of all the measures will be applied to the different dwelling typologies, shown in Table 3.15. These values will be applied to the three different dwelling types and subsequently the difference between the base case and the variant will be compared to each other. These results will be compared to the effect that measures have on the base case dwelling.

### 3.5 Performance indicator

In this research, a climate proof dwelling is assumed to be a dwelling where people feel thermally comfortable under a future climate. ASHRAE (2003) defines thermal comfort as the condition of mind that expresses satisfaction with the thermal environment. The performance indicator, which is used in this research, needs to express how thermally comfortable the dwelling is.

The Dutch building code describes the constructional requirements for newly built or rebuilt buildings (KOMO, 2012). In this code legislation is not present which describes requirements for thermal comfort. There are, on the other hand, guidelines which describe methods for predicting the thermal comfortable state of people in an indoor environment. Some of these methods will be described in the following paragraphs. The best performance indicator for this research will be discussed in paragraph 3.4.6.

#### 3.5.1 Predicted Mean Vote

Fanger (1972) performed extensive laboratory research to collect data, which predicts when an average person is satisfied with the thermal comfort in a room. With help of this data, a method was defined which is called the Predicted Mean Vote (PMV). This PMV is a value which shows the average appreciation of the thermal comfort of a certain space and is based on a steady-state human heat balance (ISSO, 2004). Fanger concluded that the heat balance of the human body depends on the temperature of the skin and the evaporation of sweat (ISSO, 2004). This information is used to create an equation which can predict the average appreciation of thermal comfort for a group of people exposed to the same environment, with the same metabolism and the same level of clothing (ISSO, 2004). The appreciation of an individual can, however, deviate from this average appreciation.

$$PMV = (0.303 * e^{-0.036(M/A)} + 0.028) * (M - W - E_d - E_{sw} - E_{re} - R - C - L)$$

**Equation 4**

- **PMV** = Predicted Mean Vote $[-]$
- **M** = Metabolic flux $[\text{W/m}^2]$
- **A** = DuBois surface area of the naked body $[\text{m}^2]$
\[ W = \text{Rate of mechanical work accomplished} \quad [\text{W/m}^2] \]
\[ E_d = \text{Heat loss by water vapour diffusion through the skin} \quad [\text{W/m}^2] \]
\[ E_{sw} = \text{Evaporation heat loss due to sweating} \quad [\text{W/m}^2] \]
\[ E_{re} = \text{Latent heat loss due to respiration} \quad [\text{W/m}^2] \]
\[ R_r = \text{Heat loss by radiation} \quad [\text{W/m}^2] \]
\[ C = \text{Convective heat flux} \quad [\text{W/m}^2] \]
\[ L = \text{Sensible heat loss due to respiration} \quad [\text{W/m}^2] \]

The PMV-values which can be obtained by using equation 4 are dimensionless values and lie between -3 and 3. Table 3.16 shows which value of the PMV corresponds to a certain level of comfort (ASHRAE, 2003). This table shows that a PMV-value of 0 is the most comfortable state that a person can reach.

Fanger (1972) created a relation between the PMV and the percentage of people who are not satisfied with the indoor thermal comfort (Percentage People Dissatisfied). This relation between the PMV and the Percentage People Dissatisfied (PPD) is shown in Figure 3.17 and can be calculated by using the following equation:

\[ PPD = 100 - 95 \times e^{-(0.03353 \times PMV^4 + 0.2179 \times PMV^2)} \quad \text{Equation 5} \]

Thermal comfort differs from person to person due to differences in metabolism, clothing level and differences in experience and appreciation of the thermal comfort (ISSO, 2004). Therefore, when the PMV has a value of 0, still 5 percent of the people exposed to the same environment, with the same metabolism and the same level of clothing, in that space are dissatisfied with the indoor thermal comfort (ISSO, 2004).

There are three different comfort classes which show the quality of the indoor environment. When the indoor comfort of a building is classified with Class A, it means that the comfort lies above typical comfort standards, Class B indicates a comfort level which represents typical comfort standards and Class C represents a comfort level which lies beneath typical comfort standards (ASHRAE, 2003). The comfort class and associated PPD and PMV values are shown in Table 3.17.

<table>
<thead>
<tr>
<th>PMV</th>
<th>Comfort level</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Hot</td>
</tr>
<tr>
<td>2</td>
<td>Warm</td>
</tr>
<tr>
<td>1</td>
<td>Slightly warm</td>
</tr>
<tr>
<td>0</td>
<td>Neutral</td>
</tr>
<tr>
<td>-1</td>
<td>Slightly cool</td>
</tr>
<tr>
<td>-2</td>
<td>Cool</td>
</tr>
<tr>
<td>-3</td>
<td>Cold</td>
</tr>
</tbody>
</table>

Table 3.16: Comfort level

Figure 3.17: Relation PMV and PPD
(Peeters et al., 2009)
### 3.5.2 Overheating hours

Another method to define the comfort in buildings is counting the amount of hours that the temperature is above a certain temperature (overheating hours). ISSO (2004) describes this method which is developed by the Dutch Government Building Department and based on the PMV-model. They assume that a “good” thermal climate is represented by satisfaction of 90% of the people (PPD of 10%) for 90% of the working time (ISSO, 2004). A PPD of 10% relates to a PMV of 0.5 and -0.5, whereby a PMV of 0.5 represents a temperature of 25 °C (clo = 0.7, MET = 1.2 and v = 0.25 m/s). The working time in an office is approximately 2000 hours (ISSO, 2004). The PPD of 10% may not be exceeded for 10% of the time, which means 100 hours when only considering the summer period. Climate year 1964/1965 must be used for the calculation of the amount of overheating hours. The described assumptions are translated into two rules, which formulate the method ‘overheating hours’:

- 25 °C may be exceeded for a maximum of 100 hours per year, assuming climate year 1964/1965;
- 28 °C may be exceeded for a maximum of 20 hours per year, assuming climate year 1964/1965.

This method has a disadvantage, which shows when the overheating hours of a “light” building and a “heavy” building are compared. When comparing the overheating hours of these two building types, no difference is shown (ISSO, 2004). However, a “lighter” building, with less thermal mass, will have higher average temperatures in practice than the temperatures in a “heavy” building, with a larger thermal mass (ISSO, 2004).

### 3.5.3 Weighted overheating hours

Counting the weighted overheating hours is a different method for assessing the indoor thermal comfort and provided by the Dutch Government Building Department (ISSO, 2004). This method takes the degree of overheating into account and also creates a possibility for adaptation by the building users, which include changing their clothing rate and the air velocity (e.g. by opening windows) (ISSO, 2004). The value of the PPD is calculated, followed by a multiplication with a weighing factor. The weighing factor which is used is directly proportional with the increased value of the PPD; e.g. a PPD of 20% weighs twice as much as a PPD of 10%. The amount of weighted overheating hours may not exceed 150 hours, when using climate year 1964/1965. By increasing the weight of higher temperatures, a difference can be distinguished between “lighter” and “heavier” buildings, which is an improvement compared to the method ‘overheating hours’.

### 3.5.4 Adaptive Temperature Limit

Research shows that people feel more comfortable in buildings which they can alter to their own preferences (de Dear et al., 1997). In the PMV-model created by Fanger (1972) it is assumed that people cannot change parameters to their preferences. This differs in a method created by de Dear et al., (1997), which describes the Adaptive Temperature Limit (ATG). This method defines an adaptive model to assess
the thermal comfort for office buildings with centralized HVAC and for office buildings with natural ventilation.

De Dear et al. (1997) analysed 160 different office buildings to develop this adaptive model. Comparing the results of their adaptive model with the results of the PMV-model showed similar results for the building with centralized HVAC and different results for the building with natural ventilation (see Figure 3.18 and Figure 3.19). There is a difference in the results for buildings with natural ventilation, because people accept higher indoor temperatures when they can influence the indoor environment by, for example, the opening of windows (de Dear et al., 1997). As visible in figure 4.18 both the PMV and adaptive model state that people accept higher indoor temperatures when outdoor temperatures are higher.

![Figure 3.18: Buildings with centralized HVAC (Dea et al., 1997)](image1)

![Figure 3.19: Buildings with natural ventilation (Dea et al., 1997)](image2)

Based on these results the Adaptive Temperature Limit was created, which defines boundaries for two types of buildings; buildings with a centralized HVAC-system (Type Beta) and buildings which are naturally ventilated (Type Alpha). The boundaries are created with the operative indoor temperature (vertical axes) and the running mean outdoor temperature (horizontal axes). The operative indoor temperature is defined as “the temperature of a uniform environment with radiant black enclosure that transfers dry heat by radiation and convection at the same rate as in the actual environment” (ASHRAE, 2003) and can be calculated using the following equation (ASHRAE, 2003):

\[
\theta_o = \frac{h_r \cdot \theta_{mrt} + h_c \cdot \theta_a}{h_r + h_c}
\]

Equation 6

\[
\theta_o = \text{Operative temperature} \quad [\degree C]
\]

\[
\theta_{mrt} = \text{Mean radiant temperature} \quad [\degree C]
\]

\[
\theta_a = \text{Ambient temperature} \quad [\degree C]
\]

\[
h_r = \text{Heat transfer coefficient for radiation} \quad [\text{W/m}^2\cdot\text{K}]
\]

\[
h_c = \text{Heat transfer coefficient for convection} \quad [\text{W/m}^2\cdot\text{K}]
\]

The running mean outdoor temperature is the weighted average of the outdoor temperature of the preceding days (ASHRAE, 2003). This is shown in the following equation (de Dear et al., 1997):

\[
T_{e,ref} = \frac{(1 \cdot T_{today} + 0.8 \cdot T_{yesterday} + 0.4 \cdot T_{day before yesterday} + 0.2 \cdot T_{day before the day before yesterday})}{2.4}
\]

Equation 7
This running mean outdoor temperature is chosen, because preceding days have a large effect on the clothing that people wear and the perception of comfort temperature (de Dear et al., 1997). These choices and preferences are not only dependent on the temperatures of that particular day.

Figure 3.20 and Figure 3.21 show the boundaries of the ATG for the two building types and three different classes. Class A shows an acceptance level of people on the indoor climate of 90%, Class B shows an acceptance of 80% and Class C shows an acceptance of 65%.

### 3.5.5 Adjusted adaptive temperature limit

The PMV-model is based on experiments in steady-state laboratory settings, which do not represent a real situation, especially when focusing on residential buildings (Peeters et al., 2009). Residential buildings have different thermal comfort requirements due to less predictable activity levels of the residents, more ways to adapt the indoor thermal environment (e.g., opening windows) and more ways for the residents to adapt to the indoor thermal environment (e.g., changing clothing levels) (Peeters et al., 2009). Peeters et al. created the adjusted adaptive temperature limit, which provides boundaries for the thermal comfort in residential buildings. Three residential functions (bedroom, bathroom and other residential functions) are distinguished and two of these will be described in the following paragraphs.

**Living room**

The level of comfort in an office differs from the level of comfort that people experience in their homes (Peeters et al., 2009). This is caused by different factors. Residents have different activity levels than people in an office situation and this activity level can easily be adapted to the situation (Peeters et al., 2009). Another factor which differs is that people feel warmer in their homes than they do in an office situation with the same temperature, because people tend to evaluate rooms as being warmer with the presence of furnishings (Oseland, 1994). Residents also accept higher temperatures in the indoor environment; because they have to pay for their own energy bill and they can adjust more easily to temperature differences (e.g., change clothing) (Peeters et al., 2009).

For the living room the boundaries used are those which are proposed for ‘other functions’ (Peeters et al., 2009). Figure 3.22 shows the boundaries for the ATG adjusted for living rooms for Class A (PPD 10%).
Bedroom

Adaptation of residents to a changing thermal comfort in bedrooms is limited, due to the fact that they are sleeping (Peeters et al., 2009). People also expect lower temperatures in their bedrooms (CIBSE, 2005). Therefore, the ATG is not directly applicable in this situation. Research has been done in 39 Belgian houses and based on this research different boundaries for the bedroom situation are proposed (Peeters et al., 2009).

These boundaries are based on the method of Fanger (1972) using the following input parameters:

- Metabolic rate of sleeping: 0.7 met;
- Clothing index (sleepwear, sheets, mattress and pillow): 0.8 clo;
- Relative humidity: 55%;
- Air velocity: 0.05 – 1 m/s.

The boundary of the upper limit is restricted with a temperature of 26 °C, because quality of sleep decreases when temperatures rise above this temperature (CIBSE, 2005). The lower limit is restricted to a temperature of 16 °C, because lower temperatures cause a decrease in resistance to respiratory infections (Peeters et al., 2009). Figure 3.23 shows the boundaries for the ATG adjusted for bedrooms for Class A (PPD 10%).
3.5.6 Performance indicator applied

All the performance indicators which are introduced in the previous sub paragraphs can indicate the level of comfort in building. However, the PMV-model has some restrictions, which are applicable on the situation in this research:

- The model is sensitive to estimates of the clothing level and activity level (ISSO, 2005). In dwellings, these values can differ significantly and therefore might not be well estimated;
- The model under-estimates the level of comfort for relatively cold situations (operative temperatures below 19/20 °C) and over-estimates the level of comfort for relatively hot situations (operative temperatures above 24/25 °C) (ISSO, 2005). This research does focuses on hot weather and therefore, the level of comfort might be over-estimated.
- The model gives estimations for buildings with limitations of users to adapt the building to their preferences (ISSO, 2005). Residents can adapt the dwelling to their preferences and therefore, the model might not predict the level of comfort well.

Due to these restrictions and because these restrictions are applicable to the situation in this research, it is chosen not to use the PMV-model. The other methods (overheating hours, weighted overheating hours and ATG) are methods which are based on the PMV-model and therefore, are also not appropriate for this research. The adjusted adaptive temperature limit provides a method, which is also based on the PMV-model, but proposes boundary conditions which are explicitly created for a residential building. Therefore, this method is chosen to be used in this research. The actual boundary conditions for this method will be explained in the following paragraphs.

Figure 3.23: Adjusted Adaptive Temperature Limit – bedroom
Bedroom

The neutral temperature is the temperature at which a human feels comfortable (de Dear et al., 1997). This temperature for the bedroom depends on the running mean outdoor temperature ($T_{e,\text{ref}}$) and is described by using the following equations (Peeters et al., 2009):

- $T_n = 16 \degree C$ for $T_{e,\text{ref}} < 0 \degree C$
- $T_n = 0.23 \times T_{e,\text{ref}} + 16$ for $0 \degree C < T_{e,\text{ref}} < 12.6 \degree C$
- $T_n = 0.77 \times T_{e,\text{ref}} + 9.18$ for $12.6 \degree C < T_{e,\text{ref}} < 21.8 \degree C$
- $T_n = 26 \degree C$ for $T_{e,\text{ref}} \geq 21.8 \degree C$

In this research we only work with the upper limit, because this research focuses on overheating. Therefore, only the upper limit is considered. This limit for the bedroom temperatures depends on the width of the comfort band ($w$ in °C) and a constant ($\alpha$) and is defined by using the following equation (Peeters et al., 2009):

$$T_{\text{upper}} = \min(26 \degree C, T_n + w \times \alpha)$$

The width of the comfort band and the associated constant depend on the PPD. These values are shown in Table 3.18. For this research is chosen to use a PPD of 10%, because this provides the strictest boundaries for the level of thermal comfort.

The boundary, which is proposed for the bedroom, only has to be met when people are sleeping, because this boundary is based on the behaviour of sleeping people. Following the same user profile as proposed in paragraph 3.1.2, people sleep between 23:00 and 06:00 hours. Therefore, the boundary conditions for the bedroom will be used in the whole dwelling during this period.

Table 3.18: Width comfort band and constant

<table>
<thead>
<tr>
<th></th>
<th>10% PPD</th>
<th>20% PPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w$ [°C]</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>$\alpha$ [-]</td>
<td>0.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Living room

The neutral temperature for the living room is described by using the following equations:

- $T_n = 0.06 \times T_{e,\text{ref}} + 20.4$ for $T_{e,\text{ref}} < 12.5 \degree C$
- $T_n = 0.36 \times T_{e,\text{ref}} + 16.63$ for $T_{e,\text{ref}} \geq 12.5 \degree C$

The upper limit for the living room is created by using the following equation (values for $w$ and $\alpha$ are shown in Table 3.18):

$$T_{\text{upper}} = T_n + w \times \alpha$$

The boundary conditions for the living room will be used in the whole dwelling between 06:00 and 23:00 hours.
3.6 Programs used

Different types of programs are used in this research to create data for the simulations, to perform the simulations and to post-process the data obtained in the simulations:

- Window (Version 6.3.54.0); used to translate glass properties for use in the simulation programs;
- Matlab R2011b (7.13.0.564); used for post-processing data obtained by simulations;
- ESP-r (Version 11.11); building energy simulation program, used for simulations;
- EnergyPlus (Version 1.41a); building energy simulation program, used for simulations.

3.6.1 Building energy simulation

Building energy simulation is used to make a prediction in the design stage of the performance of a building. This type of simulation allows users to understand the interrelation between design and performance parameters, to identify potential problem areas and so implement and test appropriate design modifications (Clarke, 2001). The building energy flow paths of building energy simulation are shown in Figure 3.24.

![Building energy flowpaths](image)

*Figure 3.24: Building energy flowpaths (Clarke, 2001)*
The simulations were performed with two different simulation programs; ESP-r and EnergyPlus. It was decided to use both programs in order to make an intermodel comparison. Simulations of vegetated roofs are only performed in EnergyPlus, since vegetated exterior surfaces are not implemented in the ESP-r (version 11.11) code.

Both programs were used in the BESTest (Building Energy Simulation Test) project as reference programs, because they are considered to represent the best state-of-the-art detailed simulation programs available in the United States and Europe (Judkoff & Neymark, 1995). Results of the BESTest show that there are differences between both programs (Judkoff & Neymark, 1995). This research does not focus on this specific aspect; however, it will have to deal with these differences. Therefore, Table 3.19 shows some of the differences between the codes of the different simulation programs which influence the results of this research (Crawly et al., 2005).

Table 3.19: Differences between EnergyPlus and ESP-r (Crawly et al., 2005)

<table>
<thead>
<tr>
<th>Factor</th>
<th>EnergyPlus</th>
<th>ESP-r</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Element conduction solution method:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Time response factor (transfer functions)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Finite difference / volume method</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td><strong>Insolation analysis:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Distribution computed at each hour</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>- Track insolation losses (outside or other zones)</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>Outside surface convection algorithm:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- DOE-2</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>- MoWiTT</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>- Ito, Kimura and Oka correlation</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>- User-selectable</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>Skymodel:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Isotropic</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>- Anisotropic</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>- User-selectable</td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

The difference between the results of the different simulation programs will be expressed in the Root Mean Square. This value represents the deviation from each other and is calculated with the following equation:

\[
RMS = \sqrt{\frac{1}{t} \int_0^t (T_{\text{EnergyPlus}} - T_{\text{ESP-r}})^2 \, dt}
\]

Equation 8

\[
\begin{align*}
RMS & = \text{Root Mean Square} \quad \left[ ^\circ C \right] \\
t & = \text{time} \quad \left[ \text{hours} \right] \\
T_{\text{EnergyPlus}} & = \text{Temperatures obtained by the program EnergyPlus} \quad \left[ ^\circ C \right] \\
T_{\text{ESP-r}} & = \text{Temperatures obtained by the program ESP-r} \quad \left[ ^\circ C \right]
\end{align*}
\]
4. Results

4.1 Base case dwelling

This paragraph will show the temperatures and operative temperatures of the three different floors in the base case dwelling. The results of the temperatures and the operative temperatures are shown per floor and as an average of these three floors. Subsequently, the results of the operative temperatures are provided in relation to the boundaries of the Adjusted Adaptive Temperature Limit. The last paragraph shows the amount of overheating hours of inside the dwelling for different orientations.

4.1.1 Ambient temperatures

The hourly ambient air temperatures of the different floors and the average of these floors are shown in Figure 4.1 – Figure 4.4. The results are shown for the dwelling oriented in the North direction. The results of the dwelling oriented in other directions are shown in appendix 3. Every top graph shows the temperatures in the period of May till September and the bottom graph show the results of the hottest week in that period.

The trend which is shown in Figure 4.1 till Figure 4.4 is that there is a difference between the simulation-programs used in this research. This difference in results is expressed in Root Mean Square (equation 8) and lies between 0.47 and 0.89 °C. The figures show that the temperatures obtained in the program EnergyPlus are higher than the temperatures obtained in the program ESP-r, with an exception for the temperatures on floor 2. The difference between the programs is not extensively investigated in this research. However, a literature study was performed on this subject and the major differences between the programs were addressed in paragraph 3.5.1. This literature study is not sufficient to define the differences in results which were obtained by the different simulation programs. Therefore, no reason for the difference in results can be provided at this stage.

The temperatures in May show the heating profile which was created for the dwelling. The highest temperatures are reached during July and August, with temperatures above 30 °C. The temperatures are highest on floor 0, where even a temperature of more than 35 °C is simulated. In the bottom graph (figure 4.1) is shown that there is a peak in temperatures at the end of the day. This peak is caused by the high internal loads which are present during this period (see paragraph 3.1.2). A small peak is also shown in the temperatures of floor 1 (Figure 4.2). This peak is smaller than the peak in temperatures on floor 0, because the internal loads are lower. There are no internal loads on floor 2 and therefore, a similar peak is not shown in the temperatures of this floor.
Figure 4.1: Air temperatures floor 0 (RMS = 0.89)

Figure 4.2: Air temperatures floor 1 (RMS = 0.50)
Figure 4.3: Temperatures floor 2 (RMS = 0.55)

Figure 4.4: Average air temperatures in dwelling (RMS = 0.47)
4.1.2 Operative indoor temperatures

The operative indoor temperatures of the different floors and the average of these floors are shown in Figure 4.5 – Figure 4.8. The same types of figures are shown as were shown for the ambient temperatures (paragraph 4.1.1). The results of the dwelling oriented in other directions are shown in appendix 4.

The results shown of the operative indoor temperatures are quite similar to the results shown of the ambient temperatures. The temperatures obtained by simulations in EnergyPlus are also higher than the temperatures obtained by the simulations performed in ESP-r. However, the differences between the results of both programs are larger, compared to the results of the ambient temperatures. This is shown in a higher RMS of 0.56 – 0.94 and caused by the difference between ambient temperatures and operative indoor temperatures. The operative indoor temperature is a combination between the ambient temperature and the mean radiant temperature (see equation 6). The mean radiant temperature increases when the indoor surfaces are irradiated by e.g. solar radiation or radiation from equipment. This causes a difference between the operative- and ambient temperature and therefore, explains the difference between the operative indoor temperatures and ambient temperatures. The operative temperatures are slightly higher than the ambient temperatures.

The figures, which show the results of the operative indoor temperatures, show that the peak temperatures of both programs do not happen on the same moment in time. Simulation program EnergyPlus shows a peak slightly earlier than the results of ESP-r show.

![Figure 4.5: Operative temperatures floor 0 (RMS = 0.94)](image-url)
Figure 4.6: Operative temperatures floor 1 (RMS = 0.56)

Figure 4.7: Operative temperatures floor 2 (RMS = 0.67)
4.1.3 **Adjusted adaptive temperature limit**

The results which are shown in this paragraph are the boundaries of the adjusted adaptive temperature limit, including the average operative temperatures of the base case dwelling oriented to the North. This is shown in Figure 4.9. Every dot shown in this figure represents an hour with the associated operative temperature and the running mean outdoor temperature. The dots, shown for boundary ‘living room’, indicate the hours between 06:00 and 23:00 and the dots, shown for boundary ‘bedroom’, are the hours between 23:00 and 06:00. Every dot, which lies above the boundary, is counted as an overheating hour. The total amount of overheating hours, which are used in this research to present the results, is the sum of the hours above the boundary for the living room and the hours above the boundary for the bedroom.
Figure 4.10 shows the amount of overheating hours for the dwelling oriented to four different directions. The length of the bar shows the range between the results of the two simulation programs.
Figure 4.10 reveals that the amount of overheating hours changes when the dwelling is oriented to different directions. When the dwelling is oriented to the West direction, the amount of overheating hours is highest (1672 - 1676). The amount of overheating hours for the dwelling oriented to the East direction is quite similar (1571 - 1637). The amount of overheating hours in the dwellings oriented to the North and South direction is almost half the amount; respectively between 604 – 836 and between 515 – 726 hours.

This difference between the orientations is likely to be caused by the position of the sun. The sun rises in the East, moves over the South and sets in the West (see Figure 4.11). This means that the sun is positioned highest, when directed in the South orientation. Therefore, when the dwelling is directed to the North or South orientation, one facade with glazing is oriented to the North and the other is oriented to the South. In this situation, the sun is positioned very high and the sun cannot shine deep into the dwelling (see Figure 4.12). Therefore, relatively to the dwelling oriented to the other directions, less solar radiation will enter the dwelling. When the dwelling is directed to the East or West orientation, the sun has a relatively low position, because it rises or sets. In this situation, the sun has a possibility to shine deep into the dwelling, which causes higher temperatures.

4.1.4 Indication older dwellings

Figure 4.13 shows the amount of overheating hours for the different dwelling typologies; reference dwelling built before 1974 (Type 1), reference dwelling 1974 – 1991 (Type 2), reference dwelling 1992 – 2011 (Type 3), reference dwelling built after 2011 (Type 4). These dwelling types are oriented to four different dwelling typologies. The horizontal axis shows the dwelling types and on the vertical axis the amount of overheating hours is shown.
Figure 4.13 shows similar results for the dwelling oriented to the North and South direction. The trend which is shown in these figures is that the amount of overheating hours decreases with an increase in the level of insulation. The amount of overheating hours decreases from approximately 800 – 1700 hours (Type 1) to approximately 500 – 800 hours (Type 4). Increasing the level of insulation causes a reduced heat flux through the construction. Less heat from the outdoor environment can flux through the construction when the level of insulation is increased. This is probably the reason for a decrease in overheating hours, when increasing the level of insulation.

The figures which represent the dwellings oriented to the East and West direction show other results. The upper boundary of the range shows that the amount of overheating hours reduces when the degree of insulation increases, while the lower boundary of the range shows that the amount of overheating hours increases when the degree of insulation increases. This is probably caused by the difference between the used simulation programs.

4.2 Passive climate adaptive measures

The results, which are shown in this paragraph, are obtained by applying the adaptive measures on the base case dwelling. Every paragraph has two sub paragraphs which show the results of the theoretical values and the feasible values for practice. The results which are shown in sub paragraph ‘theoretical values’ show the reduction in overheating hours relative to the base case situation (dwelling type 4) on the vertical axis for the different variants of the measure (horizontal axis). The actual overheating hours are shown in appendix 5. The results shown in sub paragraph ‘feasible values for practice’ show the percentage of reduction in overheating hours of the feasible value for practice (vertical axis) relative to the different types of dwellings.
4.2.1 Increasing amount of insulation

Theoretical values

The variants of measure ‘insulation’ vary in thickness of the insulation material and therefore the $R_c$-values of the material. The $R_c$-values of the construction are shown on the horizontal axis of Figure 4.1. The vertical axis shows the reduction in overheating hours, relative to the base case dwelling (type 4).

The results, which are represented by Figure 4.14, show that the reduction in overheating hours vary between 0 and 25%. The reduction is overheating hours is highest (0 – 25%) when the dwelling is oriented to the North or South direction. When the dwelling is oriented to the East or West direction, the maximum reduction which could be obtained is lowest (0 – 6%). A possible explanation of this difference can be that the amount of overheating hours is for a larger part caused by solar radiation through the windows than by heat flux through the construction. When increasing the level of insulation, still a large part of the overheating hours is caused by solar radiation through the windows. For the dwellings oriented to the North and South direction, the overheating hours are mainly caused by heat flux through the construction. Therefore, when increasing the level of insulation in the construction, this amount of heat flux is reduced and this decreases the amount of overheating hours.

The total reduction in overheating hours is relatively low. This is probably caused by the relatively high $R$-values of the insulation material in the base case situation. Increasing the level of insulation reduces the heat flux through the construction.
Feasible value for practice

The results of the feasible value for practice of the measure ‘insulation’ are shown in Figure 4.15. The feasible value for practice represents an insulation material with an R-value of 5.1 m²*K/W.

![Graphs showing reduction in overheating hours for different dwelling types oriented to North, East, West, and South.](image)

Figure 4.15: Feasible value for practice measure insulation

Figure 4.15 shows the results of the effect of increasing the level of insulation relative to the different type of dwellings. When the dwelling is oriented to the North and South direction, there is a larger reduction in overheating hours for dwelling type 1 (reference dwelling built before 1974), than for dwelling type 4 (reference dwelling built after 2011). This difference in reduction, between the different dwelling types, is probably caused by a reduction in heat flux which is caused by an increase in insulation level. The newer dwelling types have higher levels of insulation and therefore, when increasing the level of insulation by applying the measure, this has less influence. The dwelling oriented to the East and West shows a decrease in reduction hours (upper boundary), with increase in insulation level, while the lower boundary shows an increase in reduction with an increase in insulation level. This difference in results is most likely caused by a difference between the simulation programs.

The reduction in overheating hours tend to be higher when the dwelling is oriented to the North and South situation, compared to the reduction in overheating hours when the dwelling is oriented to the East and West direction. A possible explanation for this difference is the same as was described for the results in Figure 4.14.
4.2.2 Increasing thermal mass

Theoretical values

The variants of measure ‘thermal mass’ vary in thickness of the inner and outer construction of the walls. The increase in thickness of the thermal mass is shown on the horizontal axis of Figure 4.16. The vertical axis shows the reduction in overheating hours, relative to the base case dwelling (type 4).

![Diagram showing reduction in overheating hours for North, East, West, and South orientations as a function of increase in thickness of thermal mass.]

The results of the measure thermal mass, shown in Figure 4.16, reveal that a further increase in the thermal mass does not have a large effect on the amount of overheating hours in the dwellings. This reduction is, however, slightly larger for the dwelling oriented to the North and South direction (0-6%) than for the other directions (0-3%). A possible explanation for this difference might be that, by increasing the thermal mass, a reduction in temperature fluctuations is caused, because of heat storage in the construction. This effect is probably larger for the dwellings oriented to the North and South direction, because the overheating hours in these dwelling types are mostly caused by the heat flux through the construction and less by solar radiation, in comparison to the other situations.
**Feasible value for practice**

The results of the feasible value for practice of the measure ‘thermal mass’ are shown in Figure 4.17. The feasible value for practice is representing an increase of the thermal mass with 100%.

![Graphs showing reduction in overheating hours for different dwelling types and orientations.](image)

*Figure 4.17: Feasible value for practice measure thermal mass*

Figure 4.17 shows the results of the appliance of the feasible value for practice to the different types of dwellings of the measure thermal mass. These results show that when the level of insulation is increased, increasing the thermal mass does not influence the amount of overheating hours significantly (between -5 and 10%).

The reduction in overheating hours tends to be larger when the dwelling is oriented to the North and South situation, in comparison to the other orientations. This can be explained by the same reason as suggested for the results in Figure 4.16.
4.2.3 Increasing the albedo value

Theoretical values

The variants of measure ‘albedo’ vary in the value of the albedo on the outer surfaces of the walls and roof. The value of the albedo is shown on the horizontal axis of Figure 4.18. The vertical axis shows the reduction in overheating hours, relative to the base case dwelling (type 4).

Figure 4.18: Theoretical values measure albedo

Figure 4.18 presents how the amount of overheating hours is influenced by increasing the value of the albedo. The graph shows that increasing the albedo value, to a value of 0.8, causes a decrease in the amount of overheating hours with 20-50%. The graphs show that increasing the albedo value has more influence when the dwelling is oriented to the North and South direction (approximately 40 – 50%) than when the dwelling is oriented to the East and West direction (approximately 20 – 30%). This is likely to be caused by the effect that increasing the albedo of a construction reduces the heat flux through this construction. The dwellings oriented to the North and South direction probably profit more from this reduction, because the overheating hours in these situations are for the larger part caused by the heat flux through the construction. For the dwellings oriented to the East and West direction, there is also a large part of the overheating hours caused by solar radiation and this is probably the reason for the lower reduction in overheating hours.
Feasible value for practice

The results of the feasible value for practice of the measure ‘albedo’ are shown in Figure 4.19. The feasible value for practice represents an albedo value of 0.8 applied on the walls and the roof.

Figure 4.19 reveals that increasing the value of the albedo has a larger influence on dwellings with a lower level of insulation in the constructions. This is shown for the dwelling oriented to all the directions. For dwelling type 1 (reference dwelling built before 1974) a reduction could be reached between 50 and 90%, while the reduction in overheating hours for dwelling type 4 (reference dwelling built after 2011) could be between 20 and 50%. Both increasing the level of insulation and increasing the value of the albedo reduce the amount of heat flux through a construction. This is probably the reason for a decrease in reduction in overheating hours related to an increase in insulation level.

There is also a difference in magnitude of the reduction; the overall reduction in overheating hours is larger when the dwelling is oriented to the North and South direction than for the other directions. This was also shown in Figure 4.18 and the same reason, as suggested by the results of this figure, can be given.

The results which are shown in Figure 4.19 provide information about the dwelling with an albedo value of 0.8 applied on the outer surfaces. This value is based on a clean surface, after the paint is brought on to this surface. Due to pollution this value might be decreased in practice over time (Bretz & Akbari, 1997), which influences the reduction in overheating hours.
4.2.4 Implementing an overhang

Theoretical values

The variants of measure ‘overhang’ vary in the depth of this overhang applied above the vertical windows. The depth of the overhang is shown on the horizontal axis of Figure 4.20. The vertical axis shows the reduction in overheating hours, relative to the base case dwelling (type 4).

Figure 4.20 shows the results of the measure ‘overhang’ applied to the base case dwelling. The results show a decrease in overheating hours of approximately 70-100% (depth 2 meter). The reduction in overheating hours is largest when the dwelling is oriented to the North direction (85-95%) and slightly larger when the dwelling is oriented to the South direction (75-100%), compared to the other directions (70-100%). This is probably caused by the position of the sun and the effect that this has on the amount of solar radiation entering the dwelling. This can be explained by Figure 4.21. This figure shows that when the sun is positioned lower (left figure), the sun can shine deeper into the dwelling than when the sun is positioned higher (right figure). When an overhang is created, less solar radiation is blocked when the sun is positioned lower, because it can shine underneath this overhang. When the sun is positioned higher, more solar radiation is blocked by the overhang.
There is also a difference in the amount of overheating hours for the dwellings oriented to the North and South directions. This is likely caused by the large glass surface which is positioned in the back facade of the dwelling. When the dwelling is oriented in the North direction, it means that the back of the dwelling is oriented to the South orientation. Due to the large glass surface, a larger amount of solar radiation can be blocked by the overhang. This might result in a larger reduction in the amount of overheating hours for the dwelling oriented to the South direction.

**Feasible value for practice**

The results of the feasible value for practice of the measure ‘overhang’ are shown in Figure 4.22.

![Figure 4.21: Blocking of the sun by overhang](image)

![Figure 4.22: Feasible value for practice measure overhang](image)
Figure 4.22 shows the results of the application of the overhang on different dwellings, it illustrates that this measure has a higher impact on dwellings which have a higher level of insulation in the construction. This counts for all the different orientations. This is probably caused by a reduction in heat flux through the construction when the level of insulation is increased. There is a possibility that when this happens, a larger heat flux will arise through the windows. This results in the windows to be the weaker spot of the surface in relation to the heat flux. The weaker the spot, the higher the influence of the overhang, which reduces the amount of solar radiation through this weak spot. The difference in results between the orientations probably has the same reason as was described by the results of Figure 4.20.

4.2.5 Opening windows

Theoretical values

The variants of measure ‘opening windows’ vary in the indoor ambient temperature on which the windows open. The temperature at which the windows are opened is shown on the horizontal axis of Figure 4.23. The vertical axis shows the reduction in overheating hours, relative to the base case dwelling (type 4).

![Graphs showing theoretical values for opening windows](image)

Figure 4.23: Theoretical values measure opening windows

Figure 4.23 showed that an increase in set point temperature for opening of the windows means a reduction in the amount of overheating hours. The reduction is between 80-90% when opening the windows at a temperature of 24 °C. The results show that, when the dwelling is oriented to the East and West direction (around 90%), the reduction in overheating hours is slightly higher than when the dwelling is oriented to the other directions (around 85%).
Feasible value for practice

The results of the feasible value for practice of the measure ‘opening windows’ are shown in Figure 4.24. The feasible value for practice is an opening temperature of 24 °C.

When applying the feasible value for practice of opening the windows to the different dwellings (Figure 4.24), it shows that the measure has a larger effect on the dwellings which are insulated (dwelling type 1, 2 and 3) than on the dwelling which is not insulated (dwelling type 4). This difference is especially shown between dwelling types 1 (No insulation) and 2 (Indication dwelling 1974 - 1991). There is not much difference in reduction of overheating hours between dwelling types 2, 3 and 4. This might be caused by the temperature fluctuations in the dwelling, which are affected by the opening of the windows. When a dwelling has no insulation, temperature fluctuations tend to be larger than in dwellings with insulation. The heat can escape relatively easy from the building when the construction has no insulation. The effect that opening of windows have is that heat can be released from a dwelling. This process is probably more present in the dwelling without insulation, so therefore, this measure has less effect on this dwelling.
4.2.6 Implementing a vegetated facade and/or roof

Theoretical values

The variants of measure ‘vegetated facade and roof’ vary in the Leaf Area Index. The LAI, which is applied on the roof and outer surfaces, is shown on the horizontal axis of Figure 4.25. The vertical axis shows the reduction in overheating hours, relative to the base case dwelling (type 4).

![Graphs showing reduction in overheating hours vs. Leaf Area Index for different orientations (North, East, West, South).](image)

Figure 4.25: Theoretical values measure vegetated facades and roof

Figure 4.25 shows the results of the application of vegetated facades and roof to the base case dwelling. These figures do not show a range because this adaptive measure was only simulated with one simulation program (EnergyPlus). This figure shows that a reduction in overheating hours can be obtained between approximately 25 and 60% (LAI of 5). There is a difference in reduction in overheating hours between the dwellings oriented in different directions. The measure has a larger effect on the dwellings which are oriented to the North and South direction (approximately 55-60%), compared to dwellings oriented to the East and West orientation (approximately 25-35%). The vegetated facades and roof reduces the amount of overheating hours in two different ways (see paragraph 3.2.6); by evapotranspiration and by creating an extra insulation layer (soil).

The effect that the insulation layer has on the amount of overheating hours is not influenced by changing the Leaf Area Index, in contrast to the effect that evapotranspiration has. The factor which is changed in these simulations is the LAI. Therefore, when increasing the LAI, the influence that the evapotranspiration has on the amount of overheating hours increases, while the influence that the soil layer has on the amount of overheating hours stays unchanged. This is reflected in the figures by the straight lines which are drawn between variant 2 till 5. The differences between the variants 2 till 5 are caused by evapotranspiration, while the difference between 1 and 2 is also caused by the extra insulation layer created by the soil.
The measure has more effect on the orientations which are more affected by heat flux through the constructions (North and South). Due to the extra insulation layer which is created by the soil, the construction is improved and therefore, reduces the amount of overheating hours.

**Feasible value for practice**

The results of the feasible value for practice of the measure ‘vegetated roof’ are shown in Figure 4.26. The feasible value for practice is a LAI of 5.

![Figure 4.26: Feasible value for practice measure green surface](image)

Figure 4.26 shows the results of the feasible value for practice applied on the roof of the different dwelling types. The measure has more effect on the dwellings without insulation (type 1), than on the newer indications of dwellings (type 2, 3 and 4). The measure also creates a higher reduction in the amount of overheating hours for the dwellings oriented to the North and South orientation.

The results of Figure 4.26 show that the measure ‘vegetated roof’ has a larger effect on the older dwelling typologies. This is probably caused by the effect that, when implementing a vegetated roof, an extra layer of insulation is created by the soil of this vegetated roof. This reduces the amount of heat flux through this construction. When increasing the insulation level, this same heat flux is reduced and therefore is the reduction in overheating hours less.

This is also shown in the comparison between the different orientations. An improvement of the construction has a larger effect on the reduction in overheating hours on dwellings oriented to the North and South direction. The reduction in overheating hours, caused by the evapotranspiration is relative equal for every dwelling, because the vegetated roof is only applied to the roof of the dwelling.
5. Discussion

This chapter consists of an analysis of the results obtained by this research. This analysis will be performed with help of the results of the feasible values for practice applied on the different dwelling typologies. The figures show the reduction in overheating hours of the feasible values for practice relative to the different dwelling types; no insulation (type 1), indication of insulation value between 1974 and 1991 (type 2), indication of insulation value of 1992 - 2011 (type 3) and the base case dwelling (type 4).

5.1 Reference dwelling type built before 1974

The results of the feasible values for practice relative to dwelling type 1 (reference dwelling type built before 1974) is shown in Figure 5.1. The reduction in overheating hours is shown on the vertical axis, while the measures (‘insulation’, ‘thermal mass’, ‘albedo’, ‘overhang’, ‘opening of windows’ and ‘vegetated roofs’) are shown on the horizontal axis.

The four figures, shown in Figure 5.1, show the reduction in overheating hours of all the measures, relative to each other. The measure which shows the largest reduction (49 - 91%) in the amount of overheating hours is ‘albedo’. The second, third and fourth largest reduction in overheating hours is caused by the measures ‘vegetated roof’, ‘opening of the windows’ and ‘overhang’. This depends on the orientation of the
dwelling. When the dwelling is oriented to the North and South orientation, is the largest reduction in overheating hours caused by the measure ‘vegetated roof’ (66 – 72%), followed by the measures ‘opening of the windows’ (52 – 65%) and the ‘overhang’ (34 – 67%). When the dwelling is oriented to the East and West orientation, is the largest reduction in overheating hours caused by the measure ‘opening windows’ (62 – 67%), followed by the measures ‘overhang’ (30 – 52%) and ‘vegetated roof’ (33 – 38%). The measures which provide the fewest reduction in overheating hours are respectively the measures ‘insulation’ (-7 – 61%) and ‘thermal mass’ (-4 – 4%).

5.2 Reference dwelling type 1974 - 1991

The results of the feasible values for practice relative to dwelling type 2 (reference dwelling type 1974 – 1991) is shown in Figure 5.2. The reduction in overheating hours is shown on the vertical axis, while the measures (‘insulation’, ‘thermal mass’, ‘albedo’, ‘overhang’, ‘opening of windows’ and ‘vegetated roofs’) are shown on the horizontal axis.

The figures shown in figure 5.2 show the reduction in overheating of the measures, applied on dwelling type 2 (reference dwelling type 1974 - 1991). The classification of the measures is similar for the different orientations. The figures show that the measure which causes the largest reduction on the amount of overheating hours is ‘opening of the windows’ (77 – 96%), followed by the measure ‘overhang’ (49 – 95%). The third-highest reduction in overheating hours is caused by the measure ‘albedo’ (35 – 69%), while the fourth-highest reduction in overheating hours is caused by the measure the ‘vegetated roof’ (22 – 64%). The lowest reduction in overheating hours is caused by the measures ‘insulation’ (-3 – 44%) and ‘thermal mass’ (-1 – 6%).
When comparing the classification of the measures in Figure 5.2 with the classification of the measures in Figure 5.1, there are differences. These differences are caused by displacements of the reduction in overheating hours for all the individual measures. The reduction in overheating hours has increased for the measures ‘overhang’ and ‘opening of windows’. The reduction in overheating hours has decreased for all the other measures.

5.3 Reference dwelling type 1992 – 2011

The results of the feasible values for practice relative to dwelling type 3 (reference dwelling type 1992 – 2011) is shown in Figure 5.3. The reduction in overheating hours is shown on the vertical axis, while the measures (‘insulation’, ‘thermal mass’, ‘albedo’, ‘overhang’, ‘opening of windows’ and ‘vegetated roofs’) are shown on the horizontal axis.

Figure 5.3 shows the results of the measures applied on dwelling type 3 (reference dwelling type 1992 - 2011). The classification of the measures is quite similar to the classification shown in figure 5.2. However, there is a difference between the amounts of reduction caused by the measures. The measure, which has the largest impact in reducing the overheating hours, is the ‘opening of windows’ (82 – 89%), except for the situation where the dwelling is oriented to the North direction (85%). For this orientation shows the measure ‘overhang’ the largest reduction (82 – 98%). For the other orientations causes the measure ‘overhang’ the second-highest reduction (62 – 95%). The rest of the classification is, in order of largest reduction to smallest reduction: ‘albedo’ (25 – 58%), ‘vegetated roof’ (17 – 57%), ‘insulation’ (-2 – 30%) and ‘thermal mass’ (0 – 6%).
The results, shown in Figure 5.3 show similarities with the results in Figure 5.2. However, the individual measures have moved, because the reduction in overheating hours is increased or decreased. The reduction in overheating hours has decreased for the measures ‘albedo’, ‘vegetated roof’, ‘insulation’ and ‘thermal mass’. The measures ‘overhang’ and ‘opening of windows’ show an increase in reduction of overheating hours, compared to the results shown in Figure 5.2.

5.4 Reference dwelling type built after 2011

The results of the feasible values for practice relative to dwelling type 4 (reference dwelling type built after 2011) is shown in Figure 5.4. The reduction in overheating hours is shown on the vertical axis, while the measures (‘insulation’, ‘thermal mass’, ‘albedo’, ‘overhang’, ‘opening of windows’ and ‘vegetated roofs’) are shown on the horizontal axis.

The figures, shown in Figure 5.4, show the results of the measures applied to dwelling type 4. The classification of the results is slightly different from the results shown in Figure 5.3. The measure ‘overhang’ shows the largest reduction in overheating hours when the dwelling is oriented to the North and South direction (74 – 99%), while the measure ‘opening windows’ shows the largest reduction in overheating hours when the dwelling is oriented to the East and West direction (90 – 91%). The other measures are classified in the following order (from largest reduction to smallest reduction): ‘albedo’ (20 – 51%), ‘vegetated roof’ (14 – 47%), ‘insulation’ (-2 – 18%) and ‘thermal mass’ (0 – 7%).

There is a difference between the results shown in this figure and the results shown in Figure 5.3 and this is caused by the displacements of the individual measures. The reduction in overheating hours for the
measures ‘insulation’, ‘thermal mass’, ‘albedo’ and ‘vegetated roof’ is decreased. There is an increase in reduction hours for the measure ‘overhang’ and ‘opening windows’, relative to the results in Figure 5.3.
6. **Conclusions**

This chapter will describe the conclusion of this research and furthermore, answers the research question. This research question was described in paragraph 2.3.1 and was followed by three sub-questions. These questions defined the research question and the answers will be briefly summarized in the following paragraph. The last paragraph answers the research question.

6.1 **Sub-questions**

*What is a typical Dutch dwelling which can be used for evaluation of the adaptive measures?*

An overview of the Dutch dwelling stock, and properties of these dwellings, is gathered in a database (Monitor nieuwe woningen, 2012). Agentschap NL created different dwelling types, based on this database, which provide guidance for new to build dwellings (Senternovem, 2006). Concluded was that the terraced dwelling represents the largest part (36.5%) of the dwelling construction in the Netherlands. The publication also provides detailed floor plans, facades and properties of this dwelling type. These are used in this research. Three additional dwelling types were created to show indications of dwellings which were built in the past; reference dwelling built before 1974 (type 1), reference dwelling 1974 – 1991 (type 2) and reference dwelling 1992 – 2011 (type 3). These dwellings were created by reducing the amount of insulation in the constructions.

*What climate data or scenarios can be used for the evaluation of different measures applied on dwellings?*

Different research efforts show that there are different options for climate data which could be used for this type of research (Wilde et al., 2008, Gaterall & McEvoy, 2005, Klein Tank & Lenderink, 2009, Porritt et al., 2012). Climate scenarios from KNMI could be used; however, these climate scenarios provide future average temperatures and chances on extreme weather events rather than weather predictions for a specific date. Another option is the use of climate of southern countries in Europe. The disadvantage of this method is that these cities have different latitudes compared to Dutch cities, which influences the amount of solar radiation and wind speed. In this research is chosen to work with the climate data of the summer of 2003, because it is predicted that this summer will become an average summer for the 2040s (Scott et al., 2004).

*Which performance indicator can evaluate and quantify the adaptive measures?*

Out of different performance indicators it was chosen to work with the Adjusted Adaptive Temperature Limit. This performance indicator is especially created to measure the level of comfort in residential buildings. Different boundaries are proposed for the bedroom and living room. The amount of hours above these boundaries is counted as an overheating hour. These are used to show the results.
6.2 Research question

The following research question was stated at the beginning of this report:

*What are the effects of different climate adaptation measures, applied to a typical Dutch dwelling?*

The answer to this question is summarized in Table 6.1. This table shows the reduction in overheating hours per dwelling type that the measures cause, relative to the base situation of that dwelling type. The actual amount of overheating hours is shown in appendix 6. The range between the values is caused by the different orientations of the dwelling and the two different simulation programs.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Reduction in overheating hours [%]</th>
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<tbody>
<tr>
<td>Insulation</td>
<td>-7 – 61, -3 – 44, -2 – 30, -1 – 18</td>
</tr>
<tr>
<td>Thermal mass</td>
<td>-4 – 4, -1 – 6, 0 – 6, 0 – 7</td>
</tr>
<tr>
<td>Albedo</td>
<td>49 – 91, 35 – 69, 25 – 58, 20 – 51</td>
</tr>
<tr>
<td>Overhang</td>
<td>30 – 67, 49 – 95, 62 – 98, 70 – 99</td>
</tr>
<tr>
<td>Vegetated roof</td>
<td>33 – 66, 22 – 64, 17 – 57, 14 – 47</td>
</tr>
</tbody>
</table>

Table 6.1 shows the effect that the different measures have on the reduction in overheating hours. Dwelling types 1 (reference dwelling type built before 1974), 2 (reference dwelling type 1974 – 1991) and 3 (reference dwelling type 1992 – 2011) represent older dwellings which might need reconstruction. When reconstructing, it depends on the dwelling types which measures could be applied best to obtain the largest reduction in overheating hours. For dwelling type 1 shows the measure ‘albedo’ the largest reduction in overheating hours, while the measure ‘thermal mass’ shows the smallest reduction in overheating hours. The measure ‘opening of windows’ shows the largest reduction in overheating hours applied on dwelling type 2. The smallest reduction in overheating hours for this dwelling type can be obtained by applying the measure ‘thermal mass’. For dwelling type 3, the largest reduction can be obtained by applying the measure ‘overhang’ or ‘opening windows’. This depends on the orientation of the dwelling. When constructing a new dwelling (type 4), the largest reduction can be obtained by applying the measure ‘overhang’ or ‘opening windows’, which depends on the orientation of the dwelling.

6.3 Recommendations

Further research which could be performed to broaden and deepen the results obtained by this research could focus on the following subjects:

- Actual measurements performed on city level in a dwelling without and with the measures applied. These measurements could validate the results, obtained in this research. The climate data which is used in this research is measured in rural area and this does not take the Urban Heat Island effect into account. This research could be broadened when data would be used, which take the Urban Heat Island effect into account.
- This research only investigated the terraced dwelling. Senternovem (2006) created different dwelling typologies. The effectiveness of the adaptation measures could also be investigated on these other buildings types.

- There are measures which were not taken into consideration, because they were not present in the simulation programs (i.e. evaporative cooling). These measures could be an extension to this research.

- A user profile, which represented a family, was used in this research. The influence of this user profile and other user profiles, on the results, can be investigated in future research.

- This research has focused on individual measures. However, it could be interesting to investigate what the influence on overheating hours is when different measures are combined.

- In the future, more households could be equipped with air-conditioning systems (Kempen, 2000). Therefore, it might be interesting to investigate how much energy for cooling could be saved when applying the measures on a dwelling which is equipped with an air-conditioning system.
7. References


ISSO. (2011). *Publicatie 32 Uitgangspunten temperatuursimulatieberekeningen*.


Klein Tank, A., & Lenderink, G. (2009). *Climate change in the Netherlands; Supplements to the KNMI ’06 scenarios*. De Bilt: KNMI.


Knowledge for Climate. (2012). *Dutch climate adaptation research*.


Ministerie van VROM. (2010). *Energiegedrag in de woning*.


8. Appendices

I. Floor maps and facades of analysed dwelling

This appendix show the floor maps and facades of the dwelling analysed in this research. Figures 8.1 shows the front and back facades of the dwelling analysed in this research.

Figure 8.2 shows the floor maps of the three different floors which are present in the dwelling analysed in this research.
Figure 8.2: Floor maps
II. Material properties of analysed dwelling

This appendix shows the properties of the materials which are used in this research. The following overview shows the properties of the windows which are used in this research.

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<th>D(mm)</th>
<th>Tsol</th>
<th>1 Rsol</th>
<th>2 Tsol</th>
<th>1 Rvis</th>
<th>2 Tvis</th>
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Environmental Conditions: 1 NFRC 100-2010

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Optical Properties for Glazing System '10 Climaplus N'

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Table 8.1 shows the properties of the materials which are used in the construction of the dwelling analysed in this research.
Table 8.1: Material properties

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III. **Simulated ambient indoor temperatures**

The figures in this appendix show the ambient indoor temperatures on the different floors of the dwelling and an average of these ambient indoor temperatures. Every top figure shows the ambient indoor temperatures (vertical axis) for the period May – September (horizontal axis). The bottom figures show the ambient indoor temperatures measured in the hottest week of that period (horizontal axis). The graphs differ in the direction on which the dwelling is oriented.
Figure 8.3: Air temperatures floor 0

Figure 8.4: Air temperatures floor 1
Figure 8.5: Air temperatures floor 2

Figure 8.6: Average air temperatures in dwelling
Figure 8.7: Air temperatures floor 0

Figure 8.8: Air temperatures floor 1
Figure 8.9: Air temperatures floor 2

Figure 8.10: Average air temperatures in dwelling
Figure 8.11: Air temperatures floor 0

Figure 8.12: Air temperatures floor 1
Figure 8.1: Air temperatures floor 2

Figure 8.13: Air temperatures floor 2

Figure 8.14: Average air temperatures in dwelling
IV. Simulated operative indoor temperatures

The figures in this appendix show the operative indoor temperatures on the different floors of the dwelling and an average of these temperatures. Every top figure shows the operative indoor temperatures (vertical axis) for the period May – September (horizontal axis). The bottom figures show the operative indoor temperatures measured in the hottest week of that period (horizontal axis). The graphs differ in the direction on which the dwelling is oriented.
Figure 8.1: Operative indoor temperatures - Floor 0

Figure 8.15: Operative indoor temperatures floor 0

Figure 8.16: Operative indoor temperatures floor 1
Figure 8.1: Operative indoor temperatures floor 2

Figure 8.17: Operative indoor temperatures floor 2

Figure 8.18: Average operative indoor temperatures
Figure 8.1: Operative indoor temperatures floor 0

Figure 8.2: Operative indoor temperatures floor 1

Figure 8.19: Operative indoor temperatures floor 0

Figure 8.20: Operative indoor temperatures floor 1
Figure 8.21: Operative indoor temperatures floor 2

Figure 8.22: Average operative indoor temperatures
Figure 8.23: Operative indoor temperatures floor 0

Figure 8.24: Operative indoor temperatures floor 1
Figure 8.25: Operative indoor temperatures floor 2

Figure 8.26: Average operative indoor temperatures
V. Overheating hours per measure

The figures which are shown in this appendix show the overheating hours which are present in dwelling type 4 with and without the measures applied on it. The results are shown for the different orientations with the amount of overheating hours on the vertical axis and the variant of the measure on the horizontal axis.
Figure 8.2: Overheating hours measure insulation

Figure 8.27: Overheating hours measure insulation

Figure 8.28: Overheating hours measure thermal mass
Figure 8.29: Overheating hours measure albedo

Figure 8.30: Overheating hours measure overhang
Figure 8.31: Overheating hours measure opening windows

Measure: Opening windows

Figure 8.32: Overheating hours measure green surfaces

Measure: Green surfaces
### VI. Overheating hours per dwelling type

Table 8.2 shows the amount of overheating hours per dwelling type for dwelling with and without the measures applied on it. The range in results is caused by the different simulation programs and the different orientations on which the dwelling is directed.

**Table 8.2: Overheating hours per dwelling type**

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<td>Thermal mass</td>
<td>829 – 2212</td>
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<td>Overhang</td>
<td>295 – 1532</td>
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<td>Opening of windows</td>
<td>386 – 714</td>
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<tr>
<td>Vegetated roof</td>
<td>432 – 1451</td>
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