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On the predicted effectiveness of climate adaptation measures for residential buildings

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Abstract:
In a changing outdoor climate, new buildings as well as the existing building stock need to adapt in order to keep providing their inhabitants and users a comfortable and healthy indoor environment, with a minimum or – preferably – no increase in energy consumption. In this paper, the effectiveness of six passive climate change adaptation measures applied at the level of building components is assessed using building energy simulations for three generic residential buildings as commonly built in - among others - the Netherlands: (1) detached house; (2) terraced house; (3) apartment. The study involves both residential buildings that are built according to the regulations and common practice in 2012, and residential buildings that were constructed in the 1970s, with a lower thermal resistance of the opaque and transparent parts of the building envelope. The climate change adaptation measures investigated are: (i) increased thermal resistance; (ii) changed thermal capacity; (iii) increased short-wave reflectivity (albedo); (iv) vegetation roofs; (v) solar shading; and (vi) additional natural ventilation.
This paper quantifies the effectiveness of these climate change adaptation measures for new residential buildings as well as for renovation of the current building stock. The performance indicator is the number of overheating hours during a year. It is shown that exterior solar shading and additional natural ventilation are most effective for this performance indicator. Furthermore, increasing thermal insulation to reduce energy use for heating demands additional measures to prevent overheating.

Keywords: building energy simulation; climate change adaptation measures; dwellings; future climate; thermal comfort; building performance

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1. Introduction

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) states that climate change is unmistakably occurring and is already visible in some recent observations of the climate [1]. The global temperature has increased with 0.56°C to 0.92°C in the last century (1906-2005), and it is shown that 11 of the 12 hottest years between 1850 and 2007 took place in the last 12 years prior to 2007 [1]. The temperatures is expected to increase on average with 0.2°C per decade in the next two decades. When the concentrations of all greenhouse gas emissions and aerosols would have remained constant at the levels of the year 2000, the expected temperature increase would still be around 0.1°C per decade [1]. The temperature after the next two decades becomes more dependent on the emission scenarios and is therefore subject to a large uncertainty [1]. Nevertheless, a temperature increase between 1.1°C and 6.4°C is predicted until the end of this century, when compared to the temperatures in the period 1980-1999 [1].

The predicted climate change differs per continent, country and even per region [2]. The Royal Dutch Meteorological Institute (KNMI) studies climate change in the Netherlands. A measure to indicate the changing climate is the yearly number of heat waves. The KNMI defines a heat wave as a period of at least five days during which the daily maximum ambient temperature is 25°C or higher [3]. These five days must include at least three days with a maximum ambient temperature higher than 30°C. In the period between 1901 and 2009, 38 heat waves have been recorded in the Netherlands, seven of which took place in the last decade of this period (1999-2009) [4]. Moreover, in the future, it is likely that the Dutch climate will be subject to a continuous rise of temperatures; mild winters and hot summers with heat waves will become even more common than in the decade 1999-2009 [5]. While the occurrence of mild winters will decrease the energy demand for heating, the increasing number of hot summers can lead to problems regarding thermal comfort and health of building occupants, and to an increase of energy use in buildings with active cooling systems. The effect of climate change on the additional energy use in buildings in summers, and on increased levels of human morbidity and mortality, has been reported in several publications [6-8]. Figure 1, reproduced from a study by Garssen et al. [9], for example indicates the relation between the average weekly maximum outdoor air temperature and the number of deaths in the Netherlands for each of those weeks. The figure shows a very strong correlation; higher average weekly maximum temperatures result in a higher number of deaths. Since people spend around 90% of their time indoors [10], the adaptation of buildings to the predicted climate change is important to protect people against excessive exposure to high indoor air temperatures, or at least to limit the effects as much as possible. The effects of climate change on the (built) environment and thus on humans, as described above, indicate the urgency to study, analyze and implement climate change adaptation measures at different scales, including the building scale, to limit the consequences of climate change in terms of increased health problems, reduced productivity and increased energy use.
Residential buildings in the Netherlands and in many other North-Western European countries are typically neither equipped with an air-conditioning system, nor with other active cooling systems to reduce the indoor air temperature in hot periods [11,12]. Therefore, the building itself must provide sufficient protection against high air temperatures. Moreover, from an environmental point of view, it is undesirable to apply air-conditioning systems and other active cooling systems on a large scale in these residential buildings, since this will lead to a higher energy consumption and thus to higher emission levels of greenhouse gasses, which will intensify climate change and global warming even more [13]. To protect building occupants from the effects of climate change without increasing the energy use one should therefore rely on sustainable solutions to prevent indoor overheating in residential buildings, but also in other buildings, e.g. offices, schools.

In this study, the effectiveness of passive climate change adaptation measures is assessed when applied to typical Dutch residential buildings assuming an expected future climate year. A passive measure is defined as a measure which does not use energy once it has been implemented. In the past, several publications have addressed possible climate change adaptation measures on city, neighborhood, street or building scale (e.g. [4,14-23]). Porrit et al. [17,18] studied the effect of a range of passive climate change adaptation measures for residential buildings (late 19th century Victorian terraced houses with solid walls) in the UK using the dynamic thermal simulation program EnergyPlus. Among others, they studied the effect of building insulation, shading and natural ventilation. They concluded that the application of one or more passive adaptation measures may reduce the number of overheating hours with 32-99%, depending on the type of adaptation measure, and on the number of adaptation measures that are implemented simultaneously. Coley et al. [19] studied several adaptation measures for a well-insulated residential building (large house) and a school building in the UK. They analyzed both hard (structural) and soft (behavioral) adaptation measures and concluded that behavioral adaptation measures, such as opening and closing the windows at appropriate moments (night ventilation, additional daytime ventilation), shifting school hours with two hours forward, can be just as efficient as the application of structural climate change adaptation measures, such as increasing the thermal mass and adding external solar shading. Note that in the aforementioned studies only one type of residential building and only one construction period (and thus thermal resistance of the building envelope) was studied, while the study presented here provides a more broad analysis of the predicted effectiveness of climate change adaptation measures for three types of residential buildings and for two different construction years.

The present study focuses on the effectiveness of climate change adaptation measures applied at the level of building components for three generic residential buildings as commonly built in - among others the Netherlands: (1) detached house; (2) terraced house; (3) apartment. The numerical study involves both residential buildings that are built according to the building regulations and common practice in 2012, and residential buildings that were constructed in the seventies of last century, and which have a lower thermal resistance of the opaque and transparent parts of the building envelope. The climate change adaptation measures investigated are: (i) increased thermal resistance; (ii) changed thermal capacity; (iii) increased short-wave reflectivity (albedo value); (iv) vegetation roofs; (v) solar shading; and (vi) additional natural ventilation. The analysis is performed with dynamic thermal simulations using EnergyPlus [24].
The research is conducted within the Climate Proof Cities (CPC) research consortium, which is one of the research consortia investigating the climate vulnerability of urban areas and the development and effectiveness of climate change adaptation measures [25]. CPC is a mainly Dutch consortium, which groups several universities, research institutes, policy makers and city officials to perform an integrated and thorough analysis on climate change adaptation focused on several locations in the Netherlands.
Section 2 describes the adaptation measures that are studied and will provide some background on each of them. The methodology will be addressed in Section 3, after which the results of the dynamic thermal simulations will be presented in Section 4. Section 5 (discussion) and Section 6 (conclusions) conclude this paper.

2. Passive climate change adaptation measures

A range of passive climate change adaptation measures is mentioned in previous studies (e.g. [17-19]). In this study the focus is on six passive climate change adaptation measures. For each measure we define a base case situation and an alternative situation. Table 1 provides a detailed overview of the six considered adaptation measures.

2.1. Thermal resistance

In recent decades the minimum required thermal resistance values in European countries have been increased substantially to reduce the energy use for heating (e.g. [26]). For example, the building code in the Netherlands prescribes that the thermal resistance (R_C value) for all closed parts of the building envelope should be at least $R_C = 3.5$ m^{2}K/W and the U value (thermal transmittance) for the doors and windows should be lower than U = 1.65 W/m^{2}K [27]. In other West-European countries these values differ to a certain extent; for example, the building code in Germany prescribes a maximum U value of 0.28 W/m^{2}K for the floor, 0.35 W/m^{2}K for the walls, 0.2 W/m^{2}K for the roof, and 1.3 W/m^{2}K for the windows [28], while the building code in the UK prescribes a maximum U value of 0.25 W/m^{2}K for the floor, 0.3 W/m^{2}K for the walls, 0.2 W/m^{2}K for the roof and 2.0 W/m^{2}K for the windows [29]. An unwanted effect of increasing insulation levels of opaque and transparent parts of the building envelope during summer (warm days) is the fact that once a high indoor temperature is reached, for example due to solar radiation through the transparent parts (glass) of the building envelope, it will also be retained for a longer period than in the case of a lower thermal resistance, which would allow more heat transfer through the enveloped parts.
The effect of two alternative values of the thermal resistance of the closed parts of the building envelope has been analyzed in this study: $R_C = 5.0$ m^{2}K/W and $R_C = 6.5$ m^{2}K/W.

2.2. Thermal mass

In terms of thermal storage, one can distinguish between heavy-weight buildings (> 85 kg/m^2), and light-weight buildings (< 20 kg/m^2), referring to the amount of thermal mass that is available for thermal storage per visible surface area (either a wall, a floor or ceiling) (e.g. [30]). Thermal storage is known to be an effective measure to reduce temperature fluctuations during the day (e.g. [31-37]), however, it can also lead to a slower reduction of air temperature during the night. In addition to fixed thermal storage, several studies have assessed the performance of adaptive thermal storage to optimize the use of thermal storage (e.g. [38-39]). However, the application of adaptive thermal storage is outside the scope of this research.

The thermal mass of the inner leaf of the construction (exposed to the indoor conditions) is manipulated in this study to analyze its effect on indoor temperature. Since residential buildings in the Netherlands in general are heavy-weight buildings due to the use of concrete, brick, and other heavy building materials, the base case can be considered as a heavy-weight building. Therefore, for the other case, the thermal mass of the residential buildings is lowered to analyze its effect on indoor temperature during the day, and also during the night. The inner leaf of the building envelope in the alternative case consists of wooden sheets instead of limestone, and the concrete ceilings are replaced by a wooden construction as well. Therefore, this is the inverse of adaptation. Nevertheless, it serves to illustrate the effects of thermal storage on indoor overheating.

2.3. Short-wave reflectivity

The short-wave reflectivity (albedo) of a surface is the fraction of incoming short-wave radiation that is reflected. A higher short-wave reflectivity will result in lower exterior surface temperatures and thus in a lower heat flux from the exterior surface to the indoor environment through the building envelope. In countries with a Mediterranean climate (Köppen classification Csa/Csb [40]), such as Greece, it is quite common to paint external surfaces white in order to increase the solar reflectance. Several research efforts showed that changing the short-wave reflectivity of the roof and/or facades of different types of buildings can result in a reduction of the indoor air temperature during the summer (e.g. [34,41-43]). Cheng et al. [34] performed experiments and showed that lighter colors (white instead of black) of the building envelope lead to significantly lower indoor air temperatures (1-5°C). Note that the thermal resistance R_C in the experiments was only 0.76 m^{2}K/W. Akbari et al. [41] showed a decrease of the cooling load by 80% in a dwelling when the short-wave reflectivity of the roof was increased from 0.18 to 0.73. A study by Bretz and Akbari [42] showed that the energy use for cooling can be reduced by 10-70% with application of high short-wave reflectivity (0.5-0.8) coatings for a residential building in California, USA. Synnefa et al. [43] performed a case study to analyze the impact of a high short-wave reflectivity (0.89) applied to the roof construction of a 410 m^2 non-insulated school building in Athens, Greece. Their experiments showed that a high short-wave reflectivity for the roof reduced the indoor air temperature by 1.5-2°C during summer. The spread in air temperature reduction found in the aforementioned publications can be attributed to different factors; e.g. material properties, different values for the short-wave reflectivity in the base case situation, pollution of the external surfaces, the thermal resistance of the building envelope, and the location of the building.

Common values for the short-wave reflectivity are about 0.3 for red brick materials and roof tiling [44]. Therefore, in the base case the default value for the short-wave reflectivity for the facades and the roof is taken equal to 0.3, and in the alternative cases this value is increased to 0.6 and 0.8 respectively, which corresponds to the values from literature as reported above.

2.4. Vegetated roofs

By implementing a vegetated roof, the heat flux through the roof can be reduced as a result of: (1) change in short-wave reflectivity; (2) increase of insulation layer; (3) increase of thermal mass; (4) increase of convective heat transfer; and (5) evapotranspiration. As described in Section 2.3, the short-wave reflectivity (albedo) of a surface can be an important factor for the heat flux through the building envelope. However, Tabares-Velasco [45] measured the short-wave reflectivity of green roofs and found values that are in general below 0.35, which is not much higher than the default values used in this study. The second effect is the extra insulation layer that is provided by the soil used for the vegetation. This layer of soil, with a depth between 0.075 and 0.15 m, can add between 0.37 and 0.85 m^2K/W to the thermal resistance value of the building envelope [46], with the smallest addition for soil with the highest moisture content. The third effect relates to the added thermal mass due to the addition of the green roof (soil). This thermal mass is present on the outside of the insulation layer and does not affect heat storage inside the building. However, the added thermal mass does reduce and delay outside surface temperature peaks of the roof [46]. The fourth effect is due to foliage and increased surface area for convection. Tabares Velasco [45] experimentally showed that a vegetated roof has slightly higher values for the convective heat flux than the same roof without vegetation. It must be noted that the convective heat flux was calculated indirectly by subtracting all other heat fluxes from the total measured heat flux, and is therefore the least accurately "measured" heat flux [45]. However, the fifth and most important effect of the vegetated roof can be the process of evapotranspiration [46]. Evapotranspiration is a combined term, which is extracted from evaporation and transpiration, and is caused by the vegetation and the growing medium in which the vegetation is planted. The evaporation is caused by the soil, which evaporates water that has been gathered. Transpiration is the process caused by the vegetation, which occurs when there is a water vapor pressure differential between the plants and the surrounding air. As a result of this water vapor pressure difference, a water vapor flux is present from the leaf stomata of the plant into the air by diffusion and convection [46]. Research by Lazzarin et al. [47] has shown that, due to evapotranspiration from a vegetated roof, the measured heat flux through the envelope can be reduced with 12% to 25% for a dry (10% relatively humidity of soil) and a wet (100% relative humidity of soil) situation, respectively. Tabares-Velasco and Srebric [46] experimentally showed that the reduction of the heat flux by implementing a vegetated roof can vary between 18% and 75%. Niachou et al. [48] showed that indoor temperatures can be reduced significantly when applying a vegetated roof; they measured a decrease in the amount of hours that air temperatures were above 30°C and 32°C. An important conclusion from their research is that the decrease in indoor air temperatures strongly depends on thermal resistance of the surface [46], which was also concluded by Theodosiou [49]. For example, Niachou et al. [48] concluded that the reduction in energy use when applying a vegetated roof is less than 2% for a well-insulated building. Other influencing parameters are outdoor air temperature and humidity [48,49], but also foliage height, foliage density and wind speed [49]. In addition to the reduction of the heat flux through the envelope, vegetated roofs can also be beneficial in terms of storm water reduction and aesthetic appeal [50].

A distinction can be made between two types of vegetated roofs; extensive and intensive vegetated roofs (e.g. [51]). The essential difference between an extensive and intensive roof is the type of vegetation and therefore the height of the vegetation layer. It can be assumed that extensive roofs generally have vegetation lower than 0.15 meter and intensive roofs have vegetation higher than 0.15 meter [51]. Intensive roofs have a larger effect on the heat flux through the roof since the amount of vegetation is higher. However, an intensive vegetated roof requires a different construction due to the higher weight compared to an extensive vegetated roof, and is therefore not always the most straightforward option, especially where renovation is concerned.

In this research extensive vegetated roofs are added to the buildings, since the roof should also be applicable on current building constructions. In addition, two of the three studied buildings have a tilted roof, which makes it difficult to apply an intensive vegetated roof. The height of the vegetation is taken equal to 0.1 meter, which represents the height of sedum plants, which are often used as extensive roof vegetation. The Leaf Area Index (LAI) is set to 5. Scurlock et al. [52] defined the LAI as the functional vegetated leaf area of the canopy (m^2) per area of ground (m^2). A LAI value of 5 is relatively high, but it is chosen to assess the upper bounds of the effects of an "ideal" extensive vegetated roof.

2.5. Solar shading

The application of solar shading for the transparent parts of the building envelope will prevent or reduce short-wave solar radiation from entering the building through the windows. This will result in lower indoor air and surface temperatures compared to a situation without solar shading. One can make a distinction between fixed and operable (movable) solar shading, both of which can be applied horizontally and vertically. Fixed solar shading is normally positioned outside the building and can be an important part of the architectural appearance of a building. Movable solar shading can be positioned both inside and outside the building. However, the most efficient location is on the exterior side of the window, which enables blocking the solar radiation before it can actually enter the building.
In this study it is assumed that all the windows on the east, south and west facade of the building are equipped with automatic vertical exterior solar shading devices with a solar reflectivity of 0.9. The threshold for lowering the solar shading is set to 150 W/m^2 on the window (beam and diffuse solar radiation)(e.g. [53]).

2.6. Natural ventilation

In moderate climates, natural ventilation, in this particular case additional ventilation on top of the basic requirements for ventilation imposed by the building codes, can be a very efficient way to remove excess heat from a building. An increasing interest is present for ventilative cooling strategies to reduce the indoor air temperature (e.g. [54]). The ventilation flow can temporary be increased to remove warm air and to supply fresh cold air. The most straightforward method to do this is by opening windows in the building envelope.
The windows in the base case models in this research are closed throughout the day; opening the windows is considered as an adaptation measure. In this study it is assumed that the windows will be opened above a certain threshold outdoor air temperature, which is 24°C. An additional requirement is that the indoor air temperature should be higher than the outdoor air temperature in order to prevent an increase of the indoor air temperature. The opening area of the windows is indicated by the triangular shapes in the windows in Figures 2-4. The opening of windows is a human activity in the majority of residential buildings. Therefore, the behavior of the building occupants plays a very important role in the performance of this measure (e.g. [55,56]). The occupants might close the window in case of draught, a sense of insecurity, sound nuisance, nuisance by insects, wind-driven rain events, etc. All these factors can therefore strongly affect the effectiveness of this adaptation measure. However, in this study it is assumed that either (1) the windows will be systematically opened when the given thermal criteria are met irrespective of the time of the day, or that (2) the windows will be systematically opened during daytime (08:00-20:00 h) when the thermal criteria are met.

3. Methodology

For this study three types of residential buildings are considered: 1) detached house; (2) terraced house; (3) apartment. The building geometries are based on the example residential buildings as defined by Agentschap NL in the Netherlands [57]. To assess the performance of the six different adaptation measures, dynamic thermal simulations are conducted using EnergyPlus. This program was developed by the US Department of Energy and is widely used by engineers and scientists [24]. EnergyPlus has been validated extensively for thermal calculations (e.g. [58]). The airflow network model present in EnergyPlus has been – among others – successfully validated for natural ventilation flow using on-site measurements (in case the vents are automatically controlled in the building where the measurement took place) [59], furthermore, the results obtained in EnergyPlus showed a very good agreement with analytical solutions and results obtained with other airflow network models (e.g. [60]).

3.1. Building description

The three residential buildings all have one zone for the living room, and one zone for the bedrooms. The detached house and the terraced house also have a third zone, which consists of the attic. This zone will not be taken into account in the analysis of thermal comfort inside the residential buildings since these spaces in general only have a storage function. Four occupants are present in each building; two adults and two children. The simulations are conducted for four different orientations of the facade in which the entrance is situated (0°, 90°, 180°, 270°) to assess the influence of window orientation in combination with solar radiation.

3.1.1. Detached house

Figure 2 shows the ground plans and building facades. The detached house has a floor area of 61.2 m^2 for each of the three floors. The total net indoor volume (without building components) amounts to about 451 m^3. The ground floor consists of the living room and kitchen, the first floor contains the bedrooms. All surface areas of the exterior building envelope are exposed to the ambient conditions, i.e. outdoor air temperature, relative humidity, wind and solar radiation.

3.1.2. Terraced house

Figure 3 shows the ground plans and building facades. The terraced house has a floor area of 45.5 m^2 for each floor, and a total net indoor volume of about 348 m^3. The living room and kitchen are situated on the ground floor and the bedrooms on the first floor. Only two sides of the building are exposed to the ambient conditions; adiabatic conditions are assumed for the two other sides that share an internal wall with adjacent terraced houses.

3.1.3. Apartment

Figure 4 shows the ground plans and building facades. The apartment is situated on the top floor of a large apartment building. It has a floor area of 80.6 m^2. The zone with the living room is 39.7 m^2 and the other zone (bedrooms) has a floor area of 40.9 m^2. The net indoor volume is about 210 m^3. The roof and two of the facades are exposed to the ambient conditions. Two other walls, as well as the floor, are shared with adjacent apartments and are therefore modeled as adiabatic surfaces.

3.1.4. Construction details of base case buildings

The base case is a heavy-weight building, i.e. the floors are made of concrete and stone materials are used for both sides of the cavity walls. Two different insulation values have been used for the envelope of the base case buildings; a base case building built in the 1970s with low values for the thermal resistance, and a base case building according to the building regulations in the Netherlands in 2012 with high thermal resistance values [28]. Table 2 provides an overview of the construction details of the base case building from the 1970s, whereas Table 3 provides this information for the building from 2012.

3.1.5. Other settings for base case buildings

The buildings are heated with an all-air system, and no cooling is present. The exclusion of active cooling systems corresponds to the most common situation for residential buildings in the Netherlands, and also in several other North-Western European countries [11,12]. No shading devices are present in the base case situation, which again is common for newly built residential buildings in the Netherlands. Mechanical exhaust ventilation is present which ensures a constant ventilation flow rate of 0.7 dm^3/sm^2 [28]. The infiltration flow rate is set to 0.2 ACH [30]. Note that the adaptation measures regarding natural ventilation (NV_all, NV_day) entail the opening of windows to allow ventilative cooling, which results in an additional airflow on top of the basic ventilation flow rates as mentioned above.

The air temperature heating setpoints are listed in Table 4 (based on [61]). The indoor heat gains for the ground floor (living room) and first floor (bedrooms) are summarized in Table 5 (based on [30] and [62]).

3.2. Weather file

There are multiple options available to obtain a weather file that is suitable for the assessment of climate change adaptation measures. The first method is the use of a predicted future weather file. However, these are not generally available, and are subject to discussion. A second option is the use of weather data from a year in the past which was much warmer than normal, and can therefore be seen as a representation of the future climate. The latter option is used in this research. The weather data that has been used is what was measured in De Bilt, the Netherlands, during 2006 [63]. This year is known for the occurrence of several heat waves, and can therefore be seen as an example of a year with summer temperatures that will probably occur more often in the future as a result of climate change [64]. The same methodology has been used before by Porrit et al. [18] and is used throughout the CPC consortium to make the results of the different studies within the research program intercomparable (e.g. [22]). Figure 5 shows the measured air temperatures during July 2006 [63] and the air temperatures in July for the average climate between 1986-2005 [65]. Figure 5 indicates that the temperatures are relatively high during this month, especially for the Netherlands, with air temperatures over 25°C on 25 days, and air temperatures above 30°C on eight different days during the month of July. It can also be seen that the temperatures in July 2006 are much higher than on average (dashed line), indicating that the summer of 2006 was indeed exceptionally warm.

3.3. Additional simulation parameters

The dynamic thermal simulations are conducted using six time steps per hour. For the simulations with the vegetated roof the number of time steps per hour is increased to 60 to improve the numerical solution of the zone heat balance model and to obtain accurate results, as recommended by EnergyPlus [66]. The ground temperature at a depth of 1 m is taken equal to 10°C, and the ground reflection is set to 0.2. The surface convection algorithms used for the interior and exterior building surfaces are TARP and DOE-2, respectively (e.g. [67,68]. To incorporate the (natural) ventilation flow the airflow network included in EnergyPlus is used. The wind pressure coefficients to calculate the volume flow rate have been obtained from Liddament [69]. The wind pressure coefficients for a building surrounded by obstructions equal to the height of the building are used.

3.4. Thermal comfort indicator

To assess the performance of the six passive climate change adaptation measures, the adjusted adaptive temperature limit as presented in Peeters et al. [70] is used. The adjusted adaptive temperature limit is based on the PMV-model by Fanger [71] and on the adaptive temperature limit by De Dear et al. [72], but proposes limits that should be applicable for residential buildings. The fact that the level of thermal comfort in an office differs from the level of thermal comfort that people experience in their homes is caused by several factors [70]. Residents have different activity levels than people in an office situation and the activity level can more easily be adapted to the situation [70]. In addition, at the same temperature people feel warmer in their homes than in an office situation; people tend to evaluate rooms as being warmer due to the presence of furnishing [73]. Residents also accept a wider range of temperatures in their indoor environment because they have to pay for their own energy bill and they can more easily adjust to temperature differences (e.g. by changing clothing) [70]. Three residential functions (bedroom, bathroom and other residential functions) are distinguished with different boundaries (thresholds) for each of them, which are based on research in 39 Belgian houses [70].

The temperature limits are calculated based on the neutral temperature (T_n), which is the temperature at which a human feels comfortable [72]. The neutral temperature differs for each residential function, and is a function of the running mean outdoor temperature $T_{e;ref}$. The running mean outdoor temperature is the weighted average of the outdoor temperature of the preceding days [70], and can be calculated using Eq. 1:

$$T_{e;ref} = \frac{(1\,T_{today} + 0.8\,T_{yesterday} + 0.4\,T_{day\ before\ yesterday} + 0.2\,T_{day\ before\ the\ day\ before\ yesterday})}{2.4} \tag{1}$$

The running mean outdoor temperature takes into account the effect of the preceding days on the clothing that people wear and on the perception of thermal comfort, since it was shown by De Dear et al. [72] that these factors not only depend on the temperatures of that particular day, but also on the temperatures of the preceding days. Based on the neutral temperature one can define the upper limit (threshold) for thermal comfort. To assess whether thermal comfort is achieved the operative temperature is used, which can be defined as the average of the mean radiant temperature and ambient air temperature, weighted by the heat transfer coefficients for radiation and convection [62]. When the operative temperature T_O exceeds the threshold temperature an overheating hour is registered. The operative temperature can be calculated using Eq. 2 [62]:

$$T_O = \frac{h_r T_{mrt} + h_c T_a}{h_r + h_c} \tag{2}$$

with:

T_O	=	Operative temperature	[°C]
T_{mrt}	=	Mean radiant temperature	[°C]
T_a	=	Ambient air temperature	[°C]
h_r	=	Heat transfer coefficient for radiation towards a person	[W/m^{2}K]
h_c	=	Heat transfer coefficient for convection towards a person	[W/m^{2}K]

ASHRAE Standard 55 [74] indicates that Equation 2 can be approximated with $T_O = (T_{mrt} + T_a)/2$ for building occupants that are not exposed to direct sunlight, have near sedentary physical activity levels and are present in an enclosure with air speeds below 0.2 m/s. This approximation to calculate the operative temperature has been used in this study as well. It implies that the heat transfer coefficients for radiation and convection are assumed to be equally large.

3.4.1. Living room

For the living room the temperature limits are used that are proposed for 'other functions' in Peeters et al. [70]. The neutral temperature for the living room can be calculated from $T_{e,ref}$ by using the following equations [70]:

$$T_n = 0.06T_{e;ref} + 20.4 \qquad for\ T_{e;ref} < 12.5°C \tag{3}$$

$$T_n = 0.36T_{e;ref} + 16.63 \qquad for\ T_{e;ref} \geq 12.5°C \tag{4}$$

In the current research only the upper limit is considered, since this research focuses on overheating. The upper limit for the living room is obtained using the following equation:

$$T_{upper} = T_n + w\alpha \tag{5}$$

The width of the comfort band w in °C and the associated constant α depend on the Percentage People Dissatisfied (PPD). A PPD value of 10% is chosen for this study to have a relatively strict boundary for thermal comfort. The resulting value of w and α are 5°C and 0.7, respectively [70]. An upper limit in the living room and kitchen is only imposed between 06:00 and 23:00 hours.

3.4.2. Bedrooms

Adaptation of residents to a changing thermal comfort in bedrooms is limited, due to the simple fact that the residents are sleeping [70]. In addition, people expect lower temperatures in their bedrooms [75]. The upper limit boundary for bedrooms is restricted to a temperature of 26°C, which is the threshold above which the quality of sleep decreases according to CIBSE [75]. The neutral temperatures for the bedrooms can be described by using the following equations [70]:

$$T_n = 16°C \qquad for\ T_{e;ref} < \ 0°C \tag{6}$$

$$T_n = 0.23 T_{e;ref} + 16 \qquad for\ 0°C \le T_{e;ref} < \ 12.5°C \tag{7}$$

$$T_n = 0.77 T_{e;ref} + 9.18 \qquad for\ 12.6°C \le T_{e;ref} < \ 21.8°C \tag{8}$$

$$T_n = 26°C \qquad for\ T_{e;ref} \ge \ 21.8°C \tag{9}$$

The upper limit for the bedroom temperatures is defined using [70]:

$$T_{upper} = \min\,(26°C\,, T_n + w\alpha) \tag{10}$$

The values of w and α are taken equal to those for the living room; w = 5°C and α = 0.7, based on a PPD of 10% [70]. The boundary, which is proposed for the bedroom, only has to be met during the night. The bedrooms are occupied between 23:00 and 06:00 hours.

3.4.3. Overheating hours

Based on the adjusted adaptive temperature limit T_{upper} one can determine the number of overheating hours for both the base cases and for the cases including the adaptation measures, by summation of the number of hours (hr) that the operative temperature (T_O) is above the upper limit (T_{upper}). In addition to the number of overheating hours, the number of degree hours is calculated to provide some information on the level of overheating. A degree hour (dghr) is obtained by multiplying an overheating hour with the exceedance in °C, i.e. dghr = hr(T_O-T_{upper}).

4. Results

The results are presented in the next three subsections; one subsection for each type of residential building.

4.1. Detached house

As an example, Figure 6 shows the graph depicting the overheating hours for a detached house built in 2012, based on the conditions as explained in Section 3. The black line indicates the upper limit for thermal comfort, which differs for the ground floor (Fig. 6a) from the first floor (Fig. 6b) due to the different neutral temperatures. Every dot represents one hour of the year, and the dots above the black line (threshold value) are overheating hours. For the base case detached house built in 2012, the ground floor has 1102 overheating hours and 2935 degree hours, and the first floor has 528 overheating hours and 1607 degree hours.

Figure 7 depicts a summary of the simulation results for the detached house built in the 1970s. The results for the base case and the cases with the implemented adaptation measures are all combined in one single graph. Figure 7a shows the number of overheating hours for the ground floor (living room), Figure 7b shows the number of degree hours for the ground floor, and the overheating hours and the degree hours for the first floor are depicted in Figure 7c and 7d, respectively. The average, minimum and maximum number of overheating hours and degree hours are calculated for the four orientations of the building, and these values are depicted by a ■, ●, and ♦, respectively. In Figure 7a,b, one can see that the number of overheating hours and degree hours increases substantially when the thermal resistance is increased to $R_C = 5.0$ m^{2}K/W and $R_C = 6.5$ m^{2}K/W (RC50, RC65). This result might seem counter-intuitive, however, the air temperature increases significantly due to incoming solar radiation through the windows, and due to the higher thermal resistance this high air temperature is subsequently maintained, even when the outdoor air temperature has decreased during the evening and night. The second conclusion that can be made is that the average number of overheating hours (+53%) and degree hours (+162%) significantly increases for the ground floor when the amount of thermal mass is lower (TM_low), while the average number of overheating hours decreases for the first floor when thermal mass is decreased (reduction up to 45%). The reason for this difference between the two floors is depicted in Figure 8a for June-July and Figure 8b for the last week in July. The difference is attributed to the fact that although the indoor temperatures during the day are higher when the thermal mass is decreased (energy cannot be stored in the construction and directly heats the air), the lack of thermal mass causes the indoor air temperatures to decrease faster during the night than in the situation with more thermal mass on the first floor. This effect results in less overheating hours during the night. The application of higher values for the short-wave reflectivity (SWR06, SWR08) decreases the average number of overheating hours with up to 89%. Opening the windows above the described threshold during the entire day (NV_all) and the application of solar shading (SH) are the two most effective adaptation measures for the detached house built in the 1970s; the overheating hours are almost completely reduced to zero by implementing one of these two measures. Only opening the windows during daytime (NV_day) has obviously a smaller effect (average reduction up to 74%) compared to the case in which they can be opened 24 hours a day (NV_all) (average reduction up to 99%). The effect of the application of a vegetated roof (VR) on the average number of overheating hours is relatively low (reduction up to 17%). This limited reduction can be attributed to the fact that the vegetated roof increases the thermal resistance to a certain extent, which will have a negative effect on the number of overheating hours, as indicated above. This effect counteracts to some extent the expected positive effects due to evapotranspiration. In addition, the zones in which thermal comfort is evaluated are not directly adjacent to the roof construction. Furthermore, the short-wave reflectivity of the vegetated roof is not significantly lower than that of the base case. Finally, it must be noted that an extensive vegetated roof is used due to structural constraints, as described in Section 2.4.

In Figure 9 the results are depicted for the detached house based on the building regulations of 2012. Compared to the 1970s detached house in Figure 7, some similarities but also some strong differences are observed. The average number of overheating hours and degree hours for this base case are significantly higher than for the base case detached house from the 1970s. This significant increase indicates the important need for (climate change adaptation) measures to prevent overheating problems in newly built and renovated residential buildings, as the thermal resistance levels have increased in the last four decades, and will continue to increase in the near future to reduce energy use during the heating season. Although the number of overheating hours in the base case for this building is much higher than that for the building from the 1970s the application of additional natural ventilation (NV_all, NV_day) or solar shading (SH) can still reduce the average number of overheating hours to nearly zero. Figure 9b also shows a very strong increase in the average number of degree hours for the ground floor for the TM_low case compared to the base case (= 94%). This strong increase is due to the lower availability of thermal

storage, which results in very high indoor air temperatures and thus in a very large exceedance of the threshold temperature (T_O-T_{upper}), which can clearly be seen by comparing Figure 10a (base case) and Figure 10b (TM_low). Figure 10 shows that although the number of overheating hours is only 16% higher for case TM_low, the number of degree hours is increased with 94% higher when less thermal mass is present.
Another clear difference in the results can be seen when comparing Figure 7 and 9; increasing the short-wave reflectivity has less effect for a building with a higher thermal resistance; the reduction in the average number of overheating hours is up to 27% while it was up to 89% for the building from the 1970s. This reduced effectiveness is due to the fact that, irrespective of the value of short-wave reflectivity, heat transport through the building envelope is low due to the higher thermal resistance. The effects of the other adaptation measures are similar to the observed effects for the building from the 1970s and will not be discussed in detail for the sake of brevity.

4.2. Terraced house

Figure 11 shows the results for the terraced house built in the 1970s, whereas Figure 12 shows the results for the terraced house built according to the building regulations of 2012. Similar tendencies are visible as in Figures 7 and 9 for the detached house, however, there is one clear difference. The spread between the minimum and maximum number of overheating hours is much larger for the terraced house than it was for the detached house. This difference can be explained by the fact that only two of the four building sides are exposed to the ambient conditions, and thus to solar radiation. Therefore, the orientation of the terraced house has a large influence on the number of overheating hours, as can be seen in Figure 11 and Figure 12. For a west or east orientation of the front facade almost two times the number of overheating hours and degree hours is present compared to the north and south orientation of the front facade, which indicates the strong effect of building orientation for the terraced house. The following general conclusions can be made from Figure 11 and Figure 12.

- The number of overheating hours increases significantly with increasing values for the thermal resistance (RC50, RC65), especially for the building from the 1970s.
- Reducing the amount of thermal mass (TM_low) increases the average number of overheating hours (+40%) and degree hours (+117%) on the ground floor and decreases the average amount of overheating hours (-18%) and degree hours (-12%) on the first floor for the terraced house from the 1970s. However, for the building from 2012, with the higher values for the thermal resistance, the number of overheating hours on the first floor remains about equal (-1%), and the number of degree hours even increases (+17%) when decreasing the available thermal mass inside the building. The number of overheating hours and degree hours on the ground floor of the building from 2012 increases with 9% and 64%, respectively, when the amount of thermal mass is decreased.
- Increasing the short-wave reflectivity values (SWR06, SWR08) decreases the average number of overheating hours and degree hours, however, the effect is less pronounced than for the detached house. This is caused by the smaller surface area that is exposed to the ambient conditions compared to the detached house.
- Additional ventilation throughout the entire day (NV_all) and solar shading (SH) are by far most effective. The effect of additional natural ventilation when it is only applied during daytime (NV_day) is smaller than when applied throughout the entire day (NV_all).
- The effect of a vegetated roof (VR) is again small due to the negative effect of the increased thermal resistance level, which – to a large extent – counteracts the expected positive effects due to evapotranspiration.

4.3. Apartment

Figures 13 and 14 show the results for the apartment building, built in the 1970s and in 2012, respectively. There is a large difference between the number of overheating hours for the detached and terraced house on one hand, and the apartment on the other hand. The number of overheating hours and degree hours for the apartment is significantly higher. For example, the average number of overheating hours and degree hours for the ground floor for the base-case terraced house built in 2012 is 1224 and 3823, respectively, while for the living room of the apartment those numbers are 2003 and 8080, respectively. This increase can most likely be attributed to the exposure of the roof to ambient conditions, and the fact that in the apartment both the living room and the bedrooms are situated directly underneath the roof construction. In general, the tendency of the performance of the different adaptation measures is in accordance with those for the terraced and detached house. An interesting observation can be made when looking at Figure14c,d. The number of overheating hours for the bedrooms of the apartment from 2012 decreases when less thermal mass (TM_low) is present inside the building; the average number of overheating hours decreases with around 20%. However, comparison of the number of degree hours for the base case and for case TM_low shows that this number is almost equal. One can conclude that the application of less thermal mass in a building can be beneficial for the temperatures during night, but only when the heat inside the building can be released to the outside environment either through the building envelope, or by means of ventilation. The effects of the other adaptation measures are similar to the effects observed for the two other buildings and will not be discussed in detail for the sake of brevity.

5. Discussion

This paper presented dynamic thermal simulations using EnergyPlus to assess the effect of six passive climate change adaptation measures. It has been shown that the performance of the adaptation measures depends – among others – on the construction year of the building. The four best adaptation measures for residential buildings from the 1970s are the application of: (1) natural ventilation during the entire day; (2) external vertical solar shading; (3-4) an albedo value of 0.8 for the entire building envelope; and natural ventilation between 08:00-20:00 h. For the residential buildings built according to the building regulations of 2012, one can conclude that the two most effective measures (almost equally performing) are (1-2) natural ventilation during the entire day and external vertical solar shading; followed by (3) natural ventilation between 08:00-20:00 h.

5.1. Building design

Among others, the results presented in this paper showed that increasing the level of insulation to reduce energy use in the winter, as has been done extensively in North-Western European countries in the past decades, can have a strong negative effect on thermal comfort in the summer (large amount of overheating hours). Due to climate change the occurrence and intensity of these negative effects are very likely to increase in the near future. To prevent or counteract these negative effects during the summer and its shoulder seasons, one should apply additional measures, such as solar shading (prevention/reduction) or additional and correctly used natural ventilation (reduction). Building designers should focus on both the winter and summer situation to prevent thermal discomfort at this moment, and in the near future. The aim of designers should be to make (nearly) zero energy buildings (or even buildings that produce energy), while ensuring a comfortable indoor environment in the summer as well.

5.2. Costs

The climate change adaptation measures discussed and analyzed in this paper are not all equally expensive. For example, the construction of a house with a high albedo value does not cost more than building a house with a low albedo value. However, if one focuses on the two most efficient climate change adaptation measures found in this particular study, solar shading and natural ventilation throughout the entire day, one can see a clear difference in costs here. Opening the windows only requires windows that can be opened. In many cases these are already present in existing and in new residential buildings. However, this measure relies on either knowledge of the building occupants on the prevention of indoor overheating by opening the windows at the correct moments, or on automated window opening devices, which of course do have a certain cost associated with them. The application of external vertical solar shading certainly comes with a cost, which can be as large as €200-1500 per window if one would install external vertical solar screens. Therefore, the costs can vary a lot, depending on the number of windows and the desired quality and aesthetic appearance of the external solar shading. From a technical point of view both measures are (relatively) easy to implement in practice, both for existing buildings and for new buildings that will be constructed in the future.

5.3. Limitations and future work

Finally, there are several limitations in this study which indicate directions for future research:

- The most promising climate change adaptation measures in this particular study are subject to human behavior. The use of operable solar shading and the use of additional ventilation by opening windows in residential buildings are most of the time actions that require manual intervention by the occupants of a building. Due to the fact that a manual action is required there can be a large differences in the expected benefits of these measures and the benefits in practice (e.g. [55,56]). The occupants of residential buildings should have basic knowledge on how to prevent indoor overheating and should be able to apply these preventive measures in an efficient way. An alternative would be to automate the solar shading devices and the opening of the windows, however, this would interfere with the freedom of the occupants and would probably lower their acceptability for higher indoor air temperatures, if they occur, as indicated by De Dear et al. [72].
- The study can be extended to include other buildings, e.g. office buildings, schools, hospitals, which all have their own specific characteristics and heat balances and require an additional analysis.
- The study only considered one type of vegetated roof, therefore no general applicable conclusions can be drawn from this study. Future work can focus on a more exhaustive assessment of the effect of vegetated roofs, and vegetated facades, on the indoor air temperature in residential and other buildings.
- Future work can also include other climate change adaptation measures, such as evaporative cooling, water roofs, etc.
- A cost-benefit analysis for the studied climate change adaptation measures should be conducted, and the effects of these measures on energy use (synergy) should be assessed in future work.
- The research presented used the Dutch climate, which is a maritime temperate climate according to the Köppen climate classification [40], to assess the effect of different climate change adaptation measures. The work should be extended to other climates from the Köppen climate classification, and other building and construction typologies that are common in other countries and continents.

6. Conclusions

This study comprises a computational analysis of six different passive climate change adaptation measures at the building component scale using dynamic thermal simulations. The main aim of the study is to assess the performance of these measures to reduce the number of overheating hours in residential buildings. The types of residential buildings studied include: (1) detached house; (2) terraced house; (3) apartment. For every type, construction characteristics of the 1970s and in the 2012 are used. From this study the following conclusions can be made:

- The number of overheating hours and degree hours in residential buildings that are built according to the building regulations of 2012 is higher than for the buildings from the 1970s. This somewhat counter-intuitive finding can be explained by the higher thermal resistance of the former, which reduces the heat transport through the envelope once the air inside the building has been heated by solar radiation through the transparent parts of the building envelope.
- Differences in the number of overheating hours occur between the three types of residential buildings. The number of overheating hours is significantly larger for the apartment building due to the heat transfer through the roof of both the living room and the bedrooms.
- Increasing the thermal resistance of the building envelope (RC50, RC65) increases the number of overheating hours, therefore, in well-insulated buildings shading or additional natural ventilation should be provided to limit the number of overheating hours.
- Increasing the short-wave reflectivity (SWR06, SWR08) results in less overheating hours and degree hours. The magnitude of this effect depends on the thermal resistance of the building envelope and on the type of building.
- The application of a vegetated roof (VR) decreases the number of overheating hours and degree hours only to a limited extent for the cases studied.
- The effect of increasing the short-wave reflectivity (SWR06, SWR08) or of adding a vegetated roof (VR) is much larger for a poorly-insulated building than for a well-insulated building.
- Additional natural ventilation by opening the windows above a certain indoor air temperature and when the indoor air temperature is higher than the outside air temperature significantly reduces the number of overheating hours and degree hours; they can be reduced to almost zero when natural ventilation is applied throughout the day (NV_all).
- Providing additional natural ventilation only during daytime (08:00-20:00 h) (NV_day) results in a smaller decrease of the number of overheating hours compared to the case in which additional natural ventilation is applied during the entire day (NV_all), however, the reduction is still significant.
- Adding operable exterior solar shading and lowering them when the solar radiation on the window is 150 W/m^2 or larger has a very large effect on the number of overheating hours and degree hours. For the detached house and the terraced house the number can be decreased to almost zero, whereas for the apartment it can be reduced to around 200 in most cases.

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FIGURES

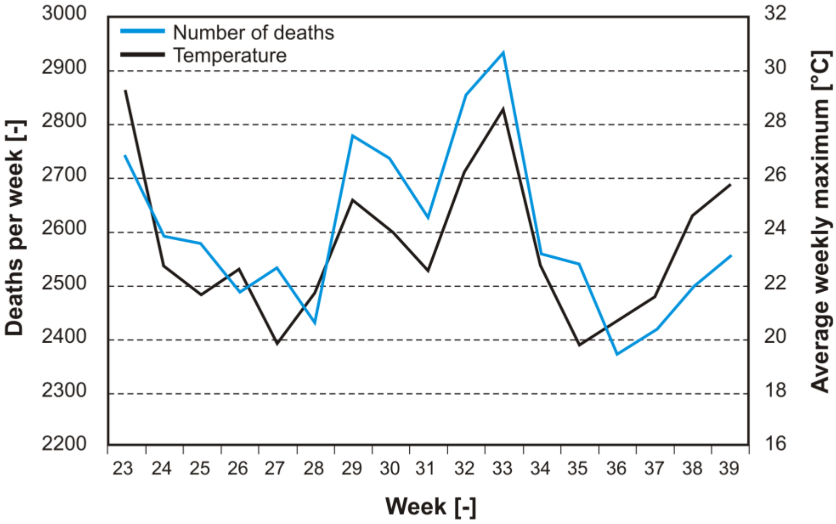

Fig. 1: Mortality and average maximum temperature per week in the Netherlands during June-September 2003 (modified from [9]).

Fig.2: Facades, floor plans and building dimensions of the detached house (modified from [57]). Triangles in windows and doors indicate operable windows/doors for the additional ventilation configuration. Dimensions in mm.

Fig. 3: Facades, floor plans and building dimensions of the terraced house (modified from [57]). Triangles in windows and doors indicate operable windows/doors for the additional ventilation configuration. Dimensions in mm.

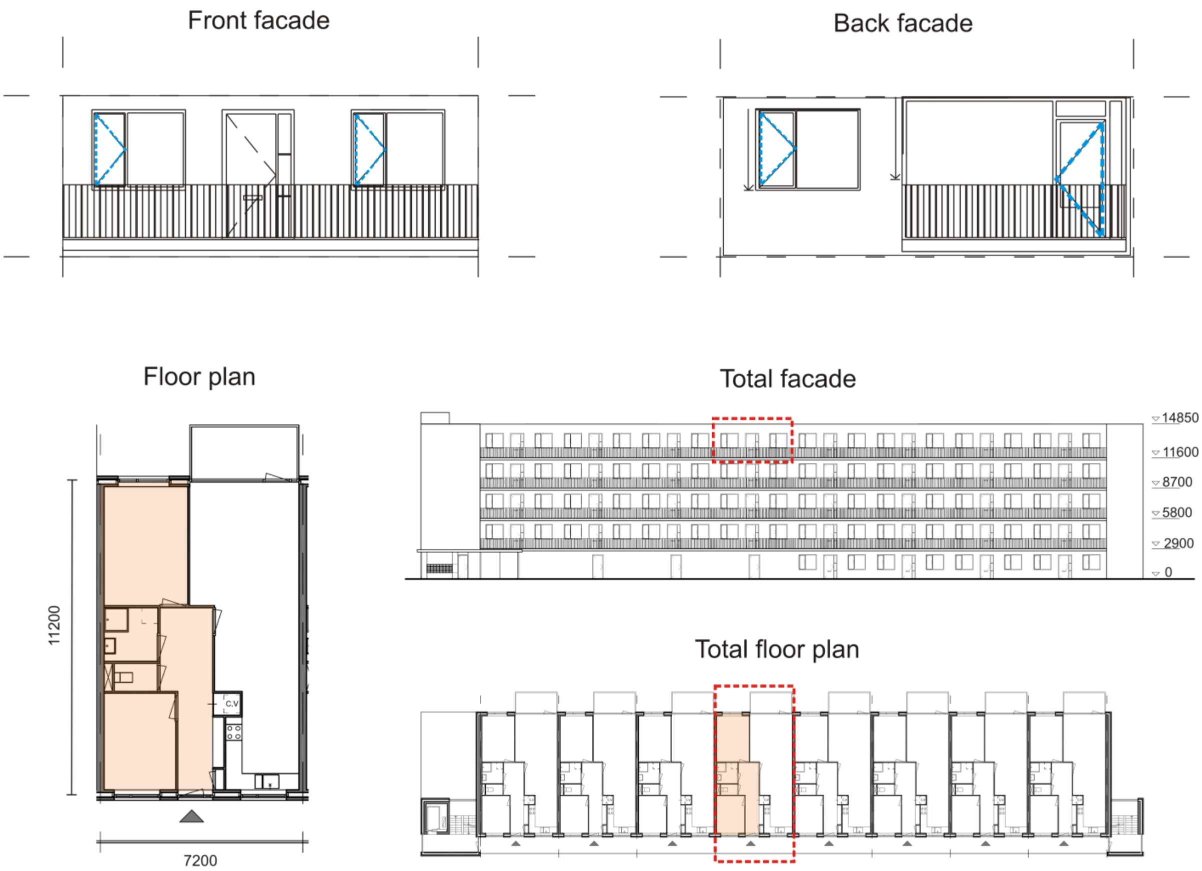

Fig. 4: Facades, floor plans and building dimensions of the apartment (modified from [57]). The colored area in the floor plan indicates the zone with the bedrooms. The dashed boxes in the figures of the total facade and total floor plan indicate the apartment under study. Triangles in windows and doors indicate operable windows/doors for the additional ventilation configuration. Dimensions in mm.

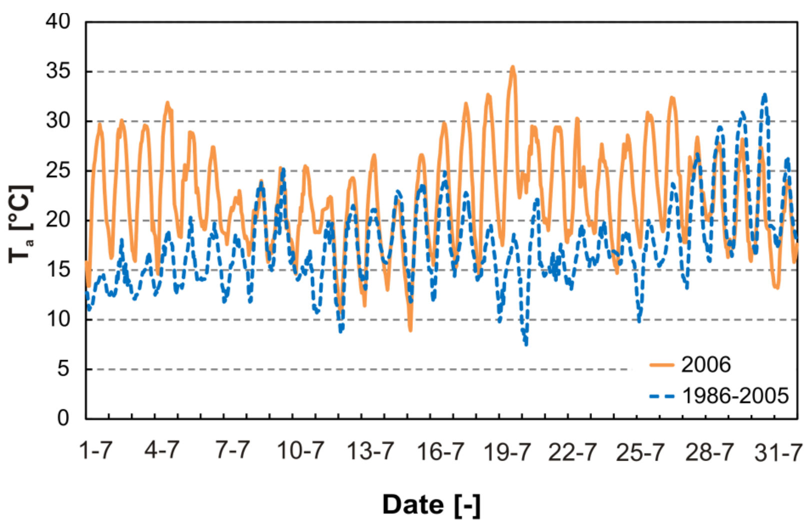

Fig. 5: Measured hourly air temperatures in De Bilt, the Netherlands, in July 2006 (solid line) and hourly air temperature for an average July in the period 1986-2005 [63,65].

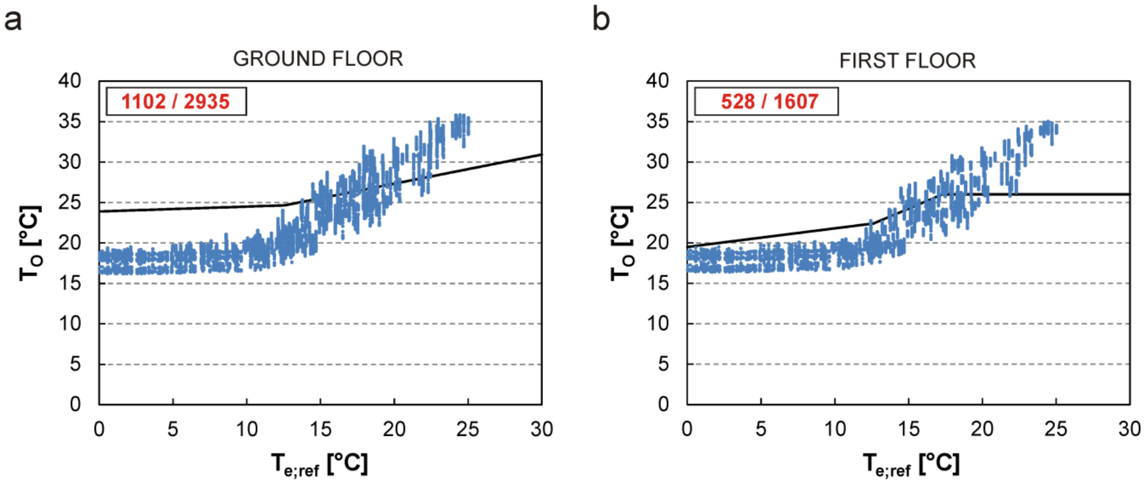

Fig. 6: Representation of overheating hours for the base case detached house built in 2012. The dots represent the operative temperature T_O during all the hours in 2006, and are a function of the running mean outdoor air temperature $T_{e;ref}$. The solid black line indicates the upper limit for thermal comfort [70], all the dots above this line are overheating hours. (a) Ground floor: 1102 overheating hours and 2935 degree hours. (b) First floor: 528 overheating hours and 1607 degree hours.

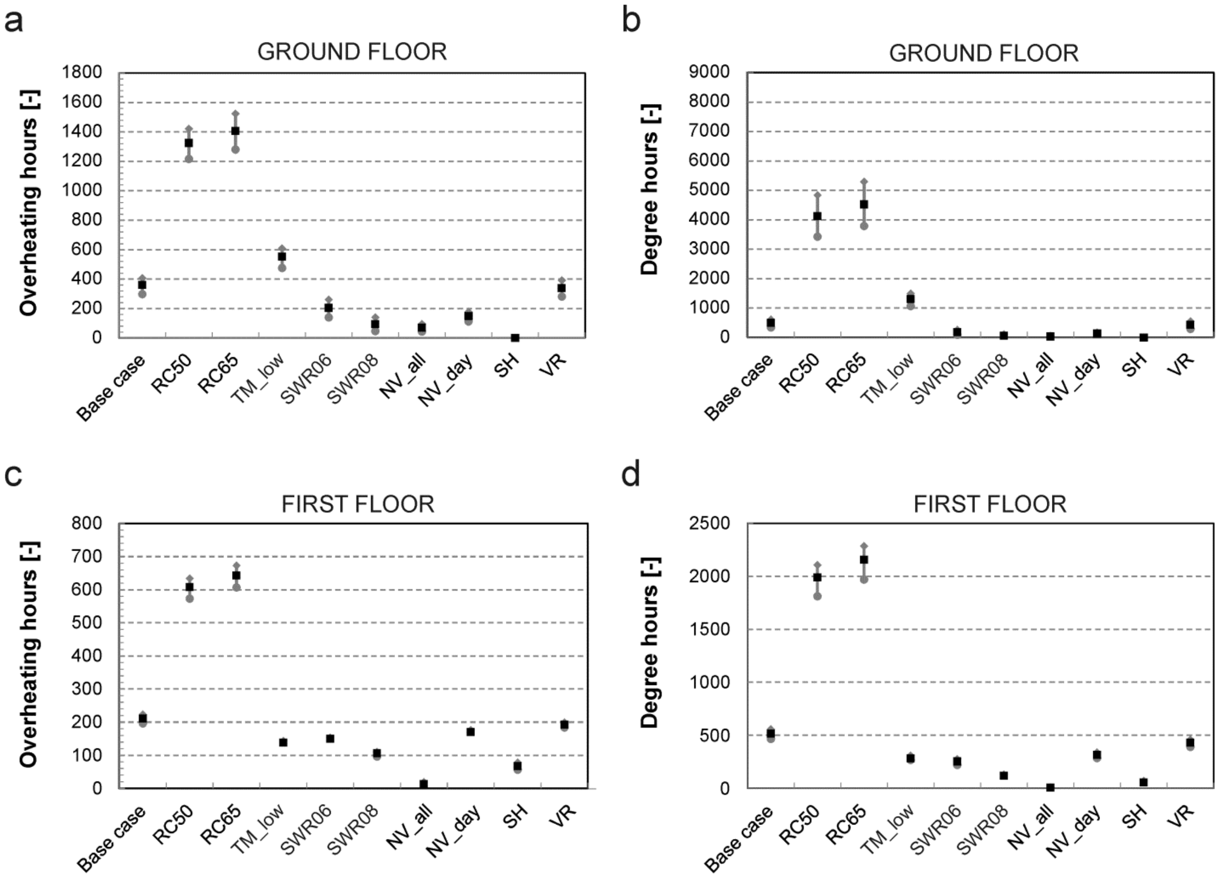

Fig. 7: Number of overheating hours (a,c) and degree hours (b,d) for the detached house built in the 1970s

and for different cases. (a,b) Ground floor. (c,d) First floor. ■ = average of the four orientations, ● = minimum value, ♦ = maximum value.

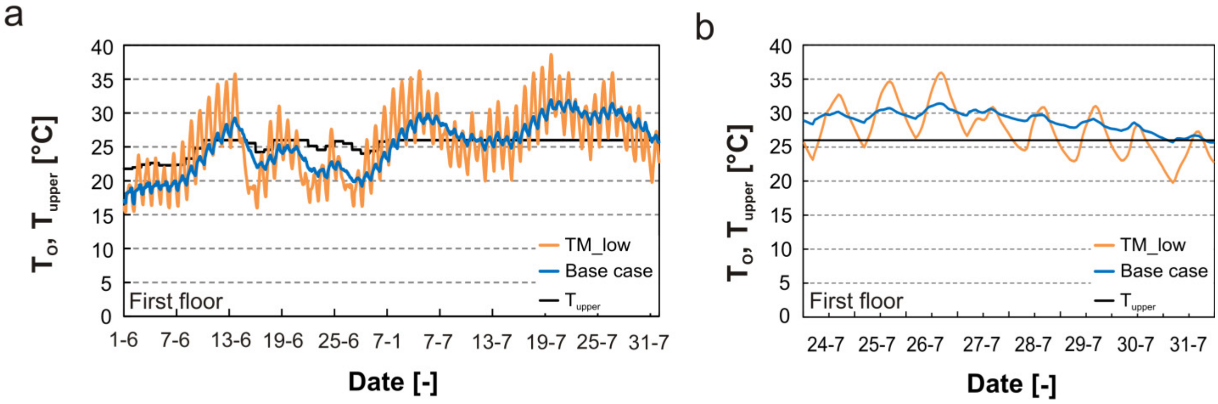

Fig. 8: (a,b). Operative temperatures on the first floor for the detached house, both for the base case and for TM_low (building from 1970s). The black line resembles the upper limit (T_{upper}). (a) Temperatures on first floor in June and July. (b) Temperatures on first floor during the last week of July.

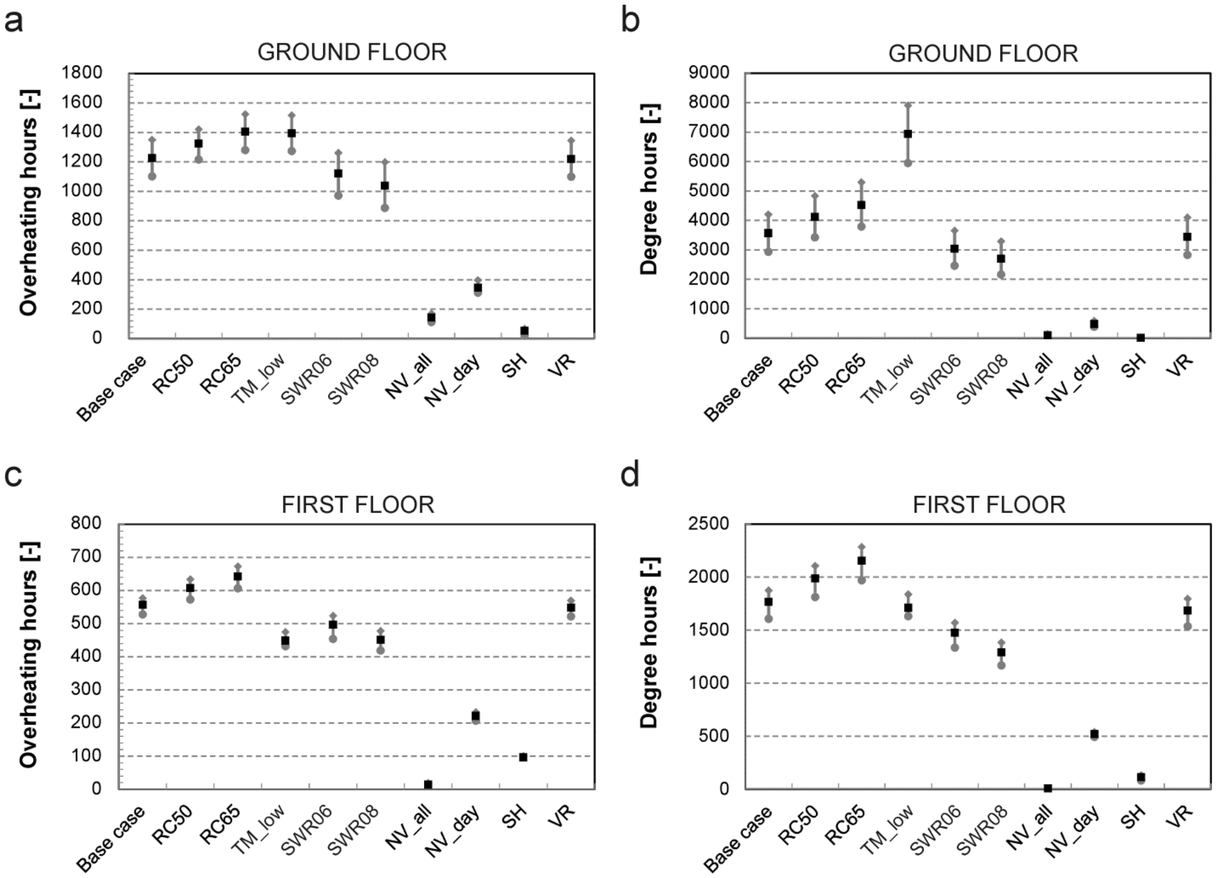

Fig. 9: Number of overheating hours (a,c) and degree hours (b,d) for the detached house built in 2012 and for different cases. (a,b) Ground floor. (c,d) First floor. ■ = average of the four orientations, ● = minimum value, ♦ = maximum value.

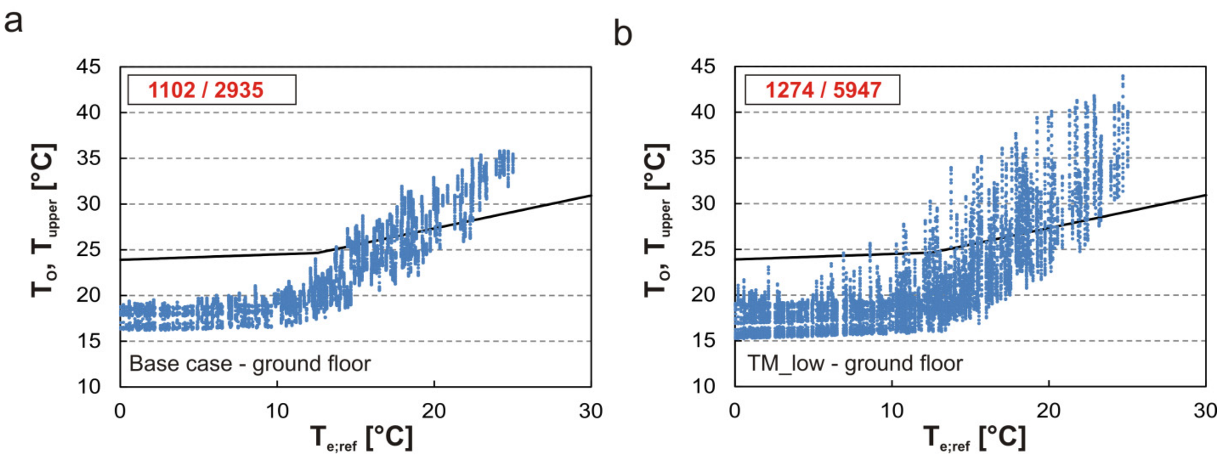

Fig. 10: (a,b) Overheating hours for the detached house built in 2012. (a) Ground floor for the base case. (b) Ground floor for case TM_low, with a much larger spread in the results and significantly higher (up to almost 10°C) maximum operative temperatures.

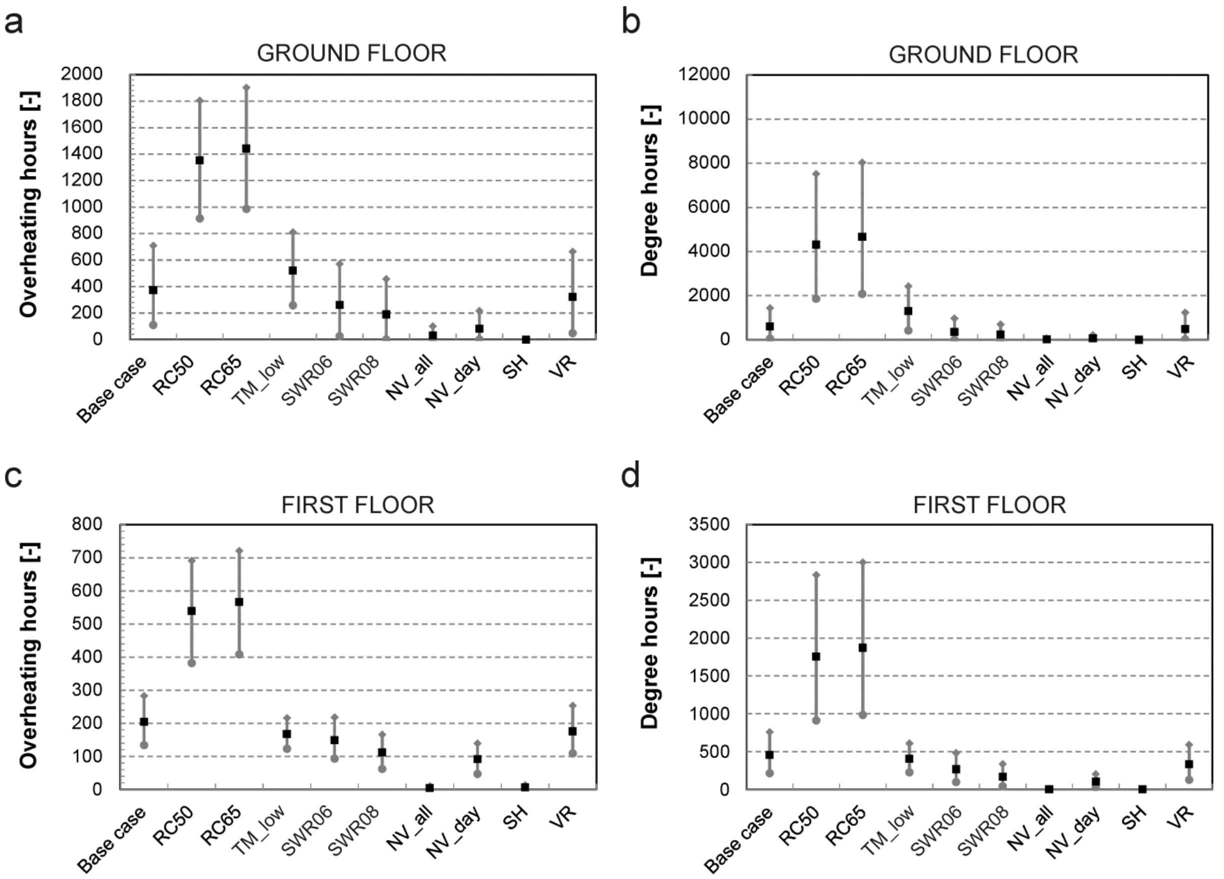

Fig. 11: Number of overheating hours (a,c) and degree hours (b,d) for the terraced house built in the 1970s and for different cases. (a,b) Ground floor. (c,d) First floor. ■ = average of the four orientations, ● = minimum value, ♦ = maximum value.

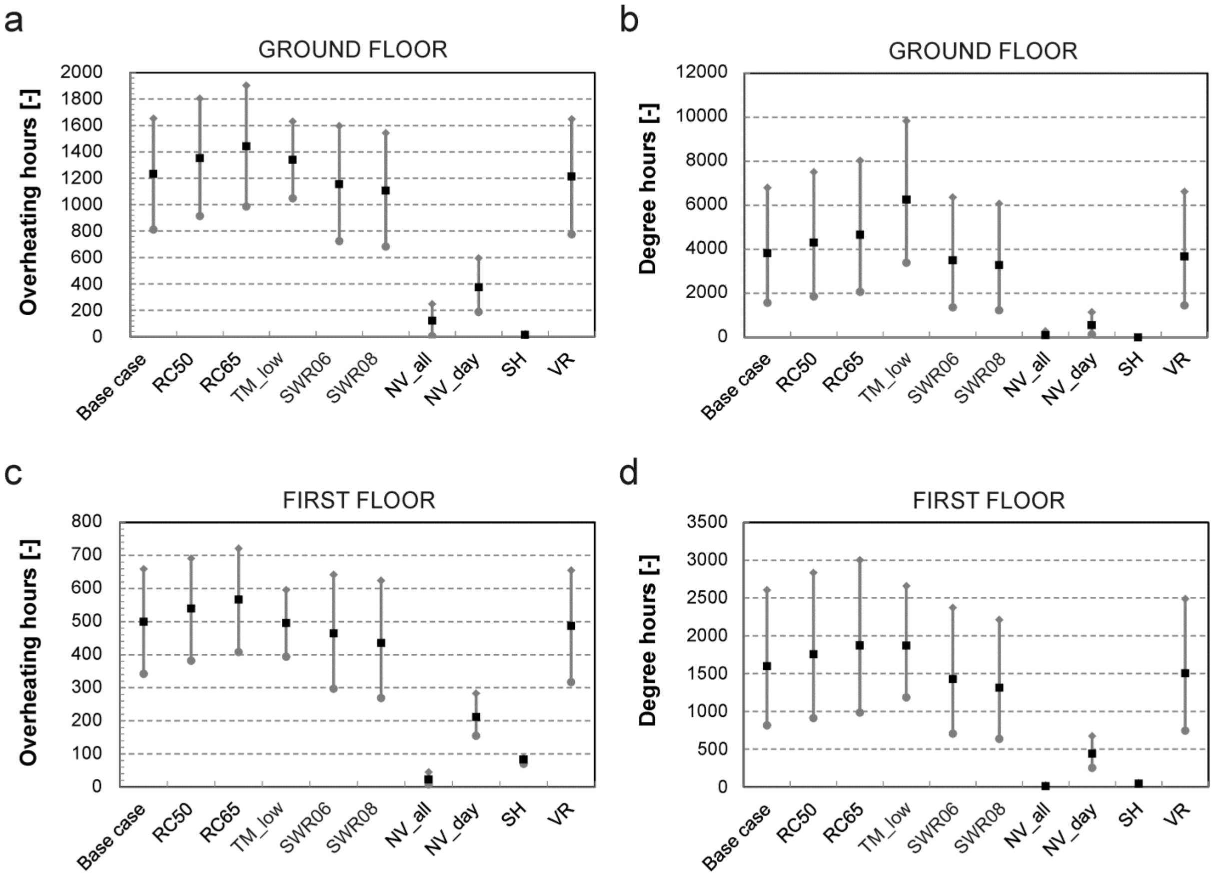

Fig. 12: Number of overheating hours (a,c) and degree hours (b,d) for the terraced house built in 2012 and for different cases. (a,b) Ground floor. (c,d) First floor. ■ = average of the four orientations, ● = minimum value, ♦ = maximum value.

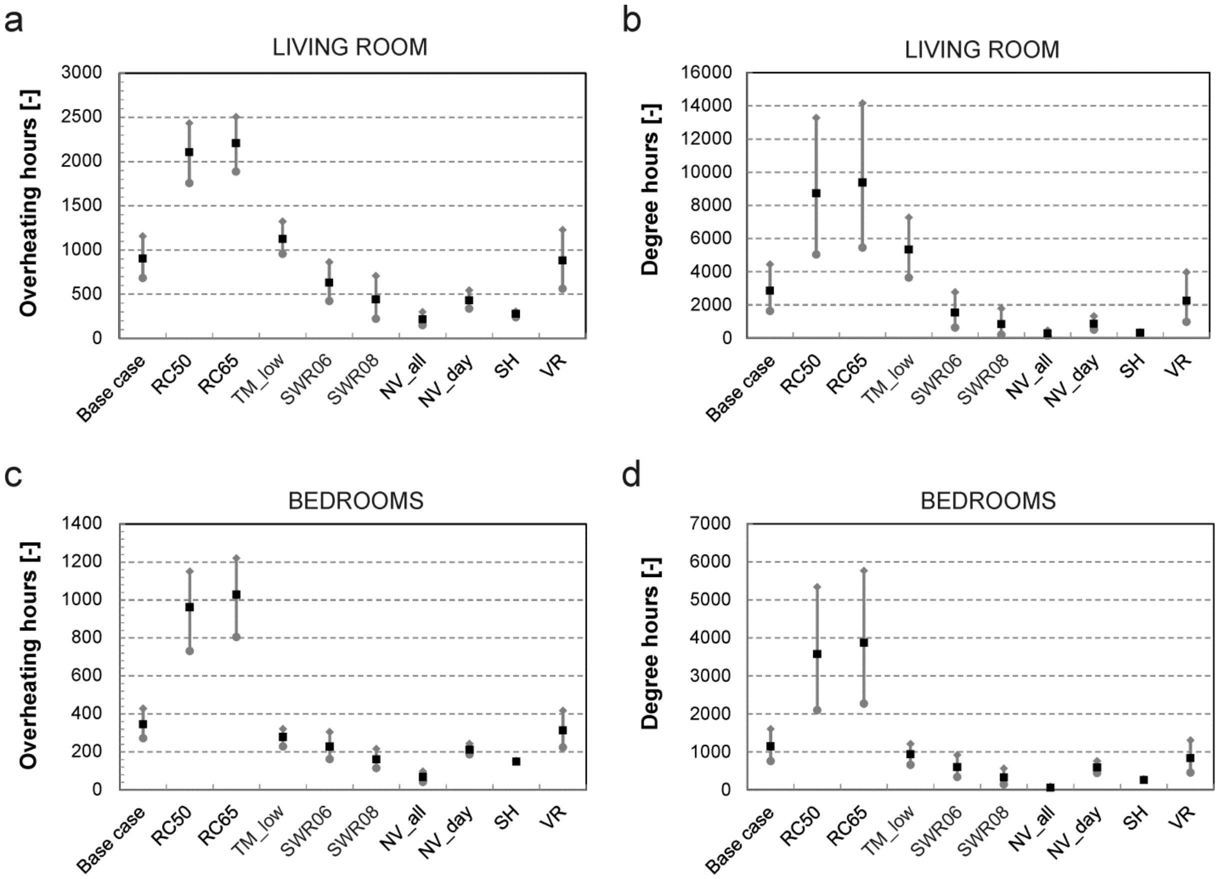

Fig. 13: Number of overheating hours (a,c) and degree hours (b,d) for the apartment built in the 1970s and for different cases. (a,b) Living room. (c,d) Bedrooms. ■ = average of the four orientations, ● = minimum value, ♦ = maximum value.

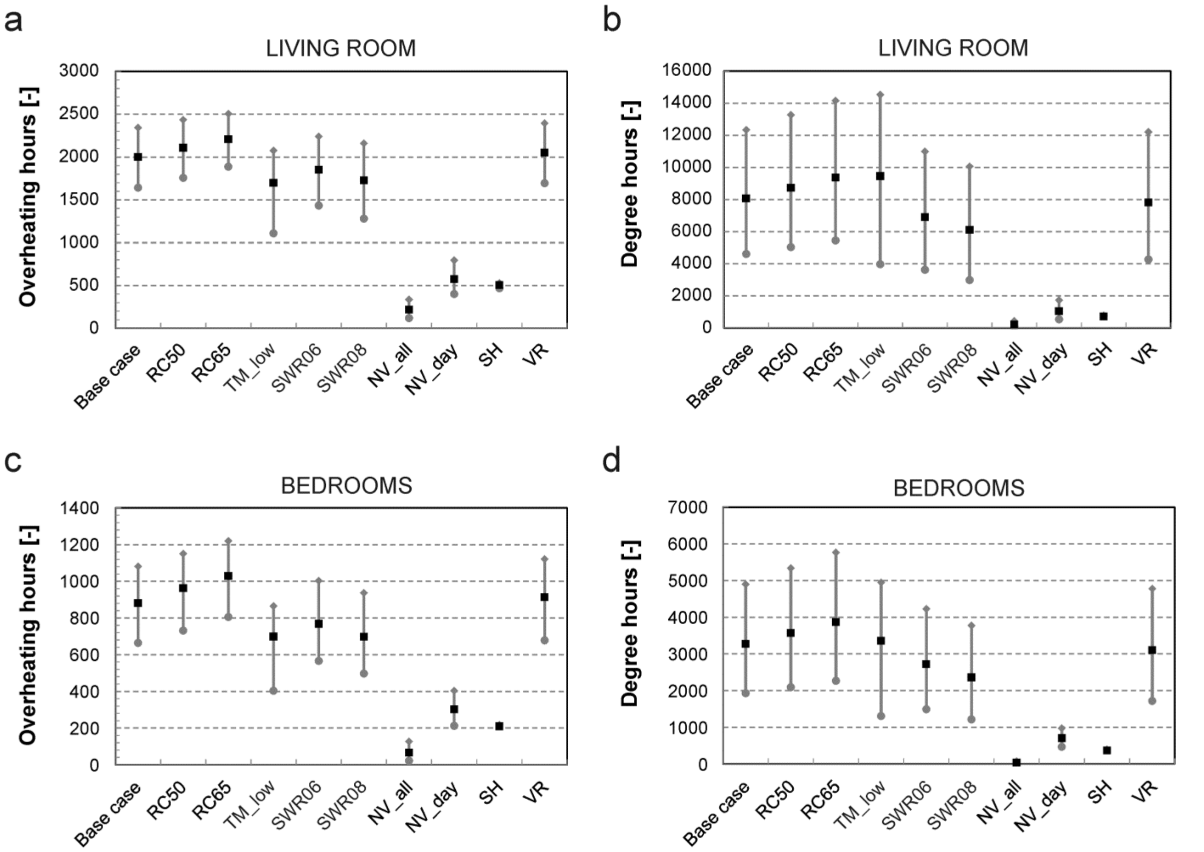

Fig. 14: Number of overheating hours (a,c) and degree hours (b,d) for the apartment built in 2012 and for different cases. (a,b) (a,b) Living room. (c,d) Bedrooms. ■ = average of the four orientations, ● = minimum value, ♦ = maximum value.

TABLES

Table 1: Overview of adaptation measures studied.

Adaptation measure	Description	Abbreviation
Increased thermal resistance	The thermal resistance of all external building surfaces is increased to R_C = 5.0 m^2K/W and R_C = 6.5 m^2K/W, for RC50 and RC65, respectively. This measure is implemented by increasing the thickness of the insulation layers.	RC50, RC65
Changed thermal capacity	The thermal capacity is lowered, since the base case is a heavy building. The thermal capacity is changed by replacing the limestone inner leaf by an inner leaf of wooden sheeting. In addition, concrete ceilings are replaced by wooden constructions.	TM_low
Increased short-wave reflectivity (albedo)	The short-wave reflectivity value of the external surfaces is increased from the default value of 0.3 to 0.6 and 0.8, for configuration SWR06 and SWR08, respectively.	SWR06, SWR08
Vegetated roof	The default roof constructions are extended to incorporate a vegetated roof with a Leaf Area Density index of 5.	VR
Solar shading	Exterior solar shading is applied for all windows on the east, south and west side of the facades. The solar shading is automatically lowered when the solar radiation on the window is at least 150 W/m^2.	SH
Additional natural ventilation	Additional natural ventilation is provided by opening (parts of) the windows. The windows will be opened when the indoor air temperature is above 24°C, but only when the indoor air temperature is higher than the outdoor air temperature. In one measure (NV_all) the windows can be opened the entire day (24 hours), in the other case (NV_day) the windows can only be opened between 08:00-20:00 h.	NV_all, NV_day

Table 2: Overview of construction details for the base case building from the 1970s.

Element	Details	R_C value (m^2K/W)
External walls	Cavity walls with (inside to outside): limestone inner leaf, air cavity, brick outer leaf.	0.4
Internal wall	Limestone wall	-
Roof (pitched)	Inside to outside: Wooden sheeting, insulation layer, air cavity, roof tiles.	0.8
Roof (flat)	Inside to outside: Concrete, insulation layer, roofing material	0.8
External floor	Concrete	0.17
Internal floor	Concrete	-
Windows	Single pane glazing. Solar transmittance coefficient = 0.7.	U value: 5.2 W/m^2K

Table 3: Overview of construction details for the base case building from 2012.

Element	**Details**	**R_C value (m^2K/W)**
External walls	Cavity walls with (inside to outside): limestone inner leaf, insulation, air cavity, brick outer leaf	3.5
Internal wall	Limestone wall	-
Roof (pitched)	Inside to outside: Wooden sheeting, insulation layer, air cavity, roof tiles.	4
Roof (flat)	Inside to outside: Concrete, insulation layer, roofing material	4
External floor	Inside to outside: Concrete, insulation	3.5
Internal floor	Concrete	-
Windows	Double pane glazing. Solar transmittance coefficient = 0.7.	U value: 1.65 W/m^2K

Table 4: Temperature setpoints for heating.

	Time interval [hour]		
	06:00-18:00	**18:00-23:00**	**23:00-06:00**
Temperature setpoint	19°C	20°C	16°C

Table 5: Heat gains inside the building (based on [30] and [62]).

Zone	**Heat source**	**Time interval [hour]**			
		06:00-18:00	**18:00-19:00**	**19:00-23:00**	**23:00-06:00**
Living room	Appliances	25 W	100 W	100 W	25 W
	Kitchen	250 W	600 W	250 W	-
	Persons	-	385 W	385 W	-
	Lighting	-	-	15 W/m^2	-
Bedrooms	Persons	-	-	-	241 W