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The impact of climate change on the overheating risk in dwellings—A Dutch case study

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ABSTRACT

Overheating in buildings has been identified as an essential cause of several problems ranging from thermal discomfort and productivity reduction to illness and death. Overheating in buildings is expected to increase as global warming continues. The risk of overheating in existing and new buildings can be reduced if policy makers take decisions about adaptation interventions quickly. This paper introduces a methodology for supporting such decisions on a national level. The methodology aims at (i) quantifying the impact of climate change on the overheating risk, (ii) ranking and characterizing the various building types in terms of their overheating risk and sensitivity to climate change, and (iii) assessing the potential of ventilative cooling to mitigate the effects of climate change. In the case study the overheating risk is evaluated in thousands of *dwelling cases* (i.e., 9216 possible combinations of several design and operation strategies) consistent with the characteristics of the Dutch dwelling stock built between 1964 and 2013. The overheating risk is assessed for four climate scenarios, which represent historical and future scenarios developed by the Royal Netherlands Meteorological Institute. Computational analyses are carried out using the detailed building performance simulation program IDA-ICE, assisted by a postprocessing calculation model developed in MATLAB®.

The results show that most of the Dutch dwelling types can effectively suppress the effects of global warming. However, poorly ventilated dwellings are vulnerable to overheating and are the most sensitive to climate change, particularly if their windows are not well protected against direct solar radiation.

1. Introduction

1.1. Heat waves, heat stress, and mortality rates

Only about a decade ago, global warming was just a hypothesis [1]. However, now it is being recognized as leading to climate change and extreme weather conditions. In recent years, climate observations (e.g., warmer summers, colder winters, and more frequent extreme weather events) indicate that the effects of climate change events are apparently having an increasing impact on society [1].

During the sweltering summer of 2003, which was the hottest summer in the last 500 years [2], over 35,000 people died across Europe from heat-related causes [3,4]. In the UK, an outdoor air temperature of 38 °C was recorded, and the UK Department of Health predicted that a 9-day heat wave might lead to over 3000 immediate heat-related deaths [5]. In the Netherlands, a maximum outdoor temperature of 35 °C was registered, and between 1400 and 2200 heat-related deaths occurred during that summer. Although there is only limited and indirect epidemiological evidence concerning the conditions of indoor temperature exposure that give rise to adverse health effects [6], it is reasonable to assume that the heat-related illness and death cases mentioned above resulted not only from unusually high peak outdoor temperatures and a reduction in the diurnal temperature swing, but also from a failure of buildings to successfully mitigate the external environment [7]. High indoor temperatures impair the ability to recover from outdoor heat stress [8]. High indoor temperatures can also increase sleep fragmentation, which is directly linked to poor health [9]. Epidemiological studies have shown that mortality begins to rise above a heat threshold of around 24.7 °C of the maximum daily temperature [10]. The observed number of deaths in August 2003 among people aged 40–59 years was 11% higher than the expected number calculated on the basis of data for the period 1995–2002.

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Furthermore, very young and older people are less resilient to extreme temperatures nowadays [11]. Children might also not be aware of the signs of heat illness and do not have the knowledge to move to a cooler place. The elderly, that is, people over 75 years of age, are more vulnerable to heat-related mortality [12]. Moreover, the elderly may be on medication that could cause them to feel ill if they are in extreme heat [13]. Socioeconomically deprived and isolated individuals may also be at higher risk as they are more likely to live in residences with inadequate heating and cooling systems, thermal insulation, solar shading, or ventilation possibilities [14].

1.2. Global warming scenarios and the urban heat island effect

If the heat-trapping emissions continue to rise at current rates (IPPC, 2000), a summer like the one in 2003 could be considered ordinary by the end of the century [15]. General circulation models of climate change project that the global mean surface temperature in the twenty-first century might increase by 1.1 °C–6.4 °C [16], which amplifies the intensity and frequency of extreme weather such as heat waves [17,18]. Moreover, the urban heat island effect will exacerbate building overheating in cities, whereby cities can be around 5–10 °C warmer than surrounding countryside areas [19].

1.3. Climate change and building performance

The projected rise in both average and extreme temperatures will make buildings more uncomfortable to live in and potentially dangerous to occupants' health because of the high internal temperatures in poorly ventilated environments [20]. These changes could also result in productivity reduction, a need to retrofit mechanical ventilation or cooling systems, and depreciation of property values. Climatic variability will also affect the performance of building technical services because of the inconsistent power outages and quality, prolonged cold and rainy seasons, flooding, and intense heat waves, as well as winter storms [21]. Buildings designed according to existing standards may become increasingly costly to operate and maintain in the future [22]. In a future characterized by significantly warmer summer temperatures and an increase in extreme climatic events [23], active cooling may become necessary to maintain thermal comfort and even to safeguard life [24]. A Dutch study of an office building with a ‘top-cooling’ concept showed that during a 30-year period, a 70% higher peak-cooling load could be needed to reach a similar thermal comfort level to the level in the original situation [22]. For an archetypical commercial office building in five Australian cities, an increase in the total design cooling equipment capacity of 9.1–25.0% was predicted to happen during the period 1990 to 2080 because of climate change [25]. The use of domestic air conditioning in the UK is estimated to rise by 8% per year [26], a phenomenon that could result in an additional six million tons of carbon dioxide (CO_2) emissions by 2020 [27].

The most important elements in the emissions considered in the building energy consumption are CO_2 emissions and the environmental implications of those emissions. However, the building sector is also accountable for significant amounts of non-CO_2 greenhouse gas emissions, such as halocarbons, chlorofluorocarbons (CFCs), hydro-chlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) because of their applications in space cooling, refrigeration, and, in the case of halocarbons, insulation materials. In 2004, it was estimated that buildings were responsible for approximately 30% of global CO_2 emissions and 60% of halocarbon emissions [2].

1.4. Using performance metrics to assess the risk of and sensitivity to overheating in buildings

Over time, more than 160 human thermal bioclimatic metrics have been introduced in the scientific literature and standards [28], and a subset of them has been specifically developed for the long-term evaluation of the general thermal comfort condition in buildings [29]. Such metrics are commonly identified as ‘long-term thermal discomfort indices’ and integrate the short-term deviations of the (actual or simulated) indoor thermal conditions with respect to a theoretical comfort target into a single value that aims at representing the thermal comfort performance of the entire building [30]. However, long-term thermal discomfort indices are developed on different assumptions that, in turn, make them weakly correlated [31]. Moreover, some metrics were specifically proposed to assess the overheating risk, for example the indices proposed by Nicol, Hacker [32] and by Robinson and Haldi [33], but these are ‘right-here’ and ‘right-now’ metrics and do not allow a long-term evaluation of the general thermal comfort condition. Since the purpose of this work is not to further investigate overheating metrics, but to estimate the sensitivity of dwellings to overheating, two new and fit-for-purpose metrics are defined in Section 2: the *Indoor overheating degree* (*IOD*) and the *Overheating escalation factor* (*OEF*). These two metrics specifically assess the thermal response of dwellings to an increase of the thermal stress due to, for example, global warming and the urban heat island effect. To calculate the new metrics, in this paper, two thermal comfort assessment schemes based respectively on fixed and adaptive temperature limits are used. The fixed temperature limits are defined according to the CIBSE Guide A [34] and the adaptive temperature limits are defined according to the Dutch regulation on thermal comfort, the ISSO standards 74 [35]. It is recommended that the fixed assessment scheme is used in mechanically conditioned buildings, and the adaptive assessment scheme is devoted to free-running buildings. The two assessment schemes have different prescriptions for living areas and bedrooms because of a major difference in the typical assumptions about occupants' metabolic activity, clothing resistance, and availability to exploit adaptive opportunities.

1.5. Contribution of this paper

As described above, it is expected that overheating increases in existing building because of climate change. Therefore, it is important to understand the impact of climate change on overheating risks. This paper introduces a methodology to assess the impact of climate change on the overheating risks of a country's building stock. The methodology aims (i) at quantifying the impact of climate change on the overheating risk, (ii) at ranking and characterizing the various building types in terms of overheating risk and sensitivity to climate change, and (iii) at assessing the potential of ventilative cooling as a mitigation strategy. The methodology is applied to dwellings in the Dutch building stock. In contrast to most (simulation) studies regarding overheating in buildings [36], this study proposes a performance assessment methodology that takes into account multiple climate scenarios. Furthermore, new performance metrics are introduced. These metrics are able to assess the long-term overheating risk of a dwelling and its sensitivity to indoor overheating.

This paper is structured as follows: the performance metrics are introduced in Section 2, the building stock and the climate scenarios are described in Section 3, the case study results are discussed in Section 4, and, hence, conclusions follow in Section 5.

2. Performance assessment methodology

In order to provide a comparative ranking for the Dutch dwelling stock, the overheating risk of a large number of possible dwelling designs (combinations of several archetypes, building ages, orientations, and shading options) and operation cases (combinations of several ventilation rates, internal gains, and occupancy profiles) are simulated under the typical and future climate scenarios. The existing building stock −assuming no renovation has been taken yet-is represented by 9216 possible combinations of building design and operation parameters (section 3.1). The climate change is represented by four climate scenarios (section 3.2). This leads to 36,864 (9216 × 4) building simulation cases.

The simulations are carried out using the detailed whole-building dynamic simulation tool, IDA-ICE version 4.6 [37,38]. The tool makes simultaneous performance assessments of all issues fundamental to building design: shape, envelope, glazing, heating ventilation and air-conditioning (HVAC) systems, controls, daylight and electric lighting, indoor air quality, thermal and visual comfort, and energy uses, etc. The accuracy of IDA-ICE was assessed using the IEA Solar Heating and Cooling program, Task 22, Subtask C [39]. Furthermore, IDA-ICE was chosen as one of the major 20 building energy simulation programs that were subjected to an extensive and thorough analysis and comparison [40].

In order to reduce the effort of setting up that large number of 36,864 building simulation cases, a new feature from IDA-ICE called 'model version facility' is used. The purpose of the model version facility is to simplify the process of repeatedly changing parameters, rebuilding the model, making runs, and comparing results. A version project may contain one or more root cases and have branches of dependent cases. The project stores the differences between each child case and the corresponding parent case. In the current study, the addressed building simulation cases are divided into groups with common characteristics (e.g., orientation) to be modeled by a number of IDA-ICE projects using the model version facility feature. In order to reduce the overall simulation time, parallel computing is used to run eight by eight building energy models simultaneously on an Intel® Core™ IS-3570 CPU@ 3.40 GHz desktop computer. The simulations' results (i.e., indoor temperature, relative humidity, and air change per hour) are saved on the computer's storage hard drive. To save further time and effort, the results of all the case studies are analyzed automatically by a homemade MATLAB script.

To provide accurate results, the dwelling cases are subdivided into a number of thermal zones related to their archetypes. Different rooms and zones within each building will have different relationships with the outdoor climate and other building zones, resulting in different overheating risks. Care was taken when subdividing each building into thermal zones for assessing the impact of climate change on the overheating risk because different zoning strategies may significantly affect the predicted thermal discomfort [41]. The variations in the dwelling designs and operation and all the adopted climate scenarios are described in detail in Section 3.

In order to assess the overheating risk in dwellings, a traditional metric such as the number of *Indoor overheating hours* (*IOH*) based on thermal comfort limits (Section 2.1) is used; in addition, the new metric called *Indoor overheating degree* (*IOD*) is introduced for a more accurate assessment (Section 2.1). Furthermore, the severity of global warming is assessed using a second new metric called *Ambient warmness degree* (*AWD*). The sensitivity of indoor overheating to climate change (caused by global warming) is assessed by a new metric called *Overheating escalation rate* (*OER*), that is, the ratio between the *IOD* and the *AWD* (Section 2.2).

2.1. Indoor overheating degree

Unlike traditional overheating metrics (e.g., degree hours above 28 °C), the *Indoor overheating degree* (*IOD*) is introduced so that different thermal comfort limits for different zones of a dwelling can be considered, taking into account the particular occupant's behavior and the adaptation opportunity he/she has in each identified zone. Furthermore, the *IOD* quantifies the overheating risk, taking into account both the intensity and the frequency of indoor overheating. The intensity is quantified by the temperature difference (ΔT) between the free-running indoor operative temperature (T_{fr}) and a chosen thermal comfort temperature limit (TL_{comf}), whereas the frequency is calculated by integrating the intensity of overheating during the occupied period (N_{occ}) into the different building zones (z) to present the overall overheating in a building. The free-running indoor operative temperature represents the indoor temperature of the zone when no heating or cooling systems are operating [42]. Only positive differences of $(T_{fr,i,z} - TL_{comf,\ i,z})^+$ are taken into the summation, as defined in Eq. (4)

$$IOD \equiv \frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)}\left[\left(T_{fr,i,z} - TL_{comf,i,z}\right)^{+} \cdot t_{i,z}\right]}{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)} t_{i,z}} \quad (1)$$

where z is the building zone counter, i is the occupied hour counter, t is the time step (typically it is 1 h), Z is the total number of zones in a building, $N_{occ(z)}$ is the total occupied hours in a given calculation period, T_{fr} is the free-running indoor operative temperature at the time step i in the zone z, and TL_{comf} is the comfort temperature limits at the time step i in the zone z.

Two types of thermal comfort temperature limits (TL_{comf}) are used for quantifying the overheating risk in free-running buildings according to different thermal comfort standards and/or approaches. The first, TL_{comf}, is a fixed temperature limit (FTL) defined according to the CIBSE Guide A [34]. The second, TL_{comf}, is an adaptive temperature limit (ATL) according to the Dutch adaptive assessment scheme incorporated into the Dutch standard ISSO Publication 74 [35] as well as the adaptive assessment scheme introduced by Peeters, de Dear [43]. Fig. 1 shows the above-mentioned fixed and adaptive comfort temperature limits, as functions of the running mean outdoor temperature, used in this study for dwellings operating in free-running mode during the summer.

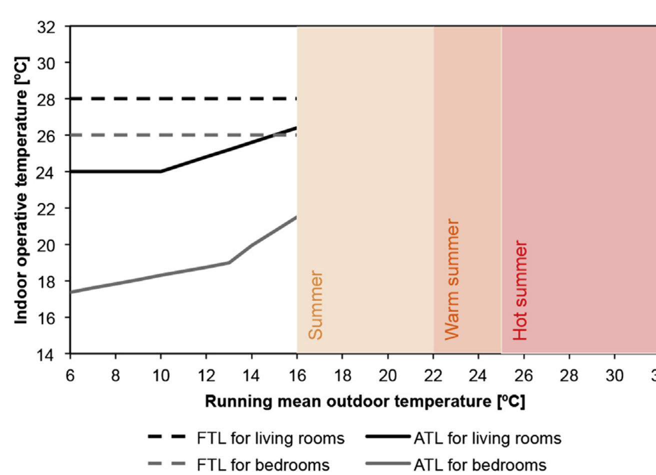

Fig. 1. The fixed and adaptive temperature limits for the overheating assessment, respectively indicated by FTL and ATL.

2.1.1. Fixed temperature limit (FTL)

According to the CIBSE Guide A [34], in free-running buildings, overheating occurs when the indoor operative temperature exceeds 28 °C in the living areas and 26 °C in the bedrooms for more than 1% of the annual occupied hours, unless ceiling fans are available. If a fan is used, higher room temperatures (i.e., up to 3 °C depending on the air speed) can be accepted [44].

2.1.2. Adaptive temperature limit (ATL)

A number of adaptive approaches have also been used for assessing thermal overheating in free-running buildings. For example, several research studies conducted in the Netherlands [45–47] brought to develop a Dutch adaptive assessment scheme incorporated into the Dutch standard ISSO Publication 74 [35] and extensively discussed in Ref. [48]. This scheme has been developed to be used for evaluating the thermal environment in naturally ventilated environments, in which occupants have free access to operable windows and are relatively free to adjust their clothing. It is acceptable to use the adaptive temperature limits (ATL) in rooms that are used for office-like activities, for example, living rooms. However, it was found that applying the ATL without maximum thresholds could lead to 'very high' values if the running mean outdoor temperature (T_{rm}) exceeds 25 °C. Rooms used for office-like activities can have acceptable indoor temperatures of up to 30 °C for a 90% acceptability level [49]. However, it should be mentioned that Oseland [50] experimentally demonstrated that people feel warmer in their home than they do in their office "even when the indoor climate was identical and they conducted the same activities and wore the same clothing" [50]. The presence of furnishing, that is, carpets, wallpaper, and furniture, was mentioned as a possible reason for this, since people tend to judge rooms with such features as being warmer. Instead, Peeters, de Dear [43] developed an adaptive approach for residential buildings and specified a set of conditions suitable for bedrooms. The adaptive temperature limits for bedrooms, $ATL_{bedroom}$, are given as a function of the neutral temperature (T_n) in Eq. (1).

$$ATL_{Bedroom} = \min\{26°C, (T_n + \omega\alpha)\}$$
$$with \begin{cases} T_n = 16°C & \text{for} \quad T_{e,ref} < 0°C \\ T_n = 0.23T_{e,ref} + 16 & \text{for} \quad 0°C \le T_{e,ref} < 12.6°C \\ T_n = 0.77T_{e,ref} + 9.18 & \text{for} \quad 12.6°C \le T_{e,ref} < 21.8°C \\ T_n = 26°C & \text{for} \quad T_{e,ref} \ge 21.8°C \\ \omega = 5°C & \text{for} \quad PPD = 10\% \\ \alpha \equiv 0.7 \end{cases} \tag{2}$$

where T_n is the neutral temperature, $T_{e,ref}$ is the reference external temperature in °C, ω is the amplitude of the thermal comfort band in °C, and α is a constant. The reference external temperature is defined in Ref. [43] and is reported in Eq. (3)

$$T_{e,ref} = \frac{T_{today} + 0.8T_{today-2} + 0.2T_{today-3}}{2.4} \tag{3}$$

where T_{today} is the average of today's maximum and minimum external temperature in °C and $T_{today-1}$ is the average of yesterday's maximum and minimum external temperature, and so on. It is similar to the running mean outdoor temperature, T_{rm}, that is defined in Ref. [51] as

$$T_{rm} \cong \frac{T_{ed-1} + 0.8T_{ed-2} + 0.6T_{ed-3} + 0.5T_{ed-4} + 0.4T_{ed-5} + 0.3T_{ed-6} + 0.2T_{ed-7}}{3.8} \tag{4}$$

where T_{ed} is the daily mean external temperature of the current day and T_{ed-1} is the daily mean external temperature of the previous day, and so on.

In this study, for the bedrooms the adaptive temperature limits (ATL) are defined according to Ref. [43], and for all the other rooms they are defined according to Class B ($PPD = 10\%$) of ISSO 74 with a maximum threshold of the indoor operative temperature set at 30 °C for running mean outdoor temperatures higher than 25 °C in order to preserve an acceptability of 90% (i.e. $PPD = 10\%$) according to Kurvers, van der Linden [49]. Furthermore, when using the ISSO 74's ATL, it is assumed that (i) occupants' metabolic rate is lower than 1.4 met, (ii) the occupants have direct control of windows, and (iii) an active cooling system is not installed in the room or building. Under these three conditions, the upper limit of the thermal comfort zone follows the Type α diagonal threshold reported in Ref. [48].

2.2. Ambient warmness degree and overheating escalation factor

The *Overheating escalation factor* (a_{IOD}) metric is used to estimate the sensitivity of dwellings to overheating. It represents the variation in the indoor temperatures when they exceed a chosen thermal comfort temperature limit in a given time period (*IOD*) as a consequence of the severity of outdoor warmness. The severity of outdoor warmness is quantified using the metric called *Ambient warmness degree* ($AWD_{18°C}$) that is defined later in this section. The *Overheating escalation factor* is defined as:

$$\alpha_{IOD} = \frac{IOD}{AWD_{18°C}} \tag{5}$$

Assuming that the relationship between *IOD* and $AWD_{18°C}$ is suitably representable with a linear regression model, the a_{IOD} is the slope coefficient of the regression line. An *Overheating escalation factor* greater than the unit ($a_{IOD} > 1$) means that indoor thermal conditions get worse when compared to outdoor thermal stress. On the contrary, an *Overheating escalation factor* lower than the unit ($a_{IOD} < 1$) means that a dwelling can suppress some of the outdoor thermal stress.

The *Ambient warmness degree* ($AWD_{18°C}$) evaluates the severity of outdoor warmness by averaging the Cooling degree hours calculated for a base temperature of 18 °C ($CDD_{18°C}$) during the summer hours when the outdoor air temperature is not lower than 18 °C.

$$AWD_{18°C} \equiv \frac{\sum_{i=1}^{N}\left[(T_{a,i} - T_b)^{+} \cdot t_i\right]}{\sum_{i=1}^{N} t_i} \tag{6}$$

where T_a is the outdoor dry-bulb air temperature, T_b is base temperature set at 18 °C, N is the number of occupied hours such that $T_{a,i} \ge T_b$ in the summer season, and t is the time step (1 h). Only positive differences are taken into the summation ($T_{a,i} - T_b$). The

Table 1
Parameters of the 9216 dwelling design and operation cases.

	Parameters	Number of options	Description
Design parameters	Archetype	8	Detached house, semidetached house, plus six flat typologies (corner/middle location per ground/middle/top floor)[a]
	Fabric characteristics according to dwelling construction age	6	According to six construction periods (pre-1964, 1965–1974, 1975–1991, 1992–2005, 2005–2012, and post-2013) representing the Dutch building stock [54]
	Orientation	4	South, North, West, and East
	Shading option	3	No shading, internal shading with control, or external shading with control
Operation parameters	Comfort criteria according to the adaptation level	2	Fixed temperature limit and adaptive temperature limit
	Ventilation rate	2	Minimum ($0.9\ l\ s^{-1}m^{-2}$) and maximum (5 and 8 ACH for bedrooms and living rooms respectively)
	Internal heat gain from electric lighting and appliances	2	Standard and slightly higher: respectively 4.3 and 5 W/m^{2}for houses and 5 and 5.3 W/m^2 for apartments considering realistic occupant behavior patterns according to the Dutch building regulation [53]
	Occupancy profile	2	Attendant at home during working hours? (Yes or No)

[a] The analyzed apartments are framed in red; see Appendix I.

base temperature of 18 °C was chosen because this value is lower than every minimum summer comfort temperature limit. Thus, $AWD_{18°C}$ is higher than zero for every climate scenario in which the outdoor air temperature is higher than the minimum summer comfort temperature limit for at least 1 h. This assures that a_{IOD} can be calculated.

Summing up, $AWD_{18°C}$ provides an averaged quantification of the warmness of a given climate scenario that considers both the accumulation of amplitude and the duration of each warmness occurrence. For this reason, it measures the severity of a yearly weather dataset and is used independently of the time evolution or the assumptions used to build the weather file.

3. Description of building stock and climate scenarios

3.1. Building stock and building operation

The Dutch dwelling stock is represented by 9216 possible combinations of building design and operation parameters (Table 1). The geometries of the dwelling types (drawn in Appendix I) are taken according to Ref. [52]. The minimum ventilation rate and the standard internal heat gain values are consistent with the Dutch building code [53]. Detailed schedules are used to present occupants' use of electric lighting and appliances in line with Ref. [53]. The maximum ventilation rate is assumed to vary according to the ventilative cooling potential, that is, outdoor air is used to cool down the dwelling if the indoor temperature is higher than 25 °C in living rooms and 23 °C in bedrooms. Shading control is assumed to apply shading when the schedule is activated and the incident irradiance incident on windows exceeds 100 W/m^2.

The occupied hours are defined according to the occupant type. For working families, the living rooms are assumed to be occupied from 7:00 to 8:00 a.m. and from 6:00 to 11:00 p.m. during weekdays and from 7:00 a.m. to 11:00 p.m. during the weekend. The bedrooms are assumed to be occupied from 11:00 p.m. to 7:00 a.m. during weekdays. For retired families, the living rooms and bedrooms are assumed to be occupied from 9:00 a.m. to 10:00 p.m. and from 10:00 p.m. to 9:00 a.m. during all days of the week, respectively.

Fixed and adaptive thermal comfort temperature limits are used to assess the overheating risk in terms of the number of *Indoor overheating hours* (*IOH*) and the degree of the *Indoor overheating degree* (*IOD*).

3.2. Climate scenarios

The overheating risks of the dwelling cases are assessed under four climate scenarios. These climate scenarios are selected to represent historical and future outdoor conditions according to historical measurements and global-warming projections made by the Royal Netherlands Meteorological Institute [55]. The four climate scenarios are called (i) *Average scenario*, (ii) *Extreme scenario*, (iii) *Future scenario*, and (iv) *Worst Future scenario*. The *Average scenario* represents a moderate climate used as a reference year for the building performance simulation in the Netherlands [22] and was developed on the basis of historical meteorological data recorded during the summers of 1964 and 1965. The *Extreme scenario* represents an extreme climate projection developed according to the meteorological data recorded during the summer of 2003. It considers the 2003 long-term heat wave. The *Future scenario* is a warm climate projection to 2100 of meteorological data recorded in 1976 and considers a global warming effect quantified by an increase in the average temperature of 2 °C. The *Worst Future scenario* is an extreme climate projection to 2100. It is based upon the dataset proposed by the Dutch standards NEN 5060 [56], which considers a probability of 5% for the occurrence of an actual warmer summer, and considers that both an increase in the average temperature of 4 °C due to a global warming effect and a further temperature rise of 1.4 °C due to the urban heat island effect can be quantified in accordance with [57].

Table 2 compares the four climate scenarios by using traditional metrics such as mean outdoor dry-bulb temperature, cooling degree days calculated with respect to a base temperature of 18 °C ($CDD_{18°C}$), direct normal radiation and diffuse radiation on a horizontal surface, and $AWD_{18°C}$

Three values of the running mean outdoor temperature, 16, 22, and 25 °C, are used by the Dutch legislation to classify summer conditions. They are respectively called *Summer*, *Warm summer*, and *Hot summer* respectively [55]. According to such classification, Fig. 2 shows how the severity of summer conditions is projected to increase, with a substantial rise in the whole distribution of values and with a wider spread of temperatures with respect to the *Average scenario*. The figure shows that the *Worst Future scenario* falls into the two highest categories for most of the summer time, specifically *Warm summer* and *Hot summer*. The median value of the running mean outdoor temperature is projected to increase by about 9 °C.

4. Results and discussion

This section presents the simulation results of the 36,864 simulated cases, that is, the 9216 combinations of dwelling designs and operations (Section 3.1) times four climate scenarios (Section 3.2). All cases were simulated in free-running mode from 1 May to 30 September. The ranges of the indoor operative temperature in the 9216 dwelling cases versus the four *Ambient warmness degrees* ($AWD_{18°C}$) corresponding to the four analyzed climate scenarios are presented in Section 4.1. Overheating is assessed in terms of *Indoor overheating degree* (*IOD*) in Section 4.2. Finally, the sensitivity of the dwelling cases to overheating is investigated in Section 4.3 using the *Overheating escalation factor* (a_{IOD}).

4.1. Indoor operative temperature

Fig. 3 presents the ranges of the maximum, mean, and minimum, and the standard deviation of the indoor operative temperatures in the living rooms and bedrooms during the occupied hours, considering all the studied dwelling cases as well as the four climate scenarios. The climate scenarios, namely *Average scenario*, *Extreme scenario*, *Future scenario*, and *Worst Future scenario* (Table 2) are represented by their *Ambient warmness degrees* of 0.6, 1.6, 3.0, and 6.0 °C, respectively. The figures on the left and right sides present the temperature ranges in the dwelling cases with minimum (about 1.5 h^{-1}) and maximum ventilation rates (about 5 h^{-1} for the bedrooms and 8 h^{-1} for the living rooms) respectively.

Firth, Benson [58] highlight large variations in internal air temperatures between various dwellings during the 2006 heat wave; they found differences of up to 5 °C. In this study, a maximum indoor temperature difference of up to 13 °C and 7 °C is observed between minimally and maximally ventilated dwelling cases, respectively, for the *Extreme Climate* scenario (similar to the heat wave of 2003) with $AWD_{18°C}$ of 1.6 °C, as shown in Fig. 3. It is worth mentioning that in minimum ventilated cases under the *Worst Future scenario*, even the daily mean temperatures will significantly exceed the safe limit identified by epidemiological studies of 24.7 °C of the maximum daily temperature [10]. The highest maximum indoor temperature, 47 °C, is reached in the *Worst Future scenario*. In particular, for this scenario, the median of the maximum indoor operative temperature should reach about 38 °C, which is even higher that the maximum indoor temperature registered in the *Average scenario*, which is about 37 °C. Furthermore, in the studied dwelling cases, there is no significant difference between the standard deviations of the indoor operative temperature among the rooms in the *Average scenario*, but the standard deviation will slightly increase as global warming continues, and the minimum temperature will also increase significantly from about 14 °C to about 20 °C on average. More generally, for a given climate scenario, the temperature differences in the bedrooms are smaller than the differences in the living rooms, as seen in Fig. 3, particularly in highly ventilated dwellings.

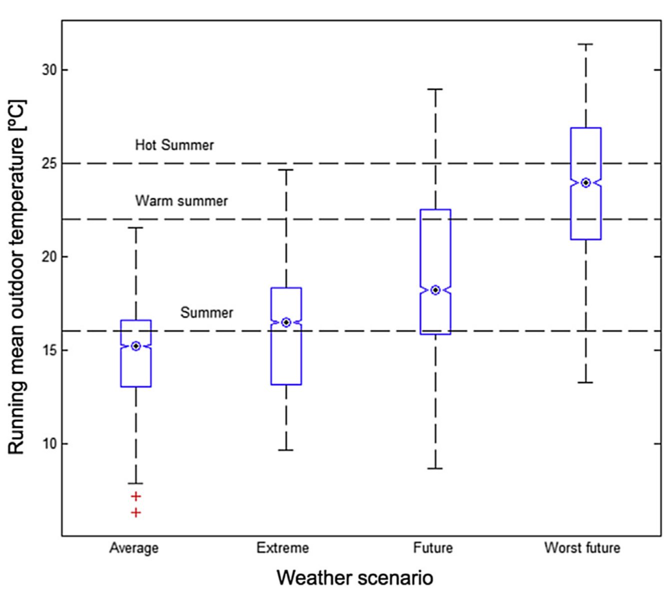

Fig. 2. Boxplots representing the distribution of the running mean outdoor temperatures of the studied period for the four climate scenarios compared with the three summer levels proposed in Dutch legislation.

In Fig. 4, it is possible to see that because of the internal and solar heat gains, the free-running indoor temperature in dwellings is most often higher than the outdoor air temperature. During the predefined simulation period (from 1 May to 30 September), on average, the mean of positive differences between the indoor and outdoor dry-bulb temperatures, $<\Delta T^{+}_{a,int-ext}>$, will slightly decrease as global warming increases. The frequency of the indoor temperature being higher than the outdoor temperature could decrease as long as there is an adequate cooling potential for (mechanical or natural) ventilation in the more severe climate scenarios with $AWD_{18°C}$ higher than 3 °C (Fig. 4).

4.2. Overheating risk

This section discusses the overheating risk by analyzing the relationship between *Indoor overheating hours* (*IOH*) and *Indoor overheating degree* (*IOD*), and the *Ambient warmness degree* ($AWD_{18°C}$). Fig. 5 and Fig. 6 show both *IOH* and *IOD* assuming fixed temperature limits (FTL) and adaptive temperature limits (ATL) as thermal comfort criteria, respectively. It emerges that the Dutch dwellings with minimum ventilation rate (0.9 $l\,s^{-1}m^{-2}$) are already vulnerable to overheating and that this is likely to get worse as global warming continues, that is, for higher values of $AWD_{18°C}$.

Furthermore, for the two climate scenarios *Average scenario* and *Worst Future scenario*, the ranges of overheating risk are classified according to the thermal comfort criteria (FTL or ATL), ventilation rate (minimum, maximum), and the eight dwelling archetypes in Fig. 7 and Fig. 8.

The figures show that for a given climate scenario, there is a significant difference in overheating risks in dwellings. This difference will increase in the future, as the ambient is going to get warmer, with the ventilation rate and the presence and correct operation of solar shading devices being the main causes of this difference. The archetype has a sound influence on the overheating degree in dwellings with minimum ventilation rate. However, it has a negligible influence on well-ventilated dwellings. Apartments on the middle floor and in the middle location of apartment buildings and apartments on the top floor and in the middle location of apartment buildings, as well as detached houses, are the dwelling archetypes most sensitive to global warming. They are at a higher overheating risk than other archetypes (e.g., semidetached houses and apartments on the ground floor) in the current climate (*Average scenario*) and they will continue to be at a higher risk in the future projections. Old dwellings (post-1964) with little or no mechanical ventilation and insufficient solar protection will be at a significant risk of overheating. However, the risk will be significantly higher in new dwellings (from 2005 to 2012) with high insulation levels and improper solar protection (Fig. 9). Such new buildings are already at a significant risk (up to $IOD = 2$ °C) of overheating in the current climate.

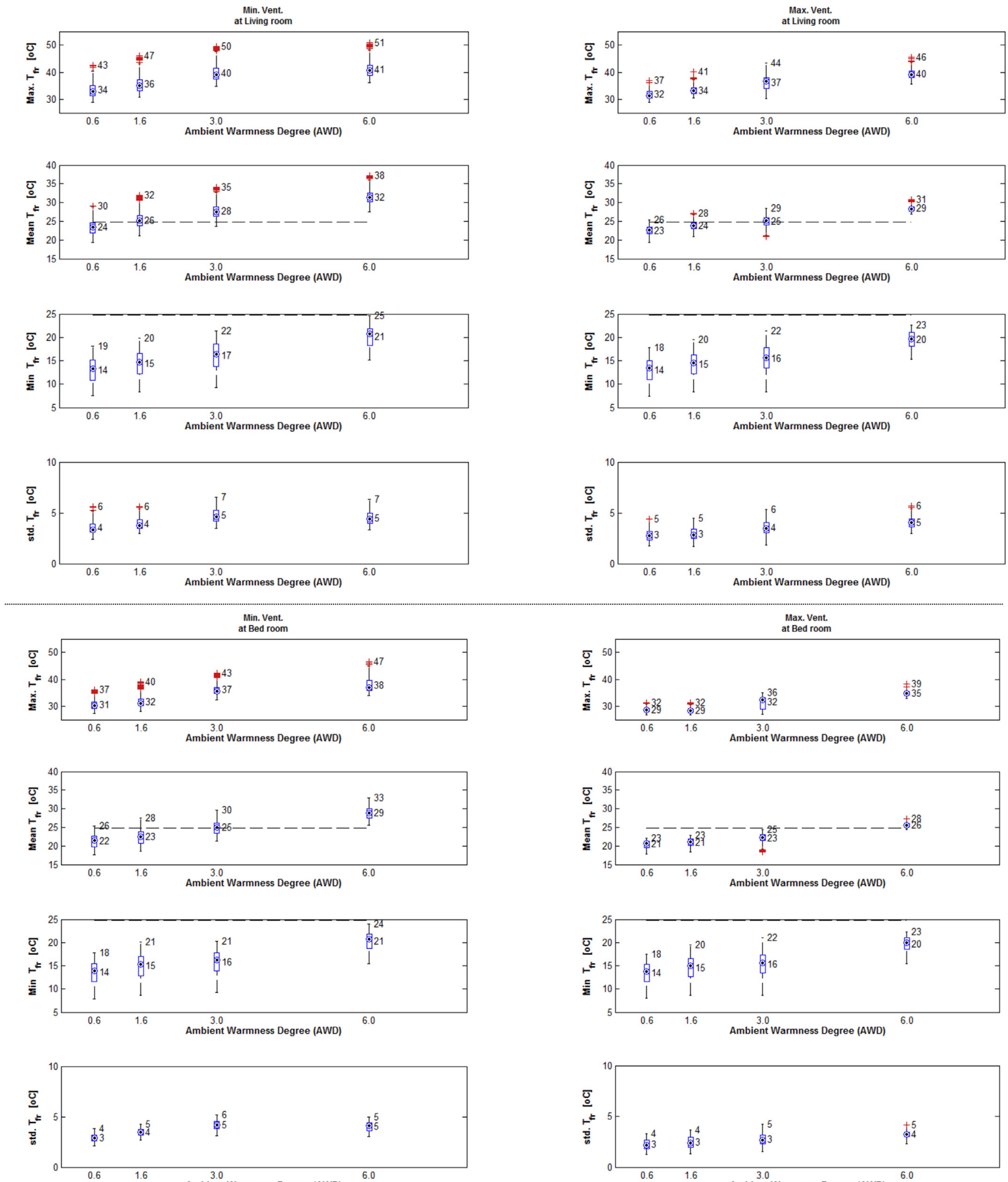

Fig. 3. The ranges of the maximum, mean, and minimum, and the standard deviation of indoor operative temperatures in living rooms (top eight figures) and bedrooms (bottom eight figures) during the occupied hours, considering all the studied dwelling cases as well as the four climate scenarios. The left and right columns present the temperature ranges when minimum (~1.5 h^{-1}) and maximum (5 h^{-1} for bedrooms and 8 h^{-1} for living rooms) ventilation rates are implemented. The dashed lines represent the safe limit of 24.7 °C, according to Ref. [10].

Table 2
Characterization of the four climate scenarios.

Weather scenario	Mean outdoor tempera-ture [°C]	Cooling degree day ($CDD_{18°C}$) [°C]	Ambient warmness degree ($AWD_{18°C}$) [°C]	Diffuse radiation on horizontal surface [W/m^2]	Direct normal radiation [W/m^2]
Average scenario - is based on the 1964/1965 datasets	14.9	0	0.6	105.9	125.7
Extreme scenario - is based on the 2003 dataset - considers the 2003 heat wave	16.6	10.7	1.6	106.1	153.0
Future scenario - is based on the 1976 dataset - accounts for projection at 2100 - +2 °C due to global warming	19.4	30	3.0	101.3	162.7
Worst Future scenario - is based on the NEN 5060, 5% dataset - accounts for projection at 2100 - +4 °C due to global warming - +1.4 °C due to the urban heat island	23.7	101.4	6.0	101.1	158.6

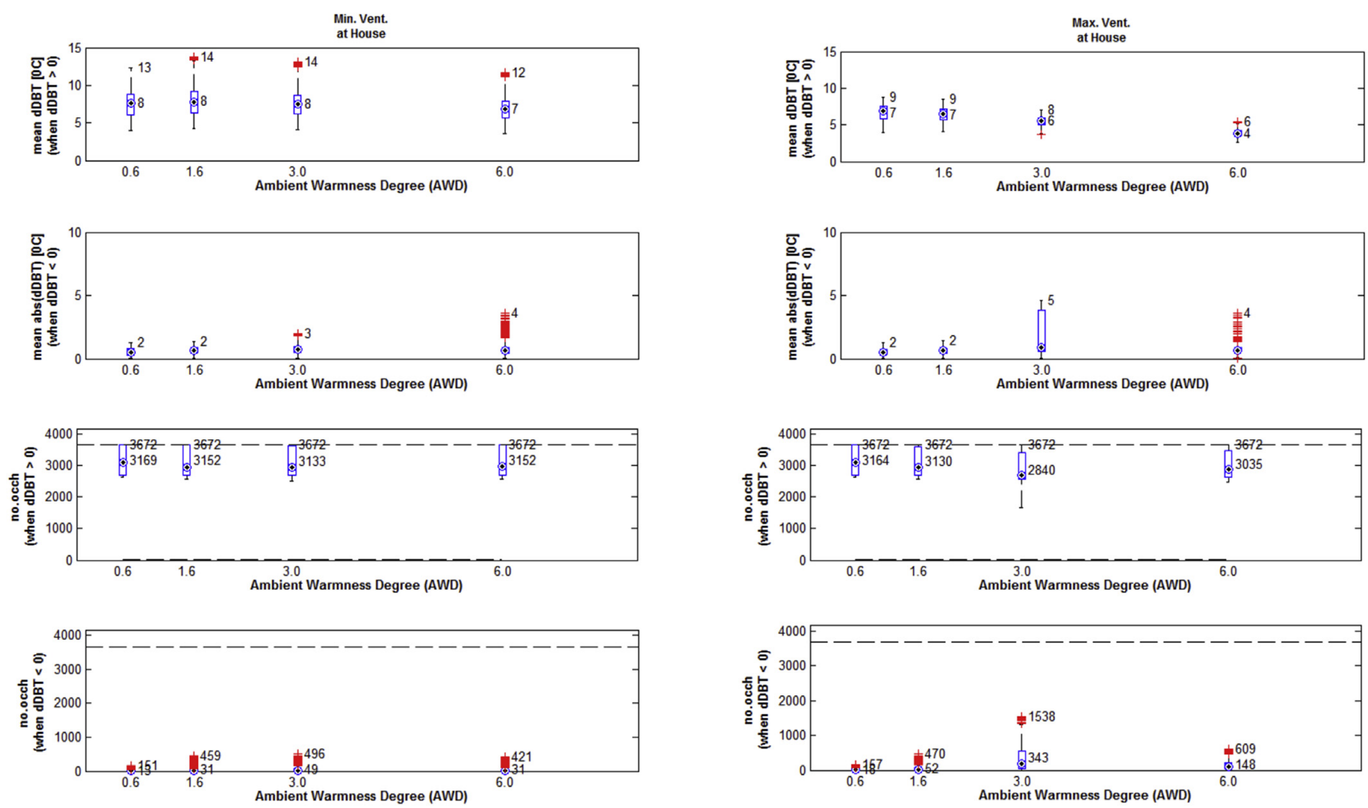

Fig. 4. Statistics on the indoor and outdoor temperature differences for the given climate scenarios represented by $AWD_{18°C}$ at the house level in the two ventilation conditions. The dashed lines represent the total simulated hours (no.occh).

4.3. Sensitivity to climate change

This section investigates the sensitivity of the Dutch dwellings to climate change using the *Overheating escalation factor*, which quantifies the increase in the *Indoor overheating degree* (*IOD*) corresponding to an increase in the *Ambient warming degree* ($AWD_{18°C}$). Fig. 8 shows the linear regression models representing *IOD* as a function of $AWD_{18°C}$ according to the several design and operation parameters given in section 3.1. Such linear regression models are developed by assuming as a thermal comfort criterion the FTL set at 28 °C and 26 °C for living rooms and bedrooms, respectively.

Fig. 10 shows that there is a direct proportionality between the *IOD* and $AWD_{18°C}$, that is, overheating will increase as the climate

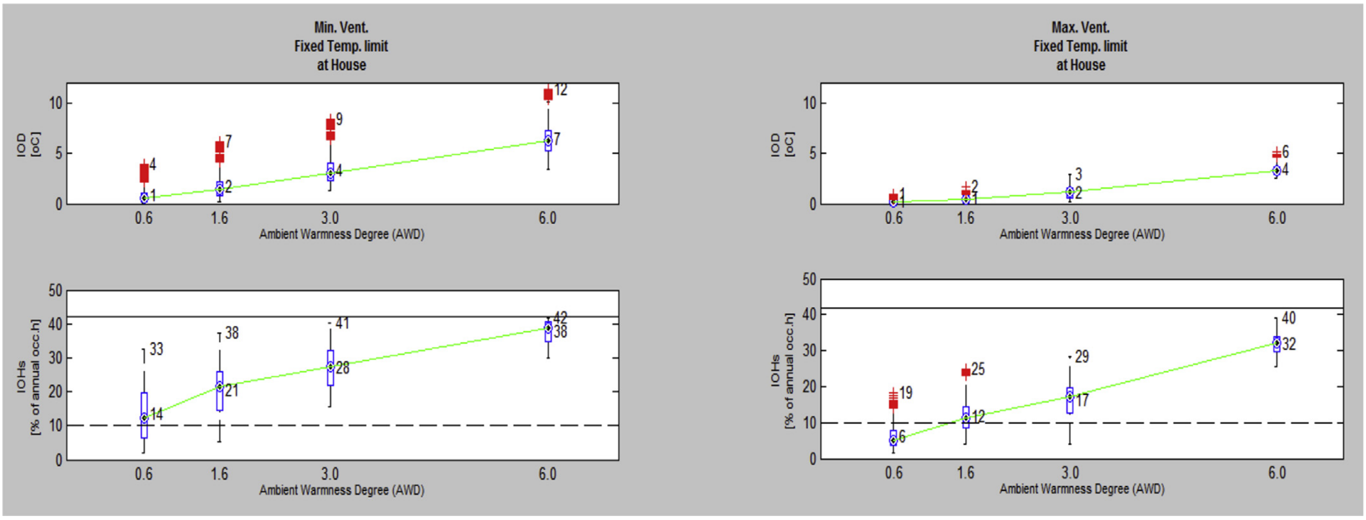

Fig. 5. The Indoor overheating degree (IOD) and the percentage of the Indoor overheating hours (IOH) for the four given climate scenarios presented by their $AWD_{18^\circ C}$ (0.6, 1.6, 3, and 6 °C). Fixed temperature limits (25 and 23 °C) are applied as thermal comfort criteria for living spaces and bedrooms, respectively. The figures on the left- and right-hand sides show the overheating risk in the dwellings with minimum and maximum ventilation rate, respectively. The dashed horizontal line represents the comfort limit according to [59].

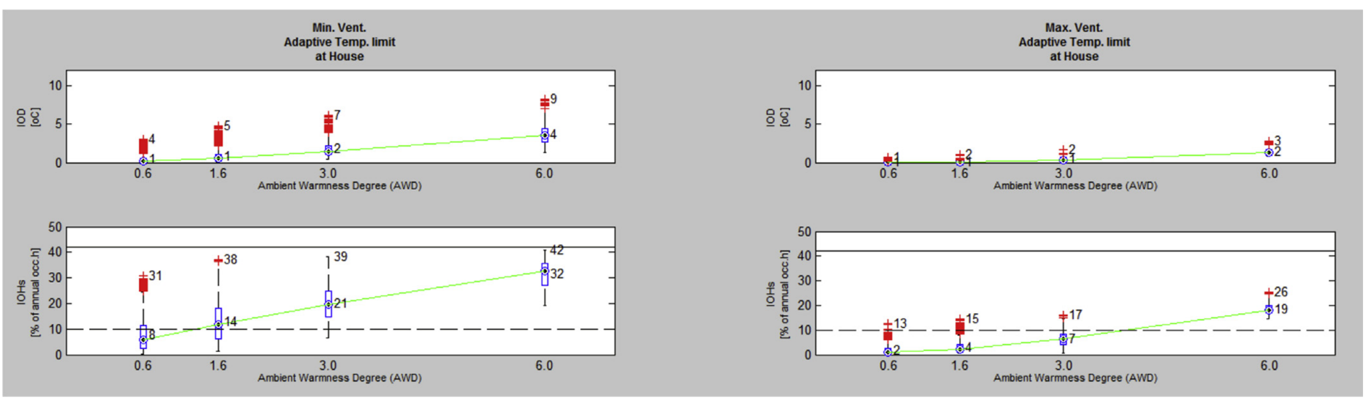

Fig. 6. The Indoor overheating degree (IOD) and the percentage of the Indoor overheating hours (IOH) for the four given climate scenarios presented by their $AWD_{18^\circ C}$ (0.6, 1.6, 3, and 6 °C). Adaptive temperature limits are applied as thermal comfort criteria for living spaces and bedrooms, respectively. The figures on the left- and right-hand sides show the overheating risk in the dwellings with minimum and maximum ventilation rate, respectively. The dashed horizontal line represents the comfort limit according to [59].

severity increases. a_{IOD} ranges from 0.1 to 0.989 depending on the aforementioned building design and operation parameters as well as the overheating criteria; however, it is less than the unity for 97% of the studied dwelling cases. This indicates that most of the simulated dwellings can suppress, though with different levels of success, the effects of global warming. The building cases with the highest slope for the linear regression line for each design variable (internal heat gain, ventilation rate, building archetype, construction period, orientation, solar shading option) represent the building variants most affected by climate change. According to the simulation that was carried out, recent buildings built between 2005 and 2012, with high internal gains, limited ventilation options, and not equipped with solar shading devices are the most exposed to the effect of climate change ($a_{IOD} = 0.98872$).

Old buildings, that is, those built before 1964, appear to be more resilient to climate change than recent buildings built according to the requirements of 2005–2012 and not equipped with solar shading devices or effective ventilation options. Although internal heat gains increase overheating (represented here by *IOD* or *IOH*), they appear not to cause a significant rise in dwelling sensitivity since the value of the *Overheating escalation factor* only increases marginally.

Building archetype and orientation appear not to be key aspects in explaining sensitivity to climate change. On the other hand, the building cases with the lowest slope ($a_{IOD} = 0.15861$) for the linear regression lines for each design variable (internal heat gain, ventilation rate, building archetype, construction period, orientation, solar shading option) represent the building variant most resilient to climate change. The simulation outcomes show that the most resilient building variant is characterized by the installation of external solar shading devices, by an East/West orientation, and by high ventilation rates. However, although the control of internal gains and the building archetype influence the evolution of indoor operative temperatures in the most resilient building variants, they appear not to be the key aspects used to describe the sensitivity of a dwelling to overheating. Finally, the construction period appears

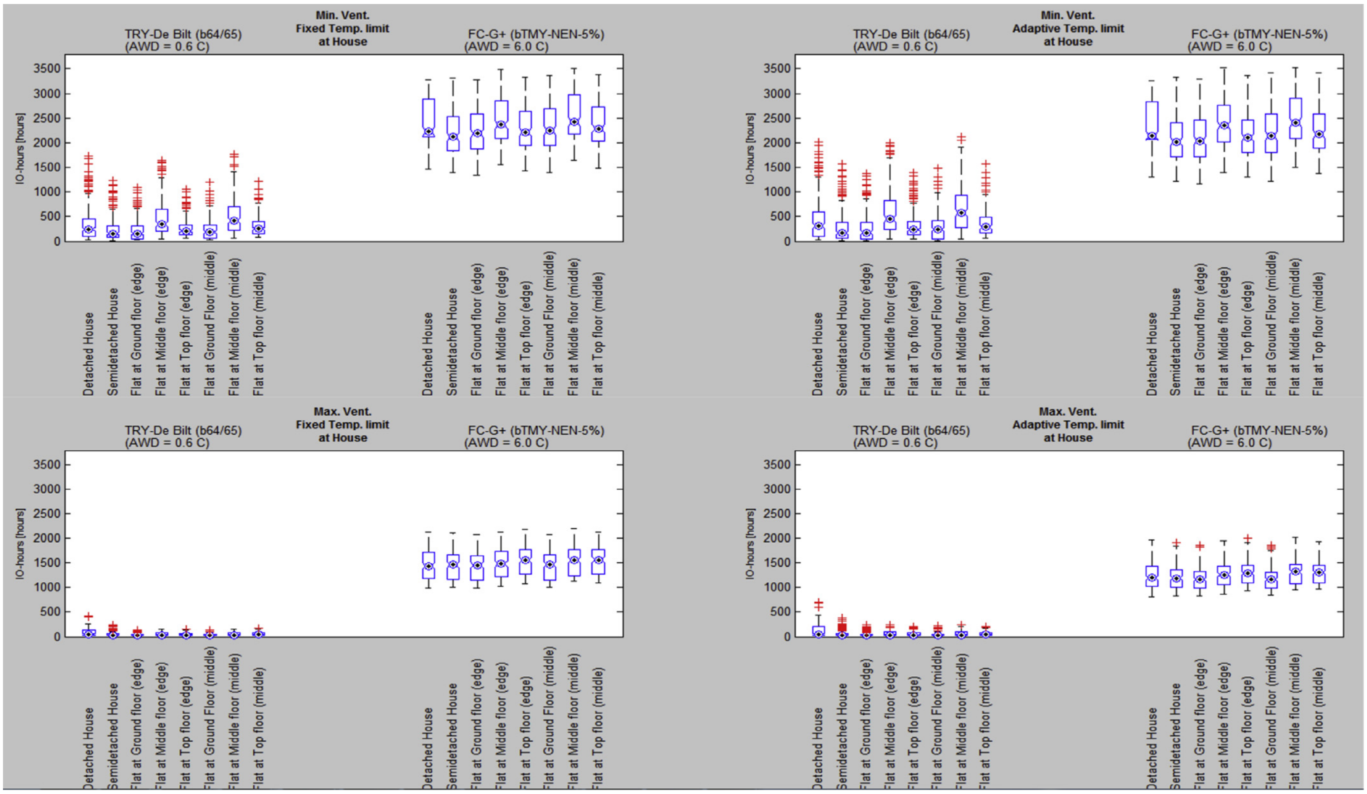

Fig. 7. The boxplots show the ranges of the Indoor overheating hours (IOH) classified according to eight dwelling archetypes, two ventilation rates, and two comfort assessment schemes (fixed and adaptive comfort temperature limits) for two given climate scenarios with 0.6 °C and 6 °C Ambient warmness degrees ($AWD_{18°C}$).

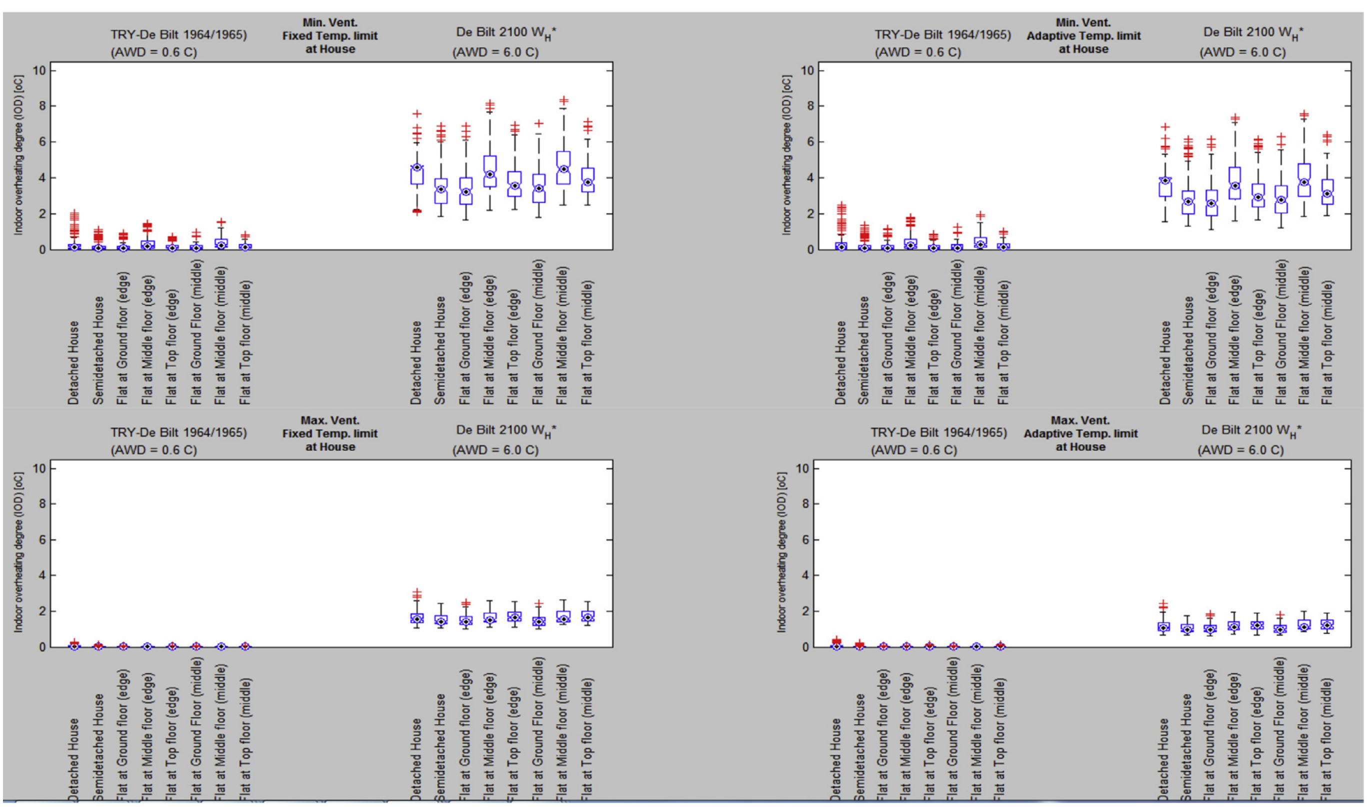

Fig. 8. The boxplots show ranges of the Indoor overheating degree (IOD) classified according to eight dwelling archetypes, two ventilation rates, and two comfort assessment schemes (fixed and adaptive comfort temperature limits) for two given climate scenarios with 0.6 °C and 6 °C Ambient warmness degrees ($AWD_{18°C}$).

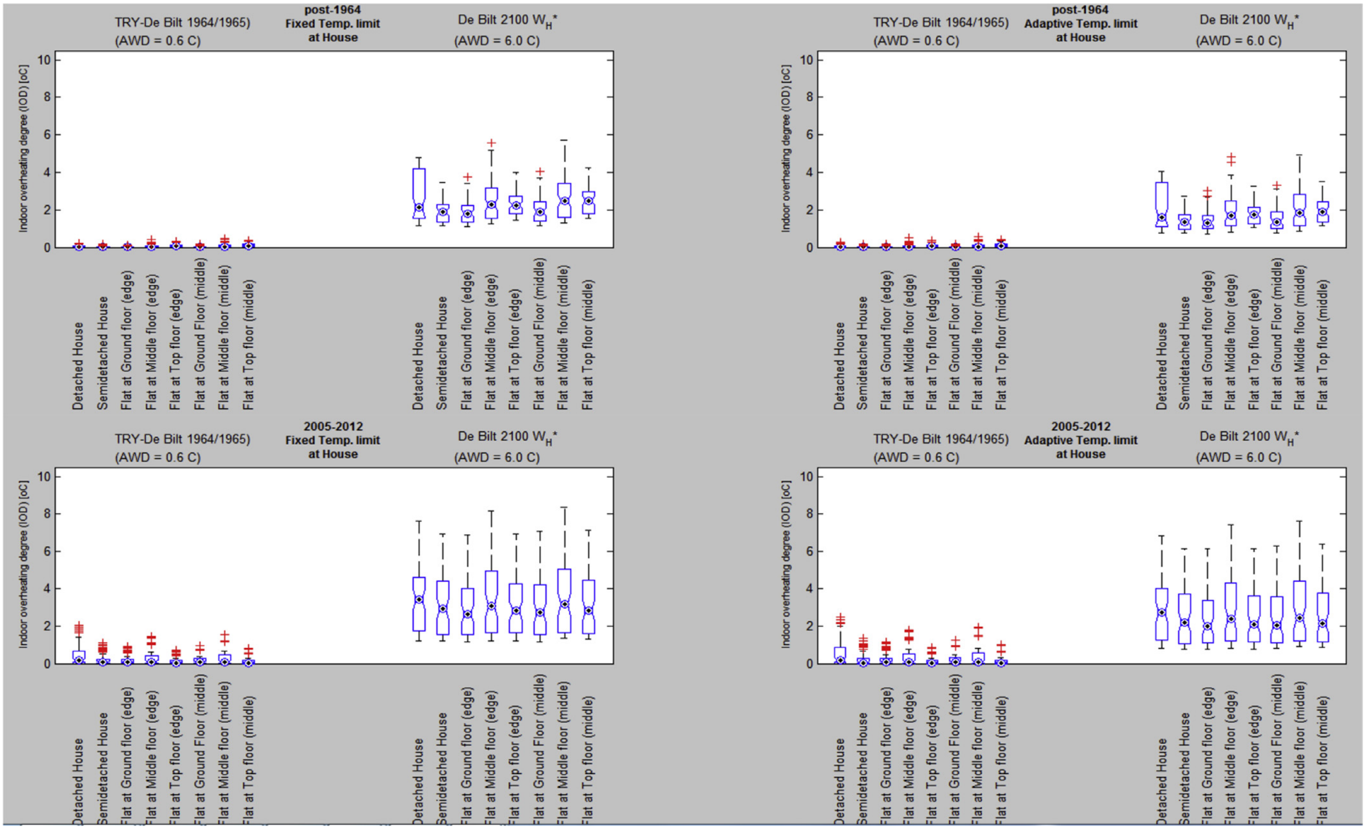

Fig. 9. The boxplots show the ranges of the Indoor overheating degree (IOD) classified according to eight dwelling archetypes, two building ages, and two comfort criteria (fixed and adaptive comfort temperature limit) for two given climate scenarios with 0.6 °C and 6 °C $AWD_{18^\circ C}$.

not to influence the most resilient building variants.

Furthermore, since the adoption of stricter overheating criteria causes higher values of the *Overheating escalation factor*, the adoption of the adaptive temperature limits (ATL), instead of fixed temperature limits (FTL), to assess overheating produces a remarkable reduction of a_{IOD} and all simulated dwelling cases are specifically characterized by an *Overheating escalation factor* lower than the unity (Fig. 11, right). Therefore, the selection of the reference thermal comfort model used to estimate overheating is also of paramount importance for the assessment of building sensitivity to climate change. Hence, researchers dealing with different topics, from the indoor environmental quality to the climate change forecast, passing through building design, have to work in synergy and collaborate in a new transdisciplinary and multidisciplinary manner.

The data in Fig. 11 has been gathered by $AWD_{18^\circ C}$, and power or polynomial regression models have been developed to represent every series. It should be noted that the two series for $AWD_{18^\circ C} = 6$ °C are characterized by a very high value for the coefficient of determination ($R^2 = 0.9919$ for FTL and $R^2 = 0.9816$ for ATL). Therefore, two such polynomial regression models can be used to estimate, with a good predictive capability, the sensitivity to climate change (represented by a_{IOD}) of any Dutch dwellings by just knowing their *IOD*, calculated using the *Worst Future scenario* (characterized by $AWD_{18^\circ C} = 6$ °C).

Fig. 11 also shows that overheating conditions are going to become more and more severe with the increase in $AWD_{18^\circ C}$. With respect to the current climate scenario, the summer indoor air temperatures are going to increase on average by up to 7 °C in the worst building variants (but only by 1 °C in the most resilient ones), meaning that these building variants need to undergo a deep renovation in order to prevent indoor environmental conditions not compatible with healthy living. More generally, Fig. 11 (left) shows that if the future climatic conditions are likely to be those represented by the *Worst Future scenario*, actions should be taken to deal with higher indoor temperatures (or higher energy needs for space cooling) even if the buildings are more resilient, since the most resilient building variant in the *Worst Future scenario* ($a_{IOD} \approx 0.2$) is characterized by at least a 1 °C rise in the indoor air temperature, which, according to the current climate scenario, pertains to weak building variants with a high *Overheating escalation factor* ($a_{IOD} \approx 0.9$).

4.4. Potential of ventilative cooling

The *Indoor overheating degree* (*IOD*) in dwellings with minimum and maximum ventilation rate is shown in Figs. 5–8. The potential of ventilative cooling for reducing the aforementioned *IOD* for the four given climate scenarios is discussed in this section and shown in Fig. 12 and Fig. 13.

These two figures show that cooling through ventilation is a relatively effective measure that can be used to combat domestic overheating. The *Contribution of ventilation*, $C_{ventilation}$, is shown in Fig. 10 and is defined hereby as

$$C_{ventilation} \equiv IOD_{min\ ventilation\ rate} - IOD_{max\ ventilation\ rate} \quad (7)$$

The increase in the ventilation rate in dwellings is estimated to provide a reduction of more than 1.2 °C in the *Future scenario* and up to about 2.3 °C in the *Worst Future scenario* (Fig. 10). Indeed,

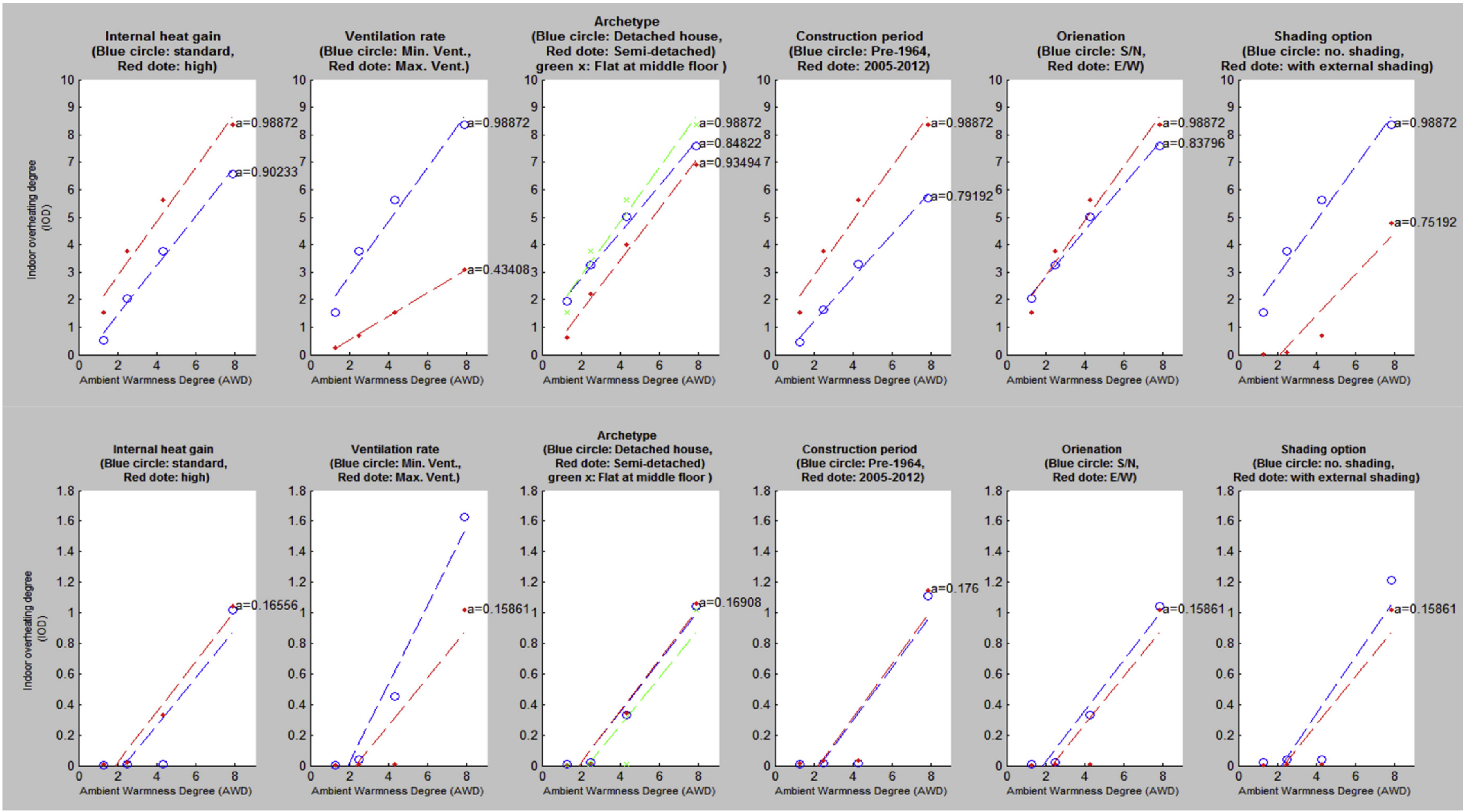

Fig. 10. Linear regression models representing IOD as a function of $AWD_{18^{\circ}C}$ according to the several design and operation parameters given in Table 1. In each graph, the maximum and minimum slopes are represented for each design and operation parameter.

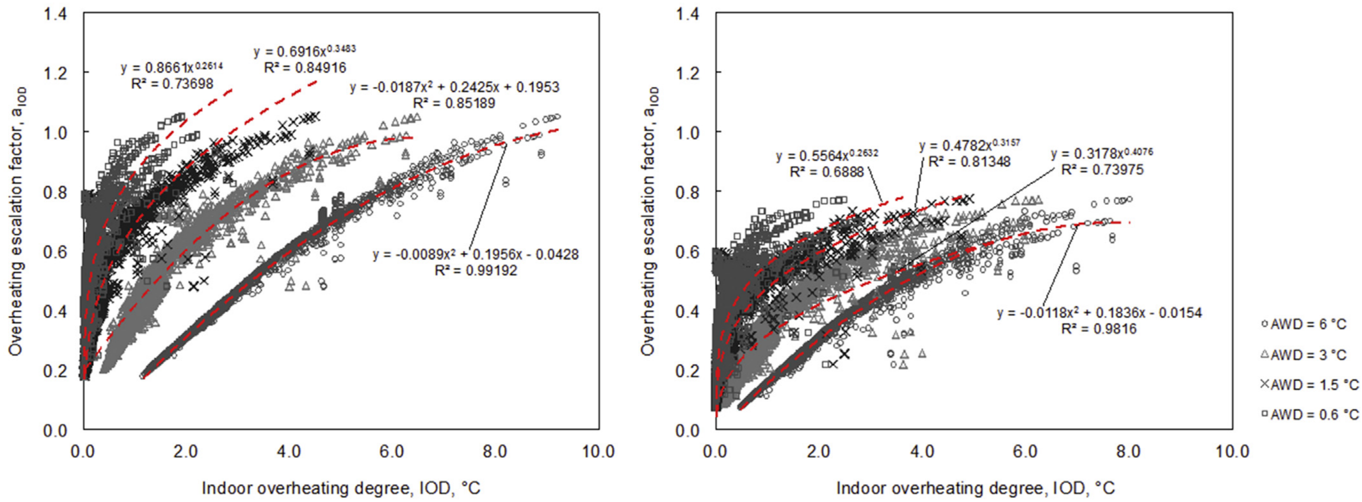

Fig. 11. The escalation factors of all the 9216 dwelling cases versus the Indoor overheating degrees for the four given climate scenarios ($AWD_{18°C}$ = 0.6, 1.6, 3, and 6 °C). The comfort criteria used to assess overheating are FTL of 28 °C and 26 °C for living rooms and bedrooms respectively and ATL with 20% PPD for living rooms and bedrooms as represented in.

ventilative cooling will be more beneficial in the future when there is much more overheating to be faced. However, ventilative cooling will not be able to fully eliminate the ever-increasing risk of overheating. In fact, defining the *Potential of adaptation*, $P_{\text{ventilation}}$, as the contribution of ventilation, $C_{ventilation}$, normalized with respect to *IOD* assessed when the minimum ventilation rate is set (0.9 l $s^{-1}m^{-2}$, approximately 1.5 ACH in the addressed models)

$$P_{\text{ventilation}} \equiv \frac{C_{\text{ventilation}}}{IOD_{\text{min ventilation rate}}}, \tag{8}$$

Fig. 11 shows that the potential of the ventilative cooling will decrease as global warming increases, that is, it will be harder and harder to reach acceptable indoor environmental conditions without integrating active cooling.

In the current climate, a high ventilation rate (on average 5 ACH) could reduce overheating by 90% on average with a maximum calculated value of 100% when compared to the minimum ventilation rate. Because of global warming, the percentages will decrease to 65% on average, and 80% as a maximum, when the average outdoor air temperatures are up to 5.4 °C higher than the current ones.

5. Conclusions

The impact of climate change on the overheating risk in dwellings is investigated comprehensively in the current study. The overheating risk in thousands of dwelling cases, consistent with the characteristics of the Dutch dwelling stock constructed from 1964 to 2012, is quantified for four climate scenarios based on historical and future projections datasets obtained from the Royal Netherlands Meteorological Institute [55]. The dwelling cases present 9216 possible combinations of design and operation parameters, including dwelling archetype, orientation, fabric characteristics, shading option, ventilation rate, internal heat gain, and adaptation opportunities, as well as occupancy time. The results supported the following concluding thoughts:

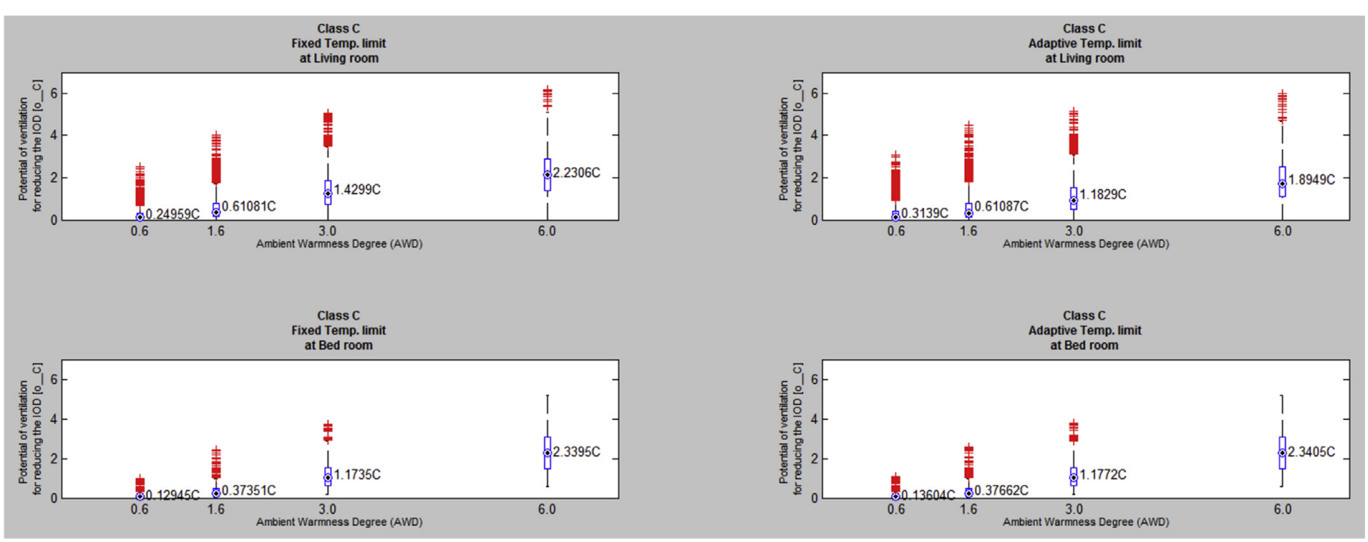

Fig. 12. Ventilative cooling potential to reduce the overheating risk expressed in average Celsius of reduction of the indoor air temperature in dwellings with minimum ventilation rate.

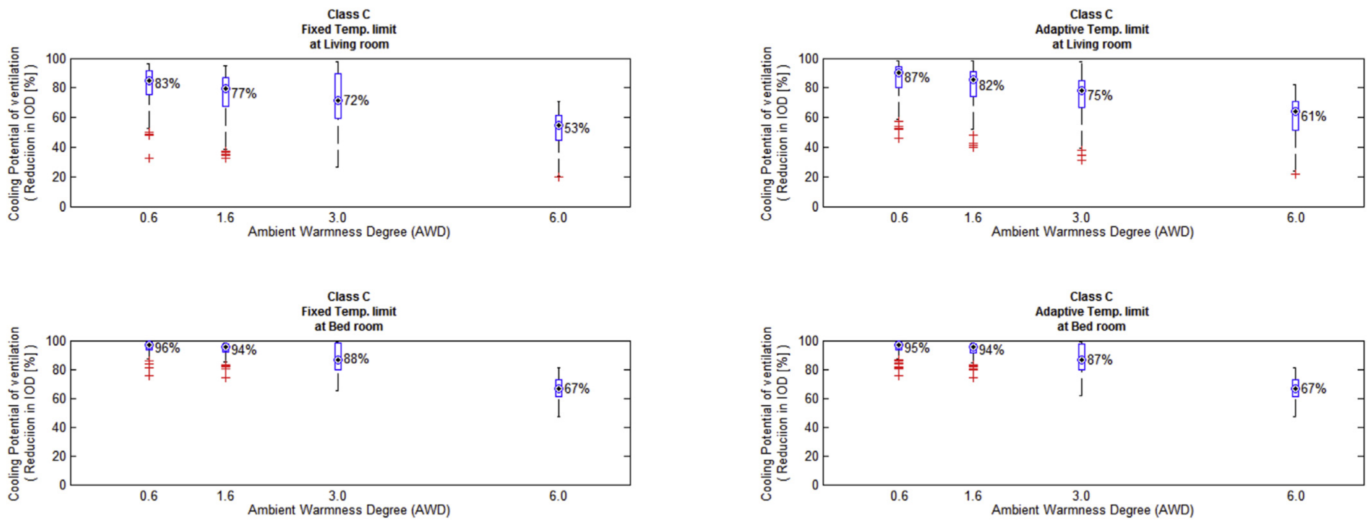

Fig. 13. Potential of ventilative cooling for reducing the overheating risk expressed as a percentage of the IOD in dwellings with minimum ventilation rate.

- Owing to internal and solar heat gains, the free-running indoor temperature (T_{fr}) in all of the studied dwelling cases is most often higher than the outdoor air temperature (T_a). On average the T_{fr} is 6 °C higher than the T_a during the calculation period (from 1 May to 30 September).
- The *Indoor overheating degree* (*IOD*) will increase as the *Ambient warmness degree* ($AWD_{18^\circ C}$) increases. However, the results show that the *Overheating escalation factor* ($a_{IOD} = \Delta IOD/\Delta AWD_{18^\circ C}$) is less than unity for 97% of the studied dwelling cases. This indicates that most of the dwellings can suppress, with a different level of success, the effects of global warming.
- The *Overheating escalation factor* (a_{IOD}) ranges from 0.1 to 1.2 depending on the building design and operation parameters as well as the overheating criteria. Stricter overheating criteria cause higher values of the *Overheating escalation factor.*
- Dwellings with higher solar heat gains (e.g., detached houses with a large, unshaded glazed area) and/or with lower heat transmission (e.g., apartments with a small, well-insulated façade area in the middle of an apartment building) are at high risk of overheating. Uppermost floors suffer a higher overheating risk than ground floors, especially in older dwellings with low insulation and low solar protection. Semidetached houses and ground-corner apartments are at a lower risk of overheating than the other studied archetypes. Dwellings showing a lower overheating risk than others in the current climate will continue to do so in future climate scenarios. This rule is valid as long as there is no significant change in solar radiation.
- Old dwellings with little or no mechanical ventilation and/or insufficient solar protection are at risk of overheating. The risk is significantly higher in new dwellings (built from 2005 to 2012), which have high insulation levels, if they are not protected by direct solar radiation.
- The Dutch dwellings with minimum ventilation rate ($0.9\ l\ s^{-1}m^{-2}$) are already vulnerable to overheating and this is likely to get worse as global warming continues, reaching indoor environmental conditions not compatible with healthy living.
- For a given climate scenario, there is a significant difference in overheating risks in dwellings and the differences will increase in the future as global warming continues.
- Ventilative cooling and solar protection seem to be the most effective adaptation measures to combat global warming. However, the potential of ventilative cooling will decrease as global warming increases. Moreover, traditional adaptation opportunities (e.g., natural cooling and solar shading, as well as occupants wearing cooler clothes and reducing their level of activity) might not be sufficient to keep the daily mean indoor temperature below 24.7 °C in all dwelling types during the whole summer season, the temperature at which mortality begins to rise [10]. Thus, in the future, when the *Ambient warmness degree* ($AWD_{18^\circ C}$) becomes as high as 3 °C, the overheating in dwellings will become seriously dangerous, and it will be harder and harder to reach acceptable indoor environmental conditions without integrating active cooling.
- Finally, there is still only limited and indirect epidemiological evidence concerning the conditions of indoor temperature exposure that give rise to adverse health effects [6]. Models of the relation between temperature and mortality are still needed to predict the consequences of global warming, particularly for those most vulnerable and least able to adapt (e.g., very young and very old people) [59].

On the basis of the above conclusions, it is recommended that the Dutch government should act, through, for example, policy decisions and adaptation interventions, to protect existing and new dwellings from the ever-increasing risk of overheating. The actions (e.g., stipulating and/or promoting the use of ventilative cooling and shading) should be taken quickly for those buildings that are sensitive to the climate change (e.g., buildings without good ventilative cooling options) and that are already suffering from some kind of overheating risk (e.g., new, well-insulated buildings without sufficient shading options).

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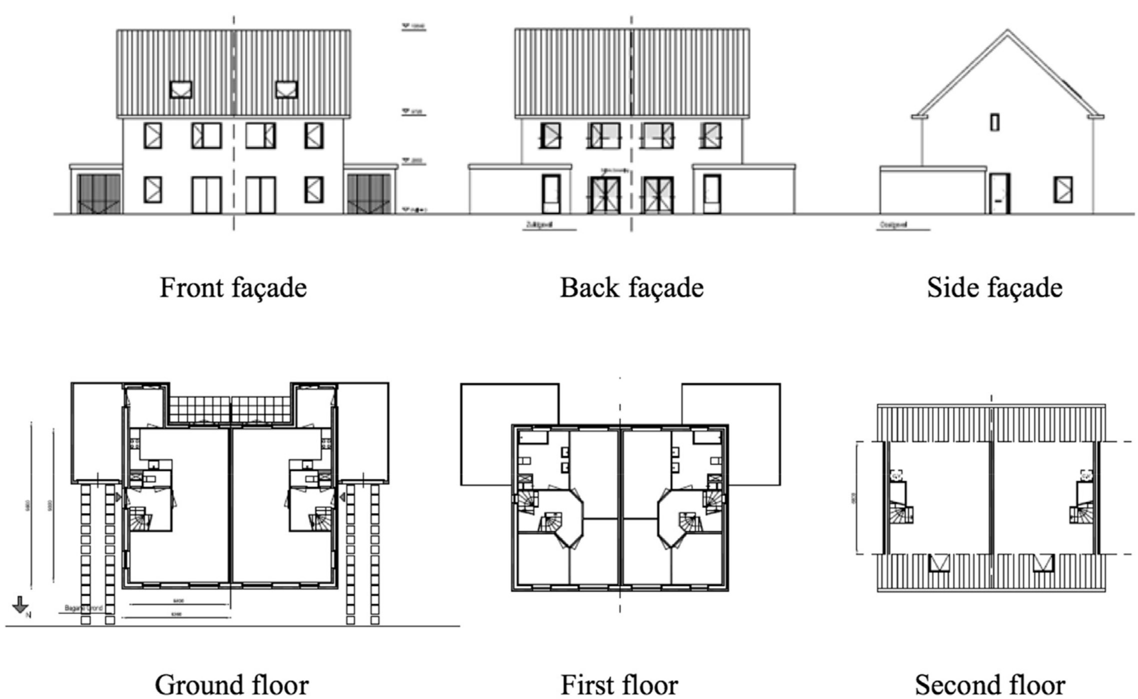
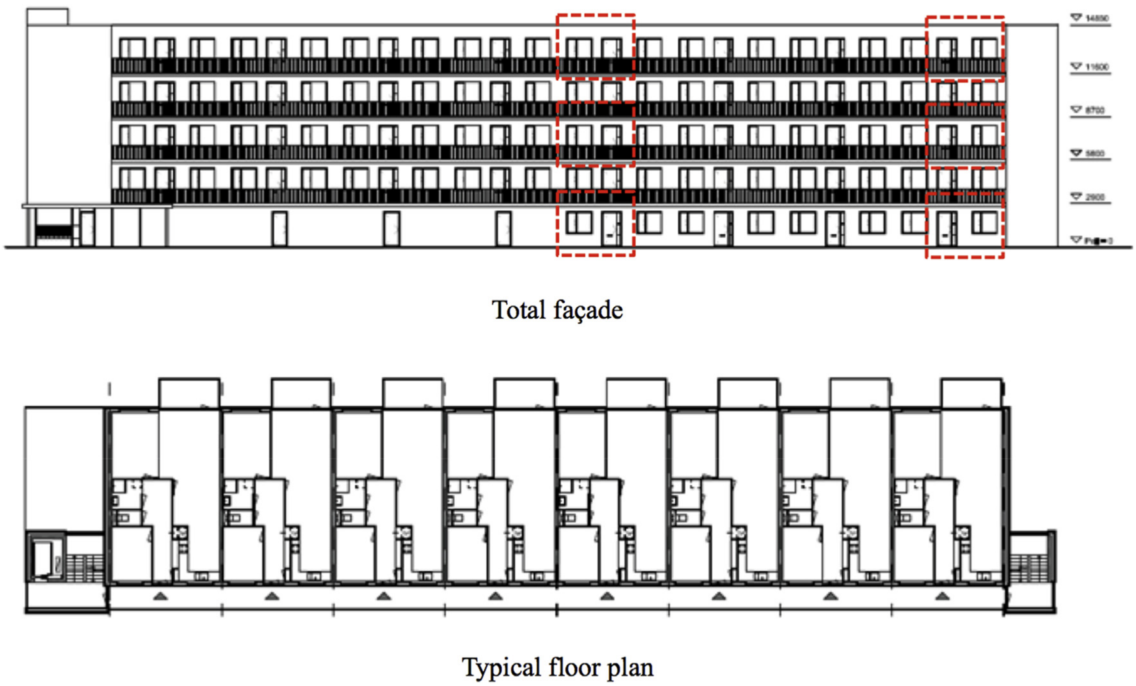
Appendix I. Building types

Geometry of the detached house. Source: Ref. [52].



Geometry of the semidetached house. Source: Ref. [52].



Geometry of the apartment block. Source: Ref. [52].

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