

Ranking of dwelling types in terms of overheating risk and sensitivity to climate change

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RANKING OF DWELLING TYPES IN TERMS OF OVERHEATING RISK AND SENSITIVITY TO CLIMATE CHANGE

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ABSTRACT

Overheating in buildings is expected to increase as global warming continues. This could lead to heat-related problems ranging from thermal-discomfort and productivity-reduction to illness as well as death. From the indoor-overheating point of view, the sensitivity of 9,216 Dutch dwelling-cases to the climate change is quantified and ranked using detailed simulation and post-processing calculations. The results show that the sensitivity depends significantly on the dwelling's design/operation characteristics. Minimally-ventilated dwellings are the most sensitive ones. According to the ventilation rate, shading type, insulation level, and other building characteristics, the sensitivity of dwellings could range from 0.15 to 1.2 indoor-overheating degree /ambient-warming degree.

INTRODUCTION

Only about a decade ago, global warming was just a hypothesis. However, now it is being recognized as leading to climate change and extreme weather. In recent years, climate observations (e.g., warmer summers, colder winters and frequent extreme weather events) indicate that the effects of climate change events are apparently having an increasing impact on society (Vardoulakis and Heaviside 2012; Yau and Hasbi 2013) as became apparent during the 2003 heat wave across Europe. Over 35,000 people across Europe died from heat-related causes in the sweltering summer of 2003 (Brücker 2005), the hottest in at least 500 years (Luterbacher et al. 2004). In the UK, temperatures as high as 38°C were reported which caused heat related illnesses all over the country. The UK Department of Health predicted that a 9-day heat wave averaging 27 °C in South East England may lead to over three thousand immediate heat-related deaths (Kovats 2008). In the Netherlands, between 1400 and 2200 heat-related deaths occurred in the summer of 2003 with a maximum temperature of 35°C (Garssen, Harmsen, and Beer 2005). The 2003 heat wave was as long as fourteen days (from 31 July to 13 August), including seven tropical days, and it was preceded by four tropical days in mid-July.

Although there is only limited and indirect epidemiological evidence concerning the conditions of indoor temperature exposure that give rise to adverse health effects (AECOM 2012), 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 modify the external environment (Coley and Kershaw 2010).

High indoor temperature impairs the ability to recover from outdoor heat stress (Kovats and Hajat 2008) and increased sleep fragmentation because of high temperatures has been directly linked to poor health (Buysee et al. 2010). Heat-related mortality was most pronounced among the elderly in nursing homes (J. Garssen, Harmsen, and Beer 2005). In the Netherlands, the observed number of elderly deaths in August 2003 among persons aged 40-59 years was 11% higher than the expected number calculated on the basis of data for the period 1995-2002 as shown by Figure 1.

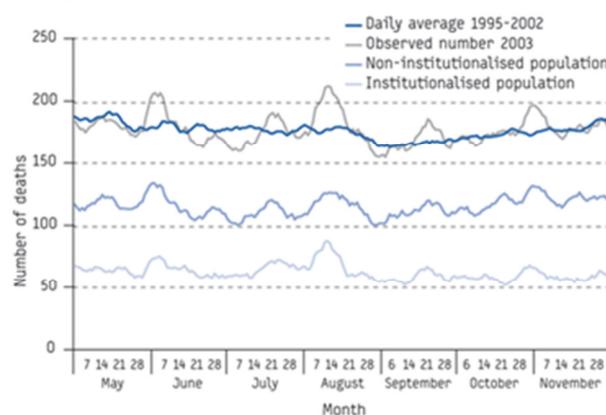


Figure 1 Observed and expected number of deaths in patients aged 80 years or more, in the Netherlands (J Garssen, Harmsen, and Beer 2005)

The aim of this study is to rank the Dutch dwelling stock according to its overheating-risk and sensitivity to the climate change considering the diversity in dwelling archetypes, orientations, fabric characteristics, shading options, ventilation rates, internal heat gains, and adaptation opportunities. The paper aims at assessing the overheating risk in

dwellings. Adaptation interventions as well as policy decisions should be taken quickly if the dwelling's indoor comfort is sensitive to the climate change.

METHODOLOGY

The overheating risk in thousands dwelling cases is quantified under four climate scenarios to investigate the dwellings' sensitivity to the climate change.

Besides, the traditional indoor overheating indices (like maximum temperature and number of indoor overheating hours *IOHs*), a new index called indoor overheating degree (*IOD*), is defined to assess the overheating risk. The new index considers not only the intensity and frequency of the indoor overheating conditions but also the differences of thermal comfort criteria for different zones of the dwelling (e.g., living spaces and bedrooms) taking into account the particular occupant behaviour and adaptation opportunity in each zone identified.

The sensitivity of the overheating risk to the climate change is quantified directly by an escalation factor (a_{IOD} , Equation 1) representing the regression slope between the indoor-overheating degree (*IOD*, Equation 2) and the ambient-warmness degree (*AWD*, Equation 3)

$$a_{IOD} = \frac{\Delta IOD}{\Delta AWD} \quad \text{Equation 1}$$

The calculations are made for the expected annual Dutch warm period from 1st May to 30th September using a detailed building performance simulation program IDA-ICE 4.6 (EQUA 2013) assisted by a post-processing calculation model built by the author using MATLAB 2013b. The calculation model is designed to analyse the hourly energy and indoor performance for thousands of dwelling cases which makes it a powerful tool for future research. In this work the sensitivity to the climate change is assessed only from the indoor overheating point of view.

Indoor Overheating Degree (*IOD*)

The *IOD* is defined to quantify the overheating risk taking into consideration both the intensity/amplitude and frequency of the indoor overheating conditions. The intensity is quantified by the temperature difference (ΔT) between the free-running indoor temperature (T_{fr}) and the thermal comfort temperature limit (TL_{comf}). The frequency is calculated by integrating the amplitudes of overheating during the occupied period (*occ.t*) at the different dwelling rooms/zones (*no.Z*) to present the overall overheating in the dwelling

$$IOD = \frac{\sum_{z=1}^{no.Z} \sum_{t=1}^{occ.t(z)} (\max\{\Delta T(z,t), 0\} \times \Delta t)}{\sum_{z=1}^{no.Z} \sum_{t=1}^{occ.t(z)} \Delta t} \quad \text{Equation 2}$$

where

$$\Delta T(z,t) = T_{fr}(z,t) - TL_{comf}(z,t)$$

t: time step (hour), *z*: zone (room), *occ.t*: occupied time. TL_{comf} : comfort temperature limit and T_{fr} is the free running temperature at time step (*t*).

The free-running temperature represents the indoor temperature of the zone when no heating or cooling is used and is the result of heat gains (solar, internal, occupancy) and air infiltration (minimal air-changes per hour) (University of La Rochelle 2009). The free running indoor operative temperature is calculated by using a detailed building performance simulation program (IDA-ICE 4.6) developed by IQUA Group specially for indoor climate analyses (Kalamees 2004; EQUA 2013). The tool considers radiative, conductive and convective heat exchange between building elements and the internal and external environment, as well as dynamic representations of occupancy densities, solar gains, air densities, and air flow. The dwelling cases are subdivided into a number of thermal zones related to their archetypes. This to consider that fact that different room within the building have different relationships with the outside climate and other building zones, resulting in different overheating risks. Care should be taken when subdividing the building into thermal zones when studying the impact of climate change on overheating risk because different zoning strategies may significantly affect the predicted thermal discomfort (Wilde and Tian 2010).

Ambient warmness degree (*AWD*)

Similar to the *IOD*, a new indicator is defined to quantify the warmness of a given climate scenario considering both the amplitude and timespan of outdoor warmness conditions. The new indicator called ambient warmness degree (*AWD*)

$$AWD = \left(\frac{\sum_{i=1}^N (T_a - T_b)_i \Delta t}{\sum_i \Delta t} \right) \quad \text{Equation 3}$$

where T_a is ambient temperature, T_b is base temperature (18 °C) and N is the number of hours provided that $T_o \geq T_b$ in the summer season. Δt is the time step (one hour).

CASE STUDY

Studied dwelling cases (Dutch dwelling stock)

The studied dwelling cases present 9,216 possible combinations of building design and operation parameters (

Table 1) consistent with the characteristics of the Dutch dwelling stock from 1964 to 2013. The geometries of the dwelling typologies (Figure 2, Figure 3, and Figure 4) are according to (RVO

2013). The minimum ventilation rate and the standard internal heat gain values are consistent with the Dutch building regulations (ISSO 2010). Detailed schedules are used to present the occupants' use of artificial lighting and appliances also in line with (ISSO 2010). The maximum ventilation rate is assumed to vary according to the ventilative-cooling potential. The maximum ventilation is emulated by proposing a virtual VAV system in the simulation model. The 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. In the simulation model, shading control is assumed to apply shading when the schedule is 'on' and the incident radiation exceeds 100 W/m² on the inside of the glass.

Table 1 Investigated parameters of the 9216 dwelling design and operation cases

Parameters	No. options	description
Design parameters	Archetype	8 detached house, semi-detached house, as well as six flat typologies (corner/middle x ground/middle/top floor)
	Fabric characteristics (e.g., U-value, WWR, etc.) according to dwelling construction age	6 According to six construction period (before 1964, 1965-1974, 1975-1991, 1992-2005, 2005-2012, post 2013) representing the Dutch building stock
	Orientation	4 South/North or West/ East
	Shading option	3 No shading, internal shading or external shading with control.
Operation Parameters	adaptation opportunity	2 Fixed and adaptive temperature limits are assumed if "there is no" and if "there is yes" adaptation opportunity, respectively.
	Ventilation Rate	2 Minimum (0.9 l/sm ²) or maximum (5 and 8 ACH variant acc. to natural cooling potential for bedrooms and living room respectively)
	Internal heat gain from lighting and appliances	2 Standard or a bit higher, about 4.3 or 5 W/m ² for houses and about 5 or 5.3 W/m ² for flat apartments considering realistic occupant behavior patterns according to ISSO32, 2010i.
	Occupancy profile	2 Attendant at home during working hours? (Yes or NO)
Number of parameters combinations	9,216	dwelling designs & operations



Figure 2 Geometry of the detached house (RVO 2013)

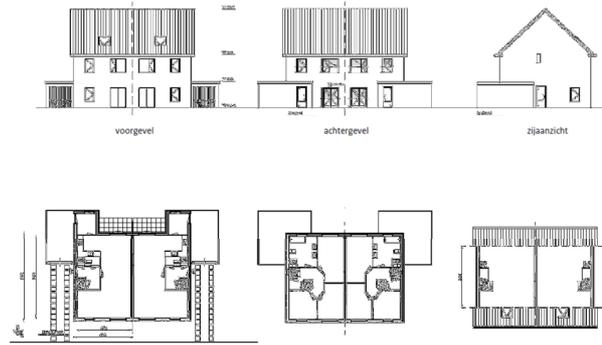


Figure 3 Geometry of the semi-detached house (RVO 2013)

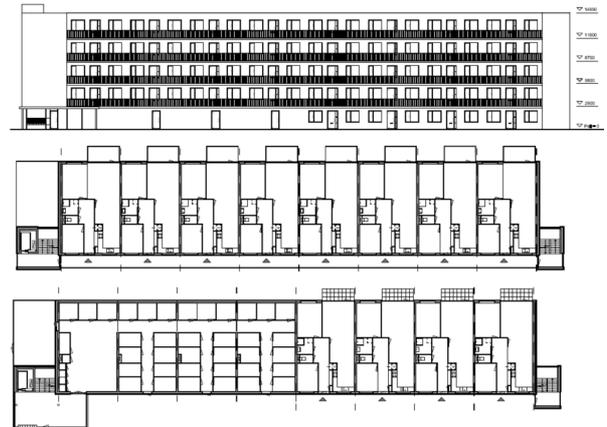


Figure 4 Geometry of the flat apartments (RVO 2013)

Climate scenarios

The overheating risks in the predefined 9,216 dwelling cases are assessed under four climate scenarios (Table 2) resulting in 36,864 (9,216 x 4) studied cases. The climate scenarios are selected to represent historical and future outdoor conditions according to historical measurements and global-warming projections made by the Dutch metrological institute (KNMI 2006). The climate scenarios include moderate climate (De Bilt 1964/1965) considering the average summer of the Netherlands, extreme weather (De Bilt 2003) considering the 2003 long-term heatwave, warm climate (De Bilt 2100 GH) assuming the 2100, 2 °C degree, global warming scenario (GH, Figure 5), and hot climate (De Bilt 2100 WH *) assuming the 2100, 4 °C degree, global warming scenario (WH, Figure 5) as well as 1.4°C temperature rise due to the urban heat island effect (*) in accordance with (Heijden, Blocken, and Hensen 2013).

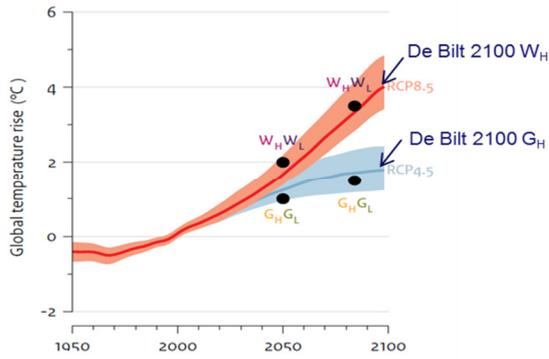


Figure 5 Climate scenarios (G and W) in accordance to the KNMI projections (KNMI 2006).

Table 2 shows the mean ambient temperature, the cooling degree days (CDD) as well as the ambient warmth degree (AWD, Equation 3) of the aforementioned climates. In addition, the direct and diffuse radiation is presented. The radiation is assumed based on three historical years (1964, 2003, 1976) as well as one typical metrological year (NEN5060-5% data set) for the four climate scenarios, respectively. According to (KNMI 2006) no significant change in solar radiation will happen in future. It is assumed that the cloud coverage, the most important factor on the global solar radiation remains unchanged. The Netherlands is situated in the transition area between Northern Europe, where the cloud coverage increases, and Southern Europe, where the cloud coverage decreases (Plokker et al. 2009).

Table 2 The investigated climate scenarios

Climates		Warmness indicators			Radiation	
		T _m °C	CDD 18°C	AWD 18°C	Direct W/m ²	Diffuse W/m ²
Historic	DeBilt 1964/1965	14.9	0.0	0.6	125.7	105.9
	DeBilt 2003	16.6	10.7	1.5	153.0	106.1
Future	DeBilt 2100 G _H	19.4	30.0	3.0	162.7	101.3
	DeBilt 2100W _H *	23.7	101.4	6.0	158.6	101.1

Overheating criteria

Fixed and adaptive comfort temperature limits (TL_{comf}) are used to assess the overheating risk in terms of the number of indoor overheating hours (IOHs) and the degree of the indoor overheating (IOD, Equation 2). Different thermal comfort criterion is used for different zones of the dwelling (e.g., living spaces and bedrooms) taking into account the particular occupant behaviour and adaptation opportunity in each zone identified.

Fixed Temperature Limits (FTL):

According to CIBSE Guide A (CIBSE 2007), 25 °C is an acceptable operative temperature (OT) in the living area of dwellings and 23 °C is acceptable for bedrooms. For an overheating threshold, 25 °C for 10% of the year is defined by the Passive House Institute (PHI) (Feist et al. 2012). The CIBSE Guide A defines 'overheating' as occurring when the OT exceeds 28 °C for more than 1% of the annual occupied hours in the living areas of (free running) dwellings or when the bedroom OT exceeds 26 °C for more than 1% of the annual occupied hours (unless ceiling fans are available). Both the CIBSE Guide A, as well as ASHRAE Standard 55-2004 indicate that higher bedroom temperatures can be accepted if a fan is used with ASHRAE indicating an acceptable increase of up to 3 °C. The fan case is considered in the adaptive temperature limits.

Temperature limits (ATL):

Air temperature alone is not the only factor that defines the thermal environment for human health and well-being. Radiant temperature, humidity, and air movement are also important, as well as the level of physical activity (metabolic rate) of the individual and the thermal characteristics of his/her clothing. Considering the above factors, a new hybrid thermal comfort guideline (Boerstra and van Hoof 2015) has been developed for the Netherlands. The developed adaptive temperature limits (ATLs, Figure 6) is used for the evaluation of the thermal environment in naturally ventilated environments, in which occupants have access to operable windows and are relatively free to adjust clothing insulation. The ATLs are acceptable for use in rooms with office like activities (e.g., living rooms). However, it was found that applying the ATLs without maximum thresholds could lead to unacceptable 'very high' limits (>31 °C), if the running mean outdoor temperature (Θ_{rm}) exceeded 25°C. The worst future climate scenario for the Netherlands (G+) shows that by 2100, the Θ_{rm} would exceed the maximum identified above (25 °C), up to 43% of the summer time. In order to avoid such unacceptable 'very high' ATLs when future climate scenarios are tested, 30°C and 31°C are taken as maximum thresholds for the thermal comfort classes B (10% complainant) and C (15% complainant), respectively. Rooms with office like activities (e.g., living rooms in houses) can have acceptable indoor temperatures of up to 30 °C for a 90% acceptability level and almost 31°C for an 80% level (van Hoof and Hensen 2007). The Dutch thermal comfort class D (25% complainant) is not used in this study because it is assumed to be unacceptable for use in the analysis of homes. Oseland (Oseland 1995) demonstrated experimentally that people feel warmer in their home than they do in their office at the same temperatures. The presence of furnishings (i.e. carpet, wall paper and furniture) was mentioned as a possible reason since people tend to judge rooms with such features as being warmer.

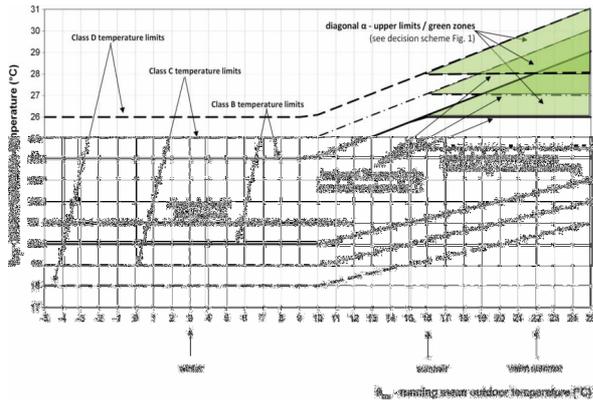


Figure 6 ISSO 74: 2014 requirements for the indoor operative temperature in relation to the running mean outdoor temperature for Classes A, B, C and D and additional set-point temperatures. (Boerstra and van Hoof 2015).

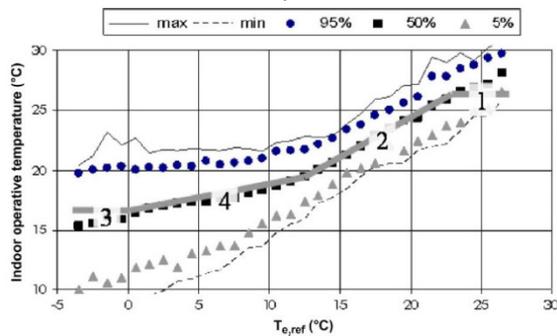


Figure 7 Daily average bedroom temperature in Belgium as function of $T_{e,ref}$; minimum, maximum, 95, 50, 5 percentiles (Peeters et al. 2009)

Fixed and adaptive temperature limits:

Figure 8 shows the fixed and adaptive temperature limits which are used in this study. The temperature limits are shown as functions of the running mean outdoor temperature (Θ_{rm}). The annual hours are divided by percentage according to the AWD (Equation 3) as well as the Dutch summer thresholds. Three thresholds ($\Theta_{rm} = 16, 22,$ and $25\text{ }^{\circ}\text{C}$) are defined in (Boerstra and van Hoof 2015) describing the summer levels in the Netherlands. The figure shows that 20% and 44% of the annual hours of the hot climate (De-Bilt 2100 WH*) are classified as warm and hot summer, respectively.

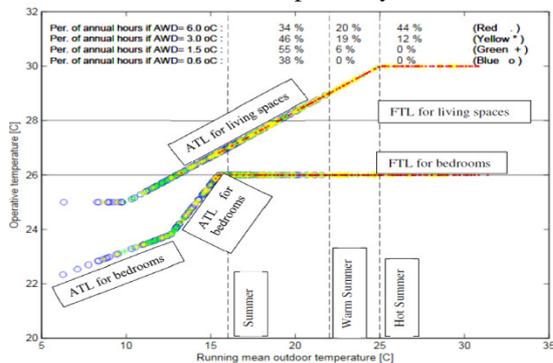


Figure 8 The fixed and adaptive temperature limits have been used in this study.

RESULTS AND DISCUSSION

Overheating assessment

The results show that due 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 ambient temperature (T_a). On average the T_{fr} is $6\text{ }^{\circ}\text{C}$ higher than the T_a during the predefined calculation period (from 31 July to 13 August). During the predefined period, on average the mean of differences between the indoor and outdoor dry bulb temperatures ($DBT_{in}-DBT_{out} > 0$) will slightly decrease as global warming increases particularly for low-insulated maximally-ventilated dwellings Figure 9. The results also show that the Dutch dwellings with minimum ventilation rate (0.9 l/sm^2) are already vulnerable to overheating and that this is likely to get worse as global warming (i.e., AWD) continues Figure 10.

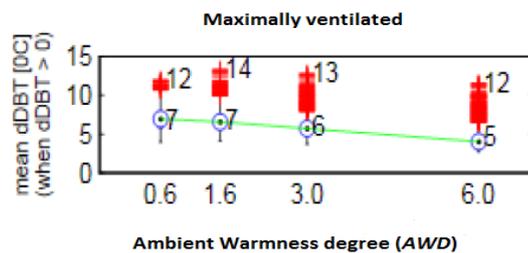
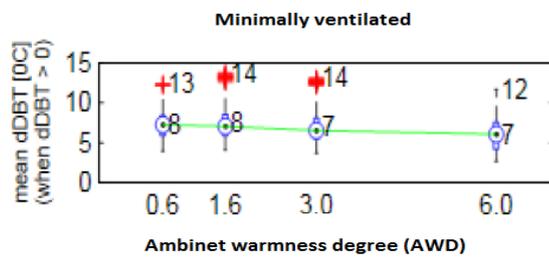


Figure 9 Mean temperature differences between indoor and outdoor temperature at the four investigated climate scenarios (Table 2)

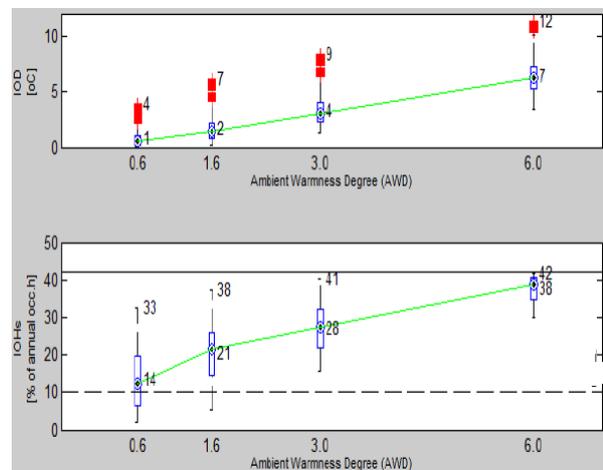


Figure 10 IOB and IOHS in minimally-ventilated dwellings versus the AWD of the four studied climates. where the predefined FTL is applied.

The ventilative-cooling can be more beneficial in the future when there is much more overheating to be eliminated. However, the it will not be able to fully eliminate the ever-increasing risk of overheating if the climate becomes 1°C warmer than the current conditions (i.e., AWD = 1°C). As a percentage of the overheating risk in dwellings with minimum ventilation rate (0.9 l/s-m², approximately 1.5 ACH), the potential of ventilative-cooling will decrease as global warming increases, Figure 11. In the current climate, the ventilation rate (on average 5 ACH) could reduce the indoor overheating by 89% 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 63% on average and 80% as a maximum when the ambient temperature is up to 5.4 °C higher than the current (AWD = 6 °C), Figure 11.

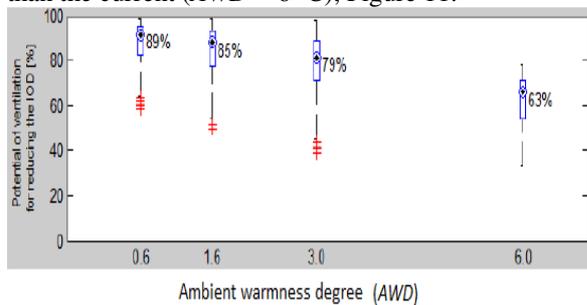


Figure 11 Potential of ventilative-cooling for reducing the overheating risk as a percentage of the IOD in dwellings with minimum ventilation rate (Figure 10).

For current and future climate scenarios (De Bilt 1964/1965 De-Bilt 2100 WH*), the ranges of indoor overheating degree (IOD) are classified according to the archetype and construction year of studied dwellings, Figure 12. 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 solar shading being the main causes of this difference. The archetype has a significant influence on the overheating degree in dwellings with minimum ventilation rate. However, it has insignificant influence on the well-ventilated dwellings. Flats in middle-floor middle-location of apartment buildings, flats in top-floor middle-location of apartment buildings as well as detached houses are the dwelling archetypes most sensitive to global warming, Figure 12. They are at a higher overheating risk than other archetypes (e.g., semidetached houses, and flats in ground floors) in the current climate (De Bilt 1964/1965) and they will continue to be at a higher risk in the future. 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. Such new buildings are already at a significant risk (up to IOD = 2°C) of overheating in the current climate, Figure 12.

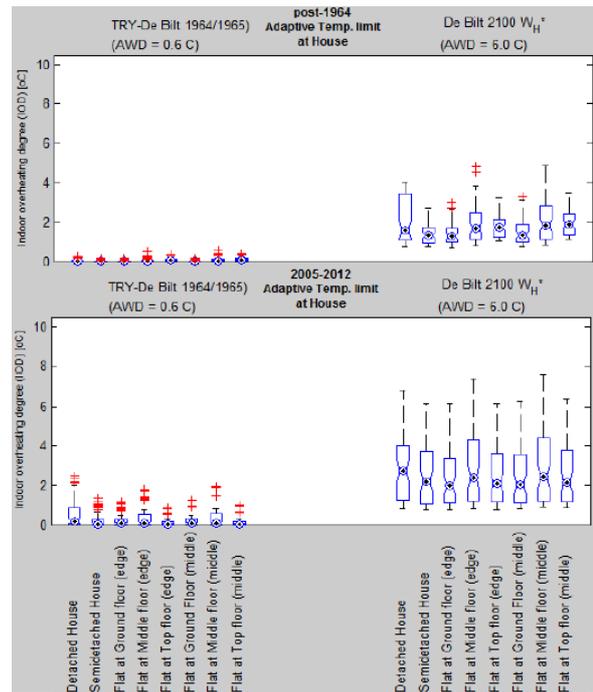


Figure 12 IOD in the eight dwelling types considering two construction period (post-1964 and 2005-2012) applying adaptive temperature limits (ATL).

Sensitivity assessment

The sensitivity of the Dutch dwelling cases to climate change is quantified by using the escalation factor a_{IOD} showing the increase of the indoor overheating degree (IOD) corresponding to an increase in the ambient warming degree (AWD), see Equation 1. Figure 13 gives examples of the linear relations between the IOD and the AWD presenting the maximum and minimum regression slopes according to the ventilation and shading options which are the most influential ones on the overheating degree. Figure 14 Figure 15 show the maximum, mean, standard deviation, and minimum of the escalation factor (a_{IOD}) according to the design and operation parameter options (Table 2).

The figures show that the escalation factor (a_{IOD}) is less than unity for 97% of the studied dwelling cases. This indicates that most of the dwellings can suppress the effects of global warming. The escalation factor ranges from 0.1 to 1.2 depending on the aforementioned building design and operation parameters as well as the overheating criteria. More strict overheating criteria have higher values of escalation. The escalation factor was lower than unity for all dwelling cases when adaptive temperature limits (ATLs) are used as the comfort criteria instead of fixed temperature limits (FTLs). Dwellings with higher solar heat gains (e.g., detached houses with a large unshaded glazing area) and/or with lower heat transmission (e.g., flats with a small well-insulated

façade area in middle of 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. Semi-detached houses and ground-corner flats are at lower risk of overheating than other archetypes. Dwellings which show lower overheating risk than others in the current climate will continue to do so for future climates. This rule is valid as long as there is no significant change in solar radiation.

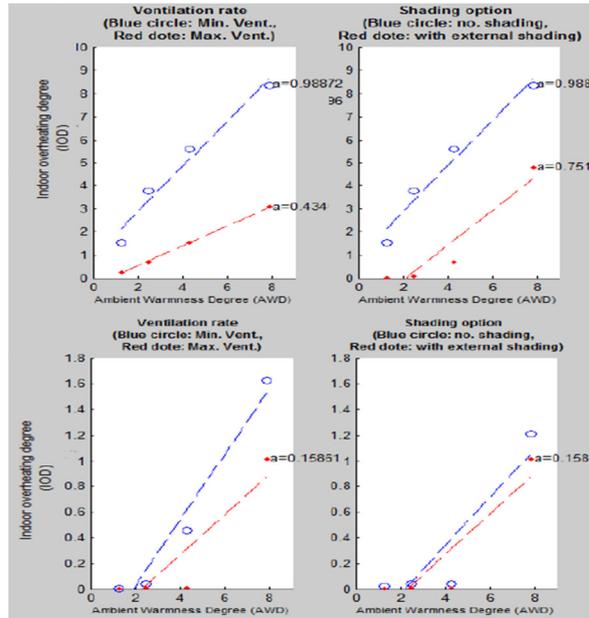


Figure 13 example of the regression slopes between the IOD and the AWD classified according to ventilation and shading options. The upper and lower figures present the maximum and minimum slopes, respectively.

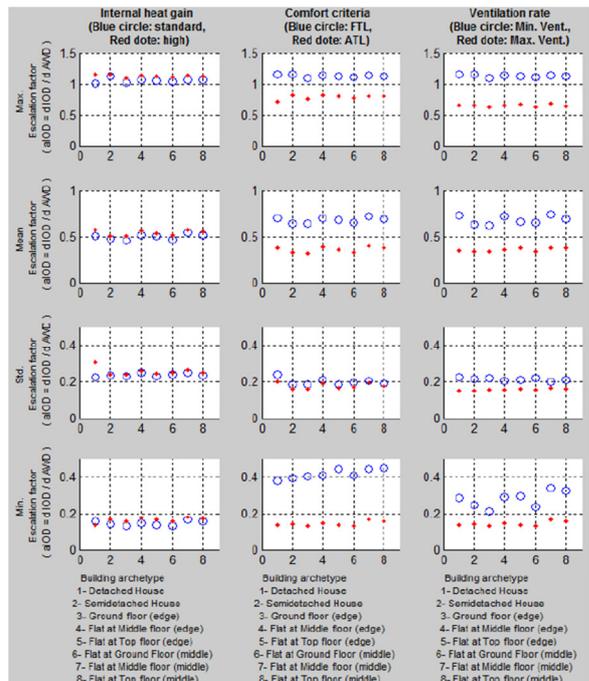


Figure 14 the maximum, mean, standard deviation, and minimum of escalation factor (a_{IOD}) classified according to internal gain, comfort criteria and ventilation rate.

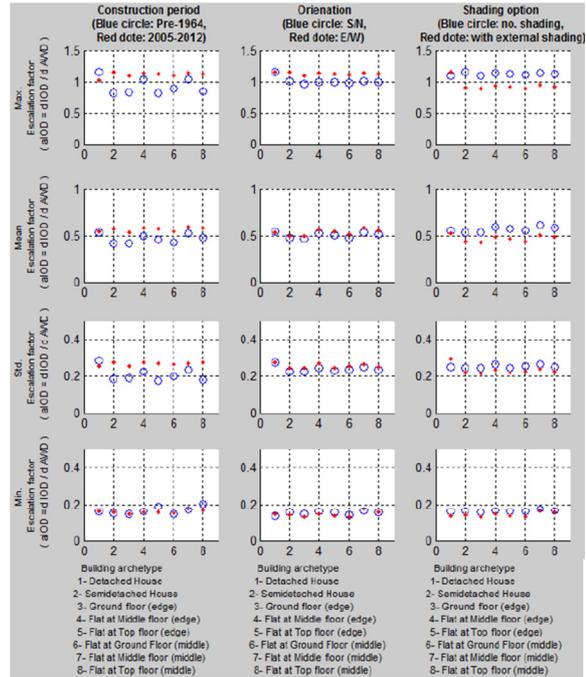


Figure 15 the maximum, mean, standard deviation, and minimum of escalation factor (a_{IOD}) classified according to construction year, orientation, and shading option.

CONCLUSION

The sensitivity of different dwelling types to the climate change is investigated comprehensively in line with the Dutch context. The overheating risk in 9,216 dwelling cases, consistent with the characteristics of the Dutch dwelling stock from 1964 to 2012, is quantified for four climates based on historical and future-scenario data sets obtained from the Dutch metrological institute (KNMI). New performance indicator (*IOD*: Indoor Overheating Degree) is introduced to consider not only the intensity and frequency of the indoor overheating conditions but also the differences of thermal comfort criteria for different zones of the dwelling (e.g., living spaces and bedrooms) taking into account the particular occupant behaviour and adaptation opportunity in each zone identified.

The results show that the *IOD* will increase as the ambient warmness degree (*AWD*) increases. However, the results show that the escalation factor ($a_{IOD} = IOD / AWD$) is less than unity for 97% of the studied dwelling cases. This indicates that most of the dwellings can suppress the effects of global warming. The escalation factor (a_{IOD}) ranges from 0.15 to 1.2 depending on the dwelling design/operation characteristics as well as the overheating criteria. More strict overheating criteria have higher values of escalation. The escalation factor was lower than unity for all dwelling cases when adaptive temperature limits (ATLs) are used as comfort criteria instead of fixed temperature limits (FTLs). Dwellings which show lower overheating risk than others in the current climate will continue to

do so for future climates. This rule is valid as long as there is no significant change in solar radiation.

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