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Summer comfort in residential buildings and small offices, using sustainable cooling systems

Margot De Pauw [a], *Jeroen* Van der Veken [b]

[a] Thomas More Kempen, Kenniscentrum Energie, Geel, Belgium; margot.depauw@thomasmore.be

[b]. Belgian Building Research Institute, HVAC laboratory, Limelette, Belgium; jvdv@bbri.be

Abstract Summer comfort gains attention due to climate change and increasing frequency of heat waves, also in small office buildings and even in residential dwellings. Active cooling systems, using an electric compressor and standard refrigerants, are widely used because of the high cooling power and comfort level they can guarantee. However, given the energy use and refrigerants inherent to those cooling systems, other more sustainable cooling systems should be considered in the first place. To accelerate the acceptance of sustainable cooling systems such as evaporative cooling or free geothermal cooling combined with high temperature emitters, and to ensure a large scale rollout of those systems, a more profound insight is needed into their performance and the provided level of comfort.

In the framework of the CORNET project SCoolS the performance of different sustainable cooling systems is evaluated for a set of residential buildings and small offices by means of TRNSYS simulations. To do so, a new future climate file for Belgium has been constructed and comfort classes were defined. A parameter study varying insulation, thermal capacity, window percentage and orientation of the building was performed. Furthermore, the impact of adding passive cooling strategies like solar shading and intensive ventilation by window opening were analyzed. The SCoolS project resulted in a decision support tool for sustainable cooling systems. This article presents the preconditions and results with focus on the non-residential cases. Results show that in office buildings the necessary cooling loads are higher than in dwellings due to more concentrated heat gains during the day and often also more solar gains due to larger window surfaces. However, also in office buildings a combination of passive cooling strategies and sustainable cooling systems (coupled to floor or ceiling cooling) proves to be able to deliver excellent summer comfort.

Keywords. Summer comfort, climatic data, sustainable cooling systems, high temperature cooling, office HVAC
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1. Introduction

1.1 Sustainable cooling systems

Due to climate change and increasing frequency of heat waves, cooling in residential buildings gains importance. The most common way of cooling in buildings is active cooling with the use of 'split units' or central air-conditioning systems, using an electric compressor and standard refrigerants. However, these systems have a relative high energy consumption, and the European parliament has called a phasedown for many of the existing refrigerants. Sustainable cooling systems with higher performance and less or no refrigerants can therefore be a superior alternative for conventional systems. These systems are however not often applied due to a lack of real performance data and guidelines for the correct selection and dimensioning. This problem was addressed in the CORNET project SCoolS, where an accessible decision support tool for cooling systems was developed. A screenshot of the main output of the tool is shown in Fig. 1. The tool is aimed to be user friendly and gives insight in the different options and applicability of sustainable cooling systems. After the selection of a limited number of descriptive input building parameters, the main graph gives an indication of the energy consumption (height of the bars) and an assessment of the comfort level (color of the bars) for different cooling systems. Another graph (not on the figure) gives the specific cooling load for each room.

The considered sustainable cooling systems are evaporative cooling systems as well as systems with free geo-cooling coupled to different high temperature emitters such as floor or ceiling cooling or large water-air heat exchangers. Compared to classical low temperature air cooling systems (with the possibility of latent cooling), they typically cause a risk of condensation problems. The high temperatures with, in addition, the control strategies that are necessary to avoid condensation, result in limited emission capacity. The results for a classical air cooling system are added to the tool as a reference.

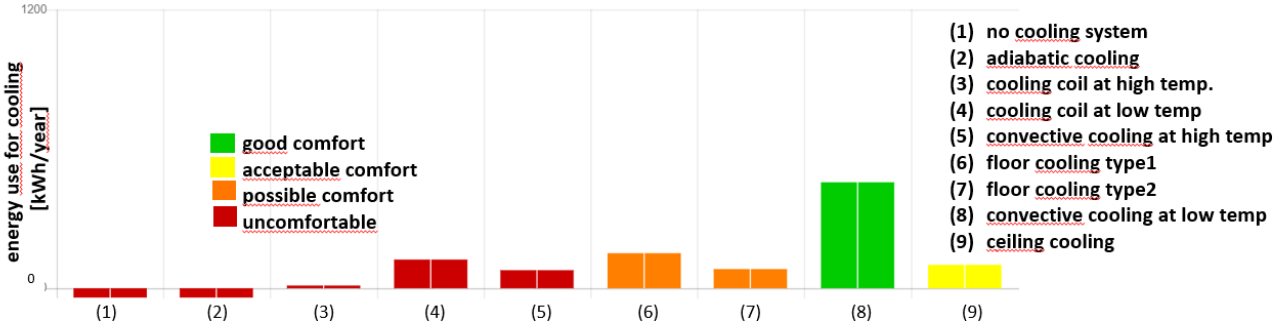

Fig. 1 – Decision support tool for sustainable cooling systems: screenshot of main output graph.

1.2 State-of-the-art

The assessment of summer comfort against future climate scenario's has gained extensive international attention. In the framework of Annex80 focus is on climate resilience of buildings. Resilience, as defined in [2], is assessed against different criteria like vulnerability, resistance, robustness and recoverability, including specifically a vulnerability assessment that considers future climate scenarios (using average, extreme, future and worst future weather conditions and short-term disruptions including brief heat waves). In [3] the importance of using future heatwaves in building thermal simulations is pointed out and a methodology is proposed to re-assemble future weather files using data from EURO-CORDEX. In the meantime weather files are constructed for Belgium according to this methodology, but unfortunately this work was not finished at the start of the simulations. An overview of available future weather data for Belgium was made in [4]. [5] presents the decrease/increase of future heating and cooling degree days for Belgium, again showing the importance of the weather files that are used for dynamic simulations.

The determination of thermal comfort is set by several different standards, but only few of them are appropriate when evaluating sustainable cooling in residential buildings under extreme weather conditions. The PMV model (EN ISO 7730) for instance was intended for application by the HVAC industry in the creation of artificial climates in controlled spaces (Fanger PO [6]).
In free running buildings where occupants have free access to operable windows and where they are relatively free to adjust their clothing, two approaches can be found to determine relevant thermal comfort limits. The first one is a fixed temperature limit, amongst others described in CIBSE Guide A [7]. This standard establishes a fixed maximum temperature for bedrooms (<26°C) and other living quarters (<28°C).
The second method is an adaptive temperature limit that relates the indoor comfort temperature to outdoor conditions. It was found by de Dear *et al.* [8] that higher indoor temperatures are acceptable in free running buildings because of a person's thermal adaptability, which is related to the outdoor temperature of that particular day and of preceding days. This is the fundament of the adaptive comfort requirements as described in EN 16798-1 (2019), ASHRAE standard 55, EN 15251 Annex A2 or CIBSE TM 51.

Chen [9] also points out that there is a risk in using the comfort assessment as defined in CIBSE TM52 and TM59 with respect to the uncertainty surrounding the used climate file: both TM52 and TM59 require the use of local Design Summer Year (DSY) weather files, defined as the year with the third highest average dry-bulb temperature within a period of 20 years. However, existing files are soon outdated with recent record-breaking summers. Moreover, this selection process based on average temperatures may exclude crucial heat waves and it could underestimate the overheating risks.

For this particular study the assessment of thermal comfort in contemporary buildings in the (near) future is therefore mainly based on the recent 'Themablad Thermisch Comfort' [10]. This method is specifically targeted towards residential buildings and future summer comfort. It contains a list of the most important boundary conditions and it demonstrates how '2018T1' can be used for the creation of a relevant climate file by collecting all the hottest months of the last 20 years.

2. Research Method

2.1 Simulation-based

The decision support tool is based on a database with simulation results. For a large set of more than 8000 cases, energy consumption and temperature exceeding hours on an annual basis were calculated using TRNSYS17 simulations, with a room-by-room approach. The model is verified by comparing the simulation results with 2 measured cases within the project and the BESTEST data on the Fraunhofer twin house. The different cases as well as the simulation model with his various preconditions are described in detail in [1] with respect to the residential buildings. A summary of the chosen typologies and varied simulation parameters is given in the text below. For the office rooms, the simulation model and preconditions deviate in a number of respects, for instance concerning hygienic ventilation, internal gains and the control of the passive cooling strategies. These aspects are described in more detail.

A parameter study has been undertaken by simulating 7 different building types (5 typical residential buildings, a small office and a conference room) , variated by insulation level, thermal capacity, window percentage and orientation of the building/room. The main characteristics of the buildings are shown in Table 1.

Tab. 1 – Building characteristics: net volume Vnet, surface area A, cooled floor area Afl, window/floor percentage W

	Vnet [m^3]	A [m^2]	Afl [m^2]	W [%]
row house	393	253	119	18
modern	486	697	169	21/30
semi det house	460	348	137	19/25
2 façade ap	206	58	62	21
3 façade ap	203	88	62	25/30
small office (2 pers)	47	12	18	32
conference room (10 pers)	97	25	38	31

The different building parameter values are described in detail in [1] and summarized Table 2.

Tab. 2 – building parameter values

Building parameter	values
insulation	current/passive standard
thermal mass	high(solid construction)/low (timber frame construction)
window percentage	depends on building type, see Tab. 1
orientation	N/S/E/W

For the assumed building variants, an assessment was made of the performance of different cooling systems and emitters, optionally combined with passive cooling strategies. More precisely, systems with free geo-cooling coupled with floor cooling, ceiling cooling, fan coils or cooling coils (in the ventilation supply air), as well as indirect adiabatic cooling systems are considered and compared with a classic air conditioning system.

Two different types of floor cooling are considered, with different thermal mass and thermal resistance, and with a nominal power of 30 W/m^2 and 20 W/m^2 respectively. Because of the high latent gains in the office rooms and the increasing risk for condensation that this entails, a dewpoint control is added: the supply temperature is not allowed to be lower than the dewpoint temperature of the room air ($Tsupply$ = max (16°C, $Ti\_dewpoint$)). The ceiling cooling has a nominal power of 45 W/m^2 and the same dewpoint control as for the floor cooling.

For the convective cooling devices, we distinguish between 2 systems. The first one can be representative for any active cooling system at low temperature and has a maximum power of 50 W/m^2 for the residential buildings, 100 W/m^2 for the small office room and 150 W/m^2 for the conference room. The second is aimed to represent a system with fan coils working at high temperature (which are assumed to be sized based on the heat demand). For the latter system a dewpoint control is added in the office rooms. As the convective system is modelled in TRNSYS as an ideal cooling system, only characterized by his setpoint and maximum power, it is not possible to adjust the water supply temperature as a function of the dewpoint Ti_dwp. So the dewpoint control consists of an adjustment of the maximum specific power $Pmax$ [W/m^2], according to equation (1):

$$Pmax = \max(0, 15/8 * (Ti - \max(16, Ti\_dwp) - 1)) \quad (1)$$

Three cooling systems operating on the ventilation unit are analyzed: a cooling coil in the supply air working at high or at low temperature and an indirect adiabatic cooling system. In the non-residential cases the extraction air is assumed to be saturated at 100% RH after the evaporation unit (whereas the saturation process was limited to a RH of 70% for the residential cases). This results in a better approach of the efficiency of higher performance evaporative systems that are on the market nowadays.

Concerning the passive strategies, solar shading devices and intensive ventilation or less intensive night cooling by opening of windows can be applied. The occupant behavior with respect to the control of solar shading and window opening is supposed to follow logical rules. For the non-residential cases the operation of solar blinds and the opening of windows is automatic, so no presence is required. The windows are opened if 3 conditions are fulfilled:

- the room temp *T_room* is > 23°C,
- *T_room* -1°C > Te (outside temp)
- *Te* > 16°C, during working hours

Windows are closed if

- or *T_room* < 21°C
- or *T_room* < Te -2°C
- or Te < 14°C, during working hours

Solar shading is operated as follows:

- Screens go down if *T_room* > 23°C and solar radiation > 125W/m^2 on the window
- Screens go up if *T_room* < 20°C or at sundown

Finally, these conditions should be true for 30 min before action is taken.

A demand controlled mechanical ventilation system with a flow rate of 25 m^3/h/pers is assumed. To maximize cooling potential a maximum flow rate is imposed between 4h and 8h in the morning. The ventilation system has a heat exchanger with an efficiency of 75%, which can be bypassed during the cooling period. The air that passes the ventilation unit heats up with 0.5K to take into account the heat gains from the ventilator.

Internal heat gains are imposed based on profiles (and other boundary conditions) developed by Witkamp et al. (2019). They are mainly due to the presence of persons, equipment and lighting during working hours (8h – 17h). For the small office 2 persons are taken into account, the conference room is occupied by 8 people most of the time (lower occupancy at noon and beginning and end of working day). At full occupancy, heat gains for lighting are 5W/m^2 and 200 W and 300W for equipment in respectively the small office and the conference room.

The office rooms are on an intermediate floor, no air or heat exchange with adjacent rooms is assumed.

2.2 assessment of summer comfort and climatic data

For this project, a new climate file has been constructed based on a selection of the most severe heat waves of the recent 10 years (2010-2020) using the official weather station data of Belgium in Uccle. This could seem a bit extreme, but the authors found a good overlap with the very recently constructed 2040-2060 weather files in the framework of Annex80 Task A (IEA 2020).

Based on literature review, a.o. IEA (2018), EN16798 (2019), ISO 7730 (2005), and given the scope of the simulations, the comfort range is expressed in terms of operative temperature (instead of PMV) and based on the individual room temperature (instead of a mean building temperature) and room occupancy. Concerning the temperature limits a difference is made between residential and non-residential cases.

For the non-residential cases the temperature limits depend on the type of building, according to EN 16798-1 (2019). For beta buildings fixed temperature limits are used. The comfort classes are indicated by the horizontal lines in Fig. 2. They correspond to comfort categories 1,2,3 of EN 16798-1 and depend on the fixed temperature limit Tlim that is not exceeded: good (*Tlim* = 26°C), acceptable (*Tlim* = 27°C), possible (*Tlim*=28°C), uncomfortable.

For alfa buildings, adaptive temperature limits are applicable. In Fig. 2 the adaptive temperature limits as a function of the running mean outdoor temperature, are indicated with the dotted sloped lines. They show the upper and lower boundaries of the comfort categories 1,2 and 3. When compared with the fixed limits of the different categories, it appears that the adaptive limits fall below the fixed limits at low outside temperatures. To avoid this, the fixed temperature limits are applied as an upper boundary, resulting in the comfort classes indicated by the green, yellow, orange, red area in Fig. 3.

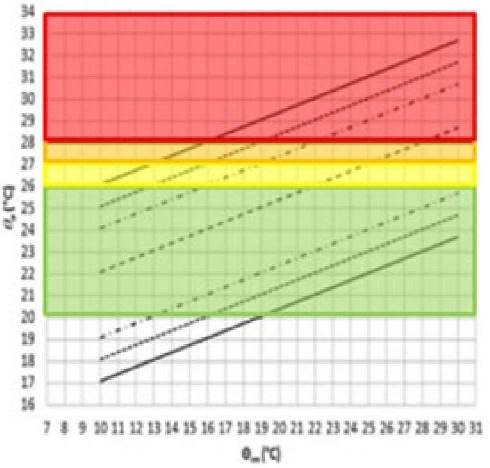

Fig. 2 – Comfort classes for beta buildings.

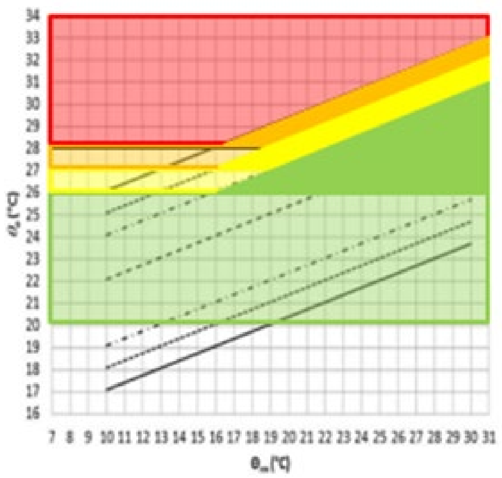

Fig. 3 – Comfort classes for alfa buildings.

One of the criteria to distinguish between alfa and beta buildings according to EN 16798-1 is the perceivability of the cooling system by the occupants. If the cooling system is clearly perceivable, the building is considered as a beta building. This means that different comfort criteria are used for, on the one hand, the cases with active cooling or fan coils and where the cooling system is thus clearly perceived (beta building) and, on the other hand, the cases with sustainable cooling systems in the ventilation unit or with floor and ceiling cooling (alfa building).

It is not certain if these adaptive criteria as described in EN 16798-1 (2019) can be applied straightforward to residential cases: the comfort limits seem very wide, especially during heat waves and compared to comfort methods using fixed limits. However it was found that these last objections are less the case if the the adaptive temperature limits of Van der Linden et al. [11] are applied. Therefore the authors chose to work basically with absolute comfort criteria. The absolute comfort criteria of CIBSE Guide A (2015) are used [7], because they distinguish between bedrooms (<26°C) and other living quarters (<28°C). Then, the following comfort classes were determined based on the exceeding hours: good (<33h), acceptable (<100h), possible (< 250h), uncomfortable. As described in [1] these boundaries implies that the 'good comfort' band corresponds with the absolute comfort boundary for the bedrooms in the CIBSE TM52 and TM59 (1% of the night time). By adding the 'average' and 'possible comfort' bands, only 0.1% of the dwellings that are in comfort band A (following Van der Linden et al. 2006) are declared as 'not comfortable'.

3. Results and discussion

3.1 General results office buildings

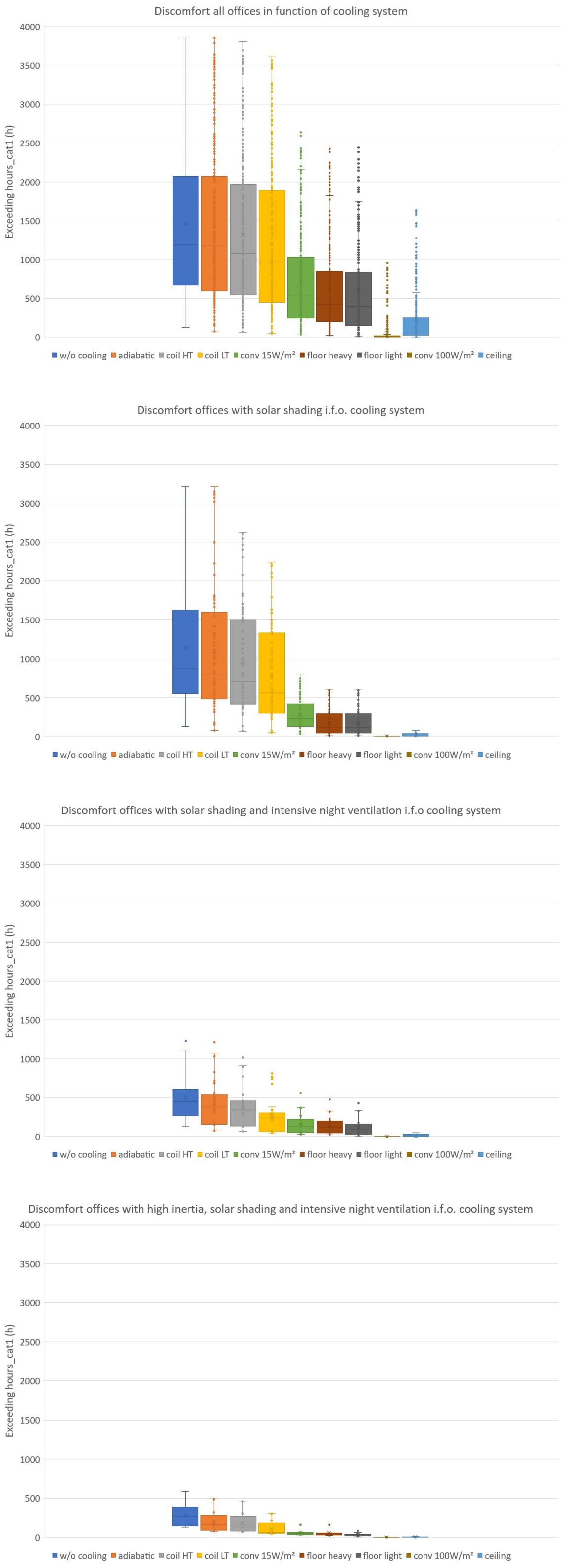

Fig. 3 – Discomfort results (exceeding hours outside comfort category 1) for different office cases in function of the implemented cooling system. The upper graph shows all offices, followed by the offices with solar shading, solar shading and intensive night ventilation, and finally the lower graph for the offices with high inertia, solar shading and intensive night ventilation.

Previous graphs sum up the discomfort scores for all simulated office building variants. The different simulated cooling systems are on the graph from left to right represented with (in general) increasing cooling capacity:

- no cooling system
- adiabatic cooling on ventilation system
- cooling coil at high regime temperatures
- cooling coil at lower regime temperatures
- convective cooling system at HT (15 W/m^2)
- heavy floor cooling (30 W/m^2)
- lightweight floor cooling system (30 W/m^2)
- standard convective cooling (100 W/m^2)
- and finally ceiling cooling (45 W/m^2).

If we compare all the systems, we see that for the office buildings it is generally quite difficult to obtain good comfort results with cooling systems that have lower cooling capacities. Certainly for the offices without any passive cooling strategies (solar shading, ventilative cooling) we need up to 100W/m^2 and more; the convective cooling that can deliver this 100W/m^2 reaches in 77% of all office cases the best comfort band (below 26°C since it is a beta building in these cases) and only in 4% cases temperatures above 28°C are attained. With dropping cooling capacity, the risk at bad thermal comfort increases; 18% for ceiling cooling, already 77% for convective cooling systems at 15W/m^2 and coiling coils and 92% of the offices without cooling system.

However, when applying solar shading the comfort of the offices is greatly improved; 100% of the cases attain the best comfort for the convective systems at 100 W/m^2, but also sustainable systems that are coupled with ceiling cooling can reach this best comfort band in 74% of the cases. Ceiling cooling and floor cooling can make sure that no office buildings with solar shading reaches temperatures outside category 3 (the red zone in Figure 3). For the cooling coils on the ventilation system, this is still the case; more than 50% of the cases have bad comfort risks.

If solar shading is combined with an intensive night cooling schedule, the situation improves further for the systems with lower cooling capacities. Certainly if finally only the buildings with more inertia are taken and coupled with these passive cooling strategies, the comfort can be well maintained; in 100% of these cases the ceiling cooling can maintain in the best comfort band, while this is also in 70% of the floor cooling cases. For floor cooling, but also for the convective cooling systems at high temperatures and 15W/m^2 and the cooling coils at lower regime temperatures 0% of the cases reaches the worst comfort band. Obviously if these passive cooling measures are taken, more and more choice is coming available when selecting a fitting sustainable cooling system.

3.2 comparison between residential and office buildings

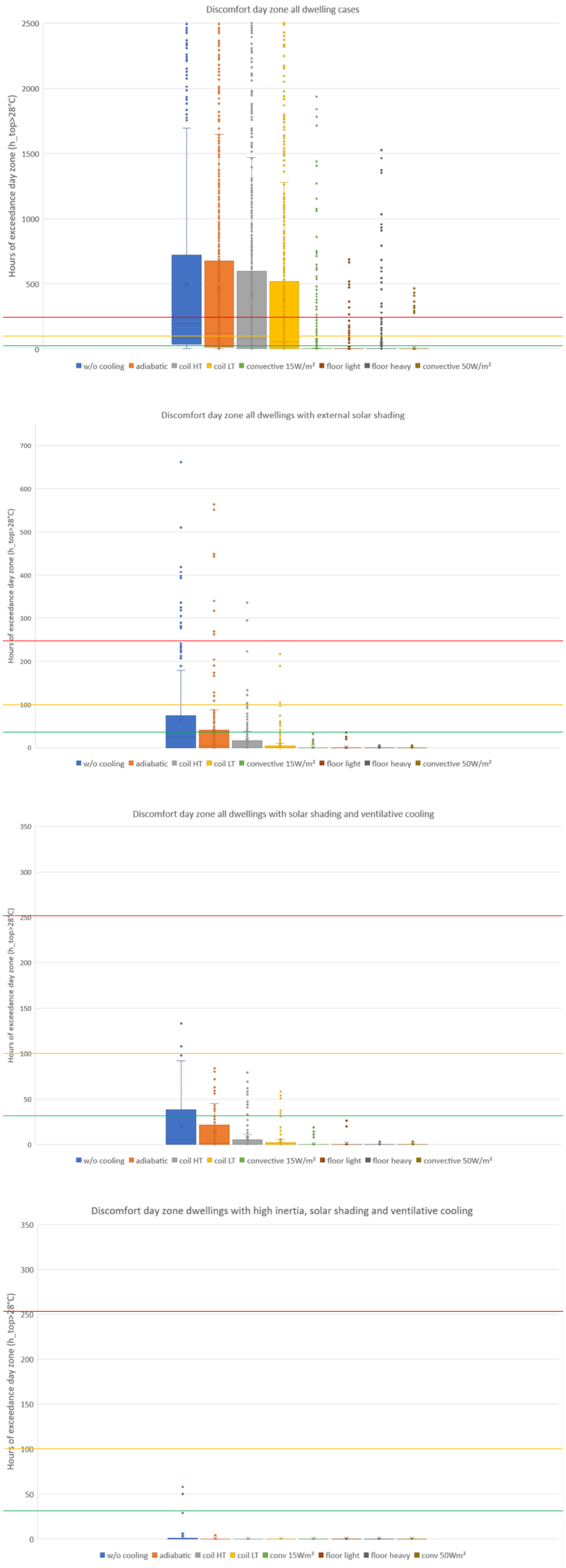

Fig. 4 – Discomfort results (exceeding hours for operative temperatures above 28°C in the day zone) for residential cases in function of the cooling systems. The upper graph shows all dwellings, followed by dwellings with solar shading, solar shading and moderate night ventilation, and finally the lower graph for the dwellings with high inertia, solar shading and night ventilation

If we compare the office simulation results with these from the dwellings (see also [1]), we see that the (sustainable) cooling systems with lower capacities reach more easily the best comfort criteria. Already all dwellings that have solar shading reach the best comfort band with floor cooling systems and the convective systems at high regime temperatures (delivering only 15 W/m^2). The situation improves further when night cooling is applied and certainly when only the massive dwellings are considered. For these last dwelling combinations all cooling system are able to maintain good comfort and even the dwellings without any system can maintain a reasonable summer comfort.

One should notice that the comfort criteria are different, but they are adapted to the use of the buildings, so that the comparison can still be made. The difference between office buildings and dwellings are caused by on the one hand larger window areas and the other hand higher heat gains that are more concentrated during the working hours in the day time. This causes a peak in heat gains that is more difficult to handle with low capacity cooling. It is clear that the combination with passive cooling strategies helps and that also more thermal inertia helps to spread the load over the whole day.

3.4 Peak demand and dimensioning

Regarding the insulation thickness, the influence works in two directions; during a heat wave the better insulated (not actively cooled) dwellings and offices reach indoor temperatures that are lower compared to less insulated buildings. However, after the heat wave, the indoor temperatures are maintained during a longer time and the cooling season will be longer if cooling systems are applied. Regarding the peak power, these are lower for the better insulated buildings.

Finally, when comparing the lower cooling capacities of sustainable cooling systems that show good comfort results in many buildings (that contain more or less passive cooling strategies), with the cooling capacities that result from the classical cooling load calculations, such as the methods prescribed by ASHRAE, VDI, or ATIC in Belgium, we see that these calculated values are often much higher. This is due to the assumptions in the cooling load calculations that a fixed temperature is to be maintained and that all excess heat will be cooled away (by air cooling systems). For surface cooling systems with high inertia and/or buildings where more fluctuations in the indoor temperature are allowed, cooling capacities can be much lower. In the new project "koeling 2.0" we will focus on a new dimensioning tool for these sustainable systems with lower cooling capacity.

Conclusions

A new decision tool has been made to compare different (sustainable) cooling systems and passive cooling strategies in dwellings and typical office zones. To make it future proof, a new (extreme) climatic data file was constructed. However, the selection of the comfort criteria showed to be difficult.

In general, the simulations show that a lot of sustainable cooling systems, although their lower specific power, can provide good comfort in most of the residential buildings, and also a great deal of the office buildings, provided that the window surfaces are not exaggerated and passive cooling strategies can be applied when necessary. Without any cooling system only the dwellings with the combination of high inertia, the best solar shading and ventilative cooling are able to maintain a reasonable comfort during the heat waves. For office buildings this will become difficult since indoor heat gains are higher and more concentrated during the day, resulting in higher cooling needs.

4. Acknowledgements

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Data Statement

The datasets generated during and/or analysed during the current study are not publicly available because of the large size and form of the data but specific information can be obtained by e-mailing the authors of this paper.