Indoor summer comfort: a study into the practical useability of sustainable cooling systems

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Abstract

To accelerate the acceptance of so called 'sustainable cooling systems' and to ensure large scale rollout in residential buildings, a more profound insight is needed into their performance and the provided level of comfort. This article presents and evaluates the performance of different sustainable cooling systems within an (evolving) Western European climate and setting: a set of five typical residential buildings – meeting all the current energy standards – was examined within a newly developed dynamic building simulation packet. A parameter study varying insulation, thermal capacity and orientation of each building confirms that, despite lower specific cooling power, most examined systems can provide sufficient comfort when combined with passive anti-heating measures. A user-friendly decision support tool for the selection of sustainable cooling systems in residential buildings was further elaborated from this simulation-packet. To facilitate the overall assessment of thermal summer comfort in residential buildings in a rapidly changing climate and to provide this new decision support tool with an intuitive and easy to use color-coded interface, this paper studies the different applicable comfort standards and proposes an updated method to define four different comfort levels. The computer model inputs were supplemented by a series of 'in situ' measurements made during the summer of 2019 and 2020 in several residential buildings, located in Belgium. Several 'hydronic' delivery systems – coupled to a heat pump system with free cooling abilities – and adiabatic cooling were monitored. These results were also used to verify simulation output results.

Introduction

The need for cooling in residential buildings is increasing year by year. First and foremost this effect is caused by changes in our climate which introduce more and longer periods of extreme heat. According to the 'trias energetica' or energy triangle, the *very first* step to reduce the need for cooling is proper insulation, preventing outside heat from entering the building during these hot spells. Primarily stemming from winter comfort (reducing heat loss & active heat production), extensive insulation is already implemented in all new buildings and renovations projects. It has become a legal requirement to meet certain standards, evolving over time. This crucial 'frontier' against overheating is already in place, but unfortunately it also brings along its own challenges specific to summer comfort: any heat coming from electrical appliances or even our own bodies remains 'trapped' inside, warming up the building over time. This heat and any outside influx needs to be removed.

When thinking of 'cooling systems' both central air-conditioning and 'split units' spring to mind almost immediately. These techniques use an electric compressor and a standard refrigerant and they are often referred to as 'active cooling systems'. They are very easy to (re-)place and while they guarantee high comfort levels, they also have a relatively high energy consumption. Moreover, the use of refrigerants is not at all environmentally friendly: the Global Warming Potential index (GWP) of these products is high, so any spillage has a highly negative impact on the environment. These fluids run throughout the whole system (not contained in a single place, prone to breaches) and even after they complete their relatively low lifespan, these appliances can remain a hazard to their surroundings if not disposed of properly.

Alternative, energy-economical systems are already widely available, yet far too often they are still being overlooked in the development of new or renovation building projects. These techniques drastically reduce energy consumption and/or limit the amount of refrigerants used, containing them in a single location and/or use refrigerants that have a lower GWP. In return, they need to be coupled to delivery systems capable of distributing low-caloric heat to a room. An example of these delivery systems is underfloor heating/cooling, which is not 'new' anymore by any standard. Passive anti-heating measures like screens can be equally beneficial when used correctly. To accelerate the general acceptance of these so-called 'sustainable cooling systems' and to ensure a large scale roll out, a more profound insight is needed into their performance and the level of comfort they can provide. This article shows and discusses the results of an extensive inquiry into the performance and the level of comfort these 'sustainable cooling systems' can provide within a Western European climate and within a Western European (spatial planning) setting.

DECISION SUPPORT TOOL BASED ON COMPUTER GENERATED DYNAMIC BUILDING SIMULATIONS

A set of five typical residential buildings meeting all the current energy standards was examined during an extensive parameter study, varying insulation, thermal capacity and orientation of each building. These computer models examine the performance of sustainable cooling systems, passive anti-heating measures and a combination of the two. Split units are also simulated to provide a reference in comfort (best) and energy usage (highest). Input parameters and preconditions are discussed before showing and examining final results more closely. A user-friendly decision support tool is further elaborated from this simulation-packet, enabling users to easily judge the level of comfort and energy usage for each delivery system within a personalized set of building parameters.

'Cooling comfort' is a subjective term. Some may already feel cold in a certain environment where others could still feel comfortable or even warm. For this study, it is however important to define certain limits in which a systems performance is considered to be 'sufficient': a set of 'comfort categories' had to be determined. A wide variety of approaches for thermal comfort assessment in buildings can be found in literature and in different European/international standards. These are either based on PPD and PMV, other indices like the ATG criterion or a more simple/static set of temperature limits that may only be exceeded for a limited amount of time in order to be deemed 'comfortable'. A relevant and easy to use comfort assessment method, also suitable for the decision support tool, was elaborated from existing standards.

IN SITU MEASUREMENTS

The performance of several 'radiative' delivery systems – coupled to a heat pump system with free cooling abilities – and adiabatic cooling was monitored in actual residential buildings in Belgium during the summer of 2019 and 2020. During these tests passive measures like efficient use of screens, night-time ventilation cooling, … were used in tandem with these sustainable cooling systems. Certain of these results were used as inputs for the computer model and these results can also be shown in conjunction with the conclusions made in the computer simulations (validating these results and checking the simulated behaviors of these systems).

International comfort standards/Literature review

Unfortunately, there is not one single standard method to assess summer comfort with respect to residential buildings. The determination of (relative) thermal comfort in function of a collection of parameters is set by several different standards: EN ISO 7730, EN 167989-1, EN15251 and CISBE all apply.

EN ISO 7730 is an international, ISO-certified standard covering 'thermal comfort' measured via PPD (Predicted Percentage Dissatisfied [%]) and PMV (Predicted Mean Vote). The PMV-index predicts the mean value of votes for 'thermal sensation', based on the thermal balance between the body and the loss of heat to the environment. However, the PMV model was intended for application by the HVAC industry in the creation of artificial climates in controlled spaces (Fanger PO [1]). According to Brager and de Dear [2] it is not applicable to naturally ventilated (or free running) buildings and in extension not applicable to most of the residential buildings, which is the scope of this study.

When assessing the overheating risk in residential buildings, Hamdy *et al.* [3] use a traditional metric such as the 'Indoor Overheating Hours' (IOH), but they also introduce the 'Indoor Overheating Degree' (IOD) for a more quantitative assessment of the overheating risk in dwellings. The IOD takes into account both the intensity and the frequency of overheating during the occupied hours and for different zones. This enables the possibility of different comfort limits, depending on the occupant's behavior and thermal adaptability for each particular room. 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, as described in CIBSE Guide A [4]. 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.* [12] 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 [5], EN 15251 Annex A2 [6] or CIBSE TM 51. A Dutch adaptive assessment scheme for naturally ventilated buildings was incorporated in the standard ISSO Publication 74 ([7],[8]). This hybrid method combines adaptive and non-adaptive criteria. For free running buildings the running mean outdoor temperature $T_{e,ref}$ and the corresponding indoor temperature limits $T_{i,lim}$ are calculated as shown in Equations (1–4). Figure 4 gives a visual representation of these very same adaptive comfort categories.

$$T_{e,ref} = (T_{today}+0.8*T_{today}-1 + 0.4*T_{today}-2 + 0.2*T_{today}-3)/2.4 \quad (1)$$

$$T_{i,lim} = 17.8+0.31*T_{e,ref}+2.5 \text{ (class A)} \quad (2)$$

$$T_{i,lim} = 17.8+0.31*T_{e,ref}+3.5 \text{ (class B)} \quad (3)$$

$$T_{i,lim} = 17.8+0.31*T_{e,ref}+4.2 \text{ (class C)} \quad (4)$$

This approach leads to acceptable indoor temperatures up to 30 °C when the running mean outdoor temperature exceeds 25 °C. This can be acceptable in rooms with office-like activities [9] or living rooms, but is probably less appropriate for bedrooms. Therefore, Peeters and de Dear [10] specified a set of adaptive conditions for bedrooms, with a maximum of 26 °C. According to CIBSE TM59 temperatures exceeding these adaptive limits are accepted for up to 3 % of the occupied hours, corresponding to circa 110 h in summer (May-September). Temperatures in bedrooms may only exceed the 26 °C mark for 1 % of the year between 10 pm and 7 am. This corresponds to approximately 33 h/year.

In this paper each room is considered as a separate zone. Indeed, it was shown by [11] that different zoning strategies may significantly affect the predicted thermal comfort. Furthermore, this room by room approach allows for different comfort limits for living and sleeping rooms and it allows for corrections to the 'exceeding hours' according to the occupancy ratio of each room. According to Hamdy *et al.* for each room the relevant indoor overheating hours (exceeding hours) can be calculated using either fixed temperature limits (28 °C for living rooms and 26 °C for bedrooms) or adaptive limits according to ISSO Publication 74 ([7], [8]). Both approaches seem interesting for the purpose of this article, mainly because both sustainable and active cooling systems are considered in the simulation models. Even though the temperature limits according to ISSO 74 seem more applicable to residential buildings than other adaptive methods (EN 16798, EN15251), they still appear very high to this article's authors. According to Van der Linden [13] these limits are partly based on data from tropical climates, which may explain why they don't seem specifically applicable for a Western European climate.

Comfort models are indeed always somewhat restricted by specific climatic data. Hamdy *et al.* [3] relates indoor overheating to climate data by defining two metrices: the 'Ambient Warmness Degree' (AWD), assessing the severity of global warming, and the 'Overheating Escalation Rate' (OER), equal to the ratio between IOD and AWD. Chen (2019) also points out that there are two risks in using the comfort assessment as defined in CIBSE TM52 and TM59. Firstly, the uncertainty of general occupant behavior, as studied in IEA EBC Annex 66 and Annex 79, certainly during heat waves. Secondly, 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' [15]. 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.

Based on the foregoing discussion, this article will propose an updated method for defining comfort classes in order to judge the performance of the different simulated cooling systems. Inversely, the results of the simulations can and will also be used to judge the current standards in their ability to assess indoor thermal summer comfort and cooling system performance.

Methods

GENERAL METHODS

For these dynamic building simulations five different typical modern-day residences were 'constructed' in TRNSYS17 with a variable level of insulation, thermal capacity, window percentage and orientation. Internal heat gains were added. Historical weather data was gathered in order to create a new climate file, used to place these buildings in critical summer conditions founded in reality. This new outdoor temperature model is based on the most severe heat waves of recent years in Belgium (2010–2019). Different cooling systems were introduced into these buildings, like underfloor cooling, cooling coils (cooling the ventilation supply air) and indirect adiabatic cooling. These cooling delivery systems are coupled to a geothermal heat pump with free cooling abilities. Performance input parameters were gathered from the In Situ measurements performed during the SCoolS-project (see acknowledgements) as well as from external sources. Besides these cooling systems, passive anti-heating strategies were also considered, like solar shading and (night) cooling through ventilation. An 'ideal' occupant behavior was assumed, supposing these strategies are followed strictly and according to a set of logical rules (or even by supposing they are automated within the building management system). Using these inputs (cooling systems, passive strategies, internal heat gains, weather data, …) a parameter study was performed on these dwellings by varying all of the different building-parameters (resulting in 7,200 different cases). The output is the energy-consumption of these cooling systems and the resulting indoor temperatures in function of time. As discussed in the previous paragraph, these indoor output-temperatures can be judged using the CISBE-standard and the adaptive limits according to ISSO standard 74 or a third, derived method. Air-conditioning systems were also studied as a reference for energy usage (highest) and comfort levels (best).

PRECONDITIONS

Building typologies & direct environment

These five different topologies were studied (with fixed building plans, which can be consulted via the online decision support tool, see acknowledgement):

- Row house
- Architectural residence (villa)
- Semi-detached house (corner)
- 2-facaded apartment
- 3-faceded apartment

Shading from nearby buildings as well as shading caused by the architectural form of the building itself are considered alongside passive anti-heating strategies. Any *additional shading* caused by *fencing* or *hedges* is not considered, since this is very situation dependent and not an integral part of architectural design.

Internal heat gains

Internal heat gains are imposed, based on a Dutch method developed by Witkamp *et al.* (2019). A daily internal gain profile was made for each building typology and this profile is applied for all days of the year. According to the same Dutch method there is always at least one person present.

Weather data

For this study a new climate file was constructed, based on the most severe heat waves during the last 10 years (2010–2019) and using the official weather station data of Belgium in Uccle, following the methods of the NEN5060:2018 as shown in Figure 1 and Figure 2.

New analysis is on the way, based on the application of the NBN EN ISO 15927-5 for the construction of extreme weather data files, based on the CORDEX future weather data base for 2040–2060. This work is undertaken by BBRI in the framework of Annex 80 Task A (IEA 2020) [14], but it is not finished yet. The first results, however, do show a good correspondence with the constructed climate file as shown above.

Hygienic ventilation & interzonal ventilation and stratification

Nominal ventilation flow rates are determined according to ventilation requirements for each room (NBN D50-001). The interior doors are considered permanently open, causing interzonal air flows in addition to the hygienic ventilation flows. For building topologies with multiple floors (terraced and 3-façade house) stratification due to buoyancy effects is also considered, assigning part of the convective gains directly to the upper floors. For the transport of air through the internal openings the Warren Relationship for air flow through a single sided opening driven by thermal buoyancy is used, as described by Caciolo (2011) and EBC_IEA Annex 62 [17]. The quantification of flow is mainly based on the geometry of the opening and the temperature difference between rooms.

BUILDING PARAMETERS

Insulation

Building insulation can be varied between 'current standard' and 'passive standard'. 'Current standard' buildings have a maximal thermal conductivity factor of 0.24 W/(m^2K). This value is set by the current present EPBD-requirements. 'Passive standard' buildings will have a thermal conductivity factor of 0.12 W/(m^2K) or under. Depending on the specifics of each room, a lower thermal conductivity may eventually result in a higher (more heat trapped inside) or lower (lower heat influx from outside) required cooling power.

Thermal mass

Thermal mass can be varied between 'high' or 'low': 'high thermal mass' refers to a structure with a high concentration of concrete or stone that are able to store relatively large quantities of energy. During a heatwave, these materials form an anti-heating buffer inside. High thermal mass is best combined with intensive night-time ventilation so these materials can again lose gained heat energy, because once warm, they will retain heat well. 'Low thermal mass' generally refers to timber frame constructions. They don't form the same buffering effect.

Window percentage

Window percentage can either follow the architectural building plans or an extra window percentage can be taken into account. Higher window percentages result in elevated heat gains caused by sun radiation and thus in elevated required cooling power.

Orientation

The orientation of each building façade can be changed to North, East, West or South. Each orientation will result in a different influx of radiational heat from the sun, depending on its architectural design.

PASSIVE ANTI-HEATING STRATEGIES

Ventilation strategies

Intensive ventilation is achieved by (manually) opening windows when there is cooling potential from external air. This will cause air flows on top of the hygienic ventilation air flow. Within the simulation packet three options are provided:

1. no ventilation: windows remain closed,
2. ventilative cooling: the width of the window openings is 15 cm (for tilted windows this refers to the width of the top opening),

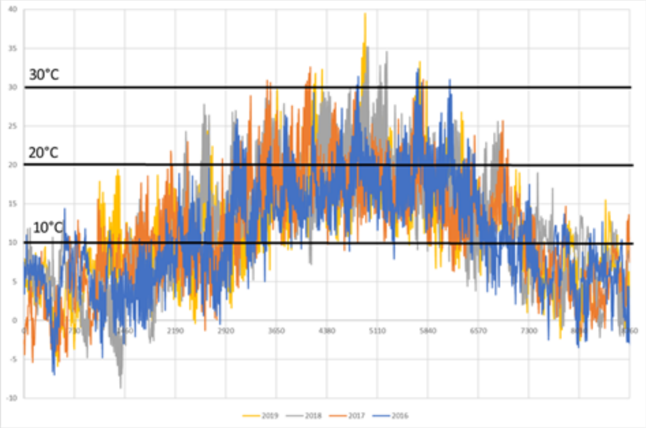

Figure 1. Outside dry bulb temperature for the weather station of Uccle during 2016–2019.

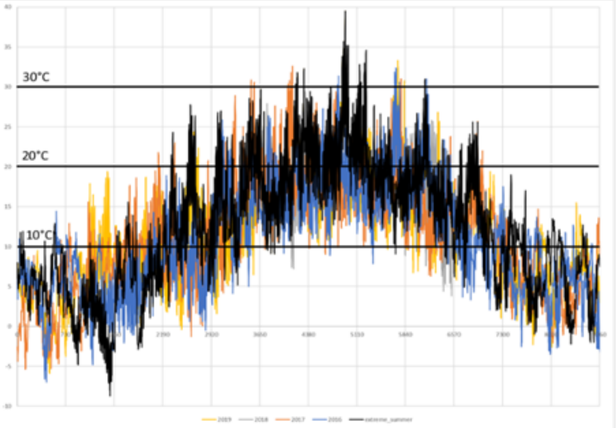

Figure 2. New climate file with 'Extreme warm summer year' based on the climatic data of Uccle 2016–2019.

3. intensive ventilative cooling: the windows are fully opened.

For the air flow through external openings the formula of Phaff and the Guide is used, as described by Caciolo (2011) and EBC_IEA Annex 62 [17]. This formula gives the air flow through a single sided opening driven by a combination of thermal buoyancy and wind. Cross flows or stack flows are not considered. It is the same as used in Standard EN15242. When screens are used at the same time, ventilation opening is reduced to 10 % of the original opening. Strict rules for window manipulation are imposed. In residential buildings windows are opened if the room temperature T_{room} is > 23 °C and

1. or 16 °C< T_e <25 °C
2. or daytime > 22 h and mean night temp will be < T_{room}

Windows are closed if

- or T_{room} < 20 °C and T_e < 14 °C
- or T_e > 25 °C and T_{room} < T_e

Conditions should be true for 30 min before action is taken.

Sun protection strategies (sun blinds & sun protected glass)

Three levels of sun protection were added to the model:

- No sun protection: g = 0.6. 60 % of solar thermal energy is transmitted through all glass surfaces.
- Protective screens on the outside of the window: g = 0.1. only 10 % of solar radiation is transmitted through this barrier (the model reduces the total window-surface by 90 %).
- Sunproof glass: g = 0.3, reducing solar radiation influx by 30 %.

Strict rules for window manipulation are imposed:

- Screens go down if T_{room} > 23 °C and $T_{outside}$ > 12 °C for at least 30 min.
- Screens go up if T_{room} < 20 °C or at sundown.

COOLING SYSTEM PARAMETERS

These simulations focus on the performance of different cooling delivery systems, more precisely:

- 'Hydronic systems' like floor cooling and convective cooling devices,
- Cooling devices implemented in the ventilation system, like cooling coils and adiabatic cooling.

The cooling source or production is not part of the model, so fixed supply temperatures are assumed. In case of a geothermal source, the source is assumed to be dimensioned correctly. All systems are controlled by a room setpoint temperature of 24 °C. Both underfloor cooling and cooling coils are controlled on/off. For the underfloor system an additional hysteresis of 1 °C is implemented. The convective systems are assumed to have an idealized modulating control.

Water based underfloor cooling

Two types of underfloor systems were implemented into the simulation model:

1. A floor cooling system with pipes embedded in 8 cm of screed, based on Type A in EN 15377, with a specific power output of 30 W/m². Internal floors are not insulated. (As used in new buildings.)
2. A floor cooling system with a very thin layer of screed (2 cm) based on type B in EN 15377, with a specific power output of 20 W/m² and well insulated internal floors. (As used in renovation projects.)

The first system is characterized by a greater inertia, higher power, but also by significant losses to the underlying rooms. For comfort reasons and to avoid condensation, the floor cooling operates at 'high temperature', with a fixed supply temperature of 16 °C.

Convective cooling

For these simulations, convective cooling is modelled as an 'idealized' cooling system (internal cooling of Type56 in TRNSYS). Two systems were included in the model, distinguished by their working principle and thus by their maximum cooling power. The first convective system is representative for an active cooling system like a split unit. Power is limited to 50 W/m². The second represents a cooling system using ventilo convectors operating at 16/18/25 °C, which are sized based on the heat demand of the building (40 W/m² at 45/40/20). Power is limited to 15 W/m².

Cooling coils

The cooling coil is placed in the supply air of the mechanical ventilation system. Two types of coils are included, based on supply temperature: low temperature cooling coils (supply 7 °C), connected to an active cooling system, and coils operating at 'high temperature' connected to a geothermal source (supply 16 °C). The efficiency of the coil was studied through the In Situ measurements and manufacturer data and was determined to be 50 %. For comfort reasons supply temperature is not allowed to be lower than 16 °C.

Adiabatic cooling

The adiabatic cooling device is situated in the extraction-side of the ventilation unit where this cooling power is passed over to the supply air through a heat exchanger. The temperature of the saturated air is calculated using Eq. (5). The efficiency of the saturation process is based on measurements and expressed as a function of the relative humidity of the extracted air Eq. (6).

$$T_{sat\_air} = T_{ret} - \eta_{sat} (T_{ret} - T_{wb}) \quad (5)$$

T_{sat_air}: temperature of saturated air (°C)
T_{ret}: temperature of extraction air (°C)
T_{wb}: wet bulb temp of extraction air (°C)

$$\eta_{sat} = 1.169 - 1.0613 * RH_{ret} \quad (6)$$

RH_{ret}: relative humidity of extraction air (-)

Simulation results and updated comfort standard

Figure 3 shows the simulated indoor operative temperatures over time (from May 1st to the 30th of September) for a terraced dwelling equipped with external shading on all windows and a free ventilative cooling (night cooling) strategy, but without any cooling system. This same graph also shows the implemented outdoor temperatures as well as the CIBSE fixed limits for the day zone (28 °C, red line) and the night zone (26 °C, green line). For this specific case the exceedance hours for the day zone (blue graph) are limited to 30 h, but in the bedrooms temperatures exceed the 28 °C limit for up to 221 h. This is far above the comfort limits in the CIBSE TM59 (1 % of the night time or approx. 33 h). Moreover, one of the bedrooms, situated under the pitched roof and equipped with 2 large roof windows, remains above 27 °C for 14 consecutive days. This confirms obvious comfort issues.

If the same case would however be evaluated in function of the adaptive temperature limits of the EN15251 or the new EN16798-1 (as is allowed by the same CIBSE and other methods such as the 'Themablad thermisch comfort'), all zones are deemed 'perfectly comfortable', since all resulting operative temperatures are within the Category I band, as shown in Figure 4 on the left hand side.

Other cases also show large discrepancies in thermal comfort between different methods; the EN16798-1 comfort limits seem very wide, especially during heat waves. When the adaptive temperature limits of Van der Linden *et al.* (2006) are applied, there seems to be a better match with the fixed temperature limits of Figure 3. In this case at least the bedroom with the highest indoor temperatures is categorised in the less favourable comfort class B (see Figure 4 on the right-hand side).

Figure 5 shows the 'exceedance hours' of all simulated cases versus the time outside of comfort class A. Certainly for the day zone (blue) a clear correlation is present. The cases on the lower right corner of the graph – with worse adaptive comfort compared to the fixed temperature boundaries – are mainly due to control issues at lower outdoor temperatures. The cases on the left hand side that show higher exceeding hours and 0 hours out of comfort band A can be studied more in depth in order to avoid many 'false negative' comfort ratings in a context of passive cooling strategies and/or sustainable cooling systems.

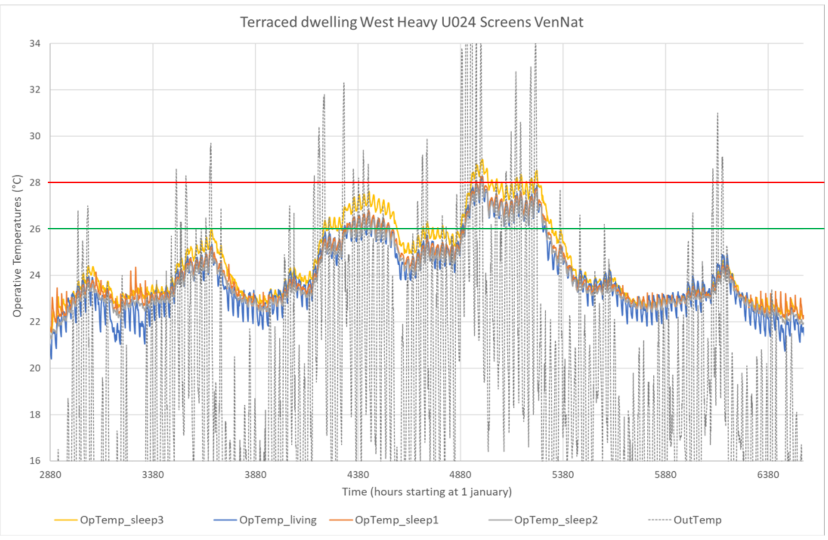

Figure 3. Simulated indoor temperatures for day zone (blue) and sleeping rooms for the terraced dwelling with external solar shading and free ventilative cooling.

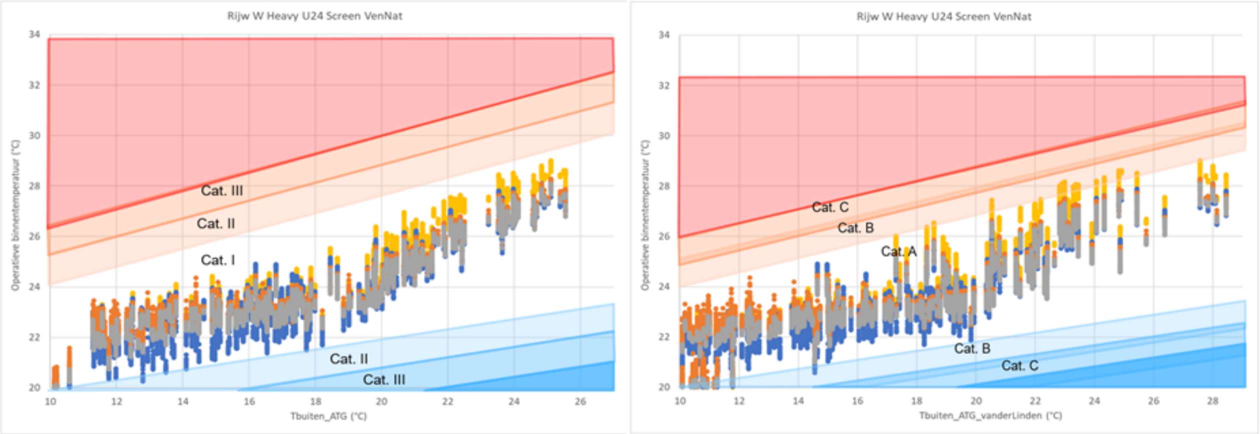

Figure 4. Simulated indoor operative temperatures with respect to the adaptive temperature limits of EN16798-1 (left) and Van der Linden et al. (right) for the same terraced dwelling case.

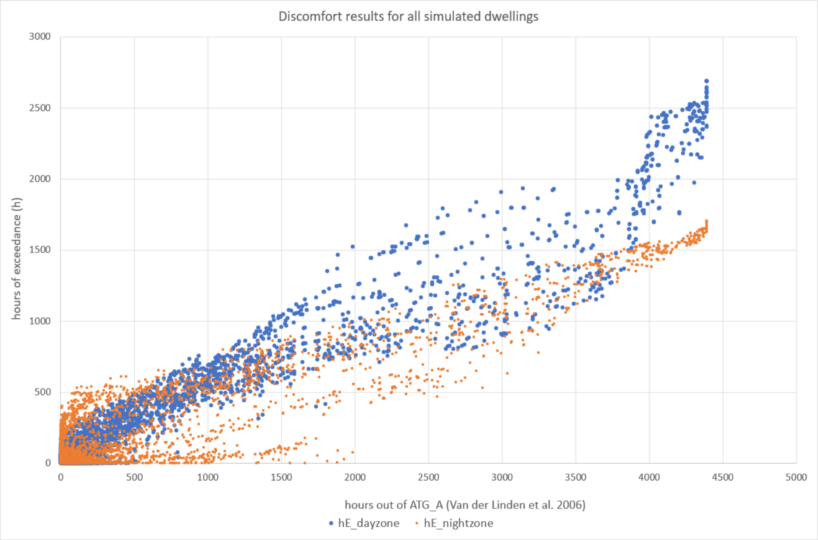

Figure 5. Hours of exceedance for the day zone (>28 °C) and night zone (>26 °C) compared with the hours outside of the comfort band A following the adaptive limits of Van der Linden et al. (2006).

If the 3 % summertime limit (or 110 h), as used in the CIBSE TM52 and TM59, is applied as the upper comfort boundary on these results, based on the adaptive comfort method of Van der Linden *et al.* (2006) and if the corresponding exceedance hours for the static method (>28 °C) is factored in, an absolute maximum of 250 exceeding hours and another intermediate level at 100 h can be defined. Figure 5 can be a bit misleading when focusing on the area around the origin as a lot of points are amassed there. If only the cases are selected that remain within comfort band A all the time (0 hours out of ATG_A), 99.9 % of these cases show less than 106 exceeding hours in the day zone (>28 °C) and less than 266 exceeding hours in the night zone (>26 °C).

Based on these results four comfort levels can be defined:

1. Good comfort: exceeding hours < 33 h (green color in tool)
2. Average comfort: 33 h ≤ exceeding hours < 100 h (yellow color in tool)
3. Possible comfort: 100 h ≤ exceeding hours < 250 h (orange color in tool)
4. No comfort: exceeding hours ≥ 250 h (red color in tool)

This way 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'. This method falls in line with the used comfort boundaries such as used in the 'Themablad Thermisch Comfort', using a more future proof 'extreme' weather file. The example of the terraced dwelling with exclusively passive cooling strategies as shown in Figure 3 with 221 hours of exceedance in the night zone may yet still be declared as 'comfortable'. With 32 exceeding hours in the day zone, that zone is declared as comfortable. More generally, the simulation results do often show a difference in day and night zone, depending on the location, orientation and other specifications of these rooms.

Discussion

SIMULATION RESULTS

As discussed above, the simulation results often show a significant difference between day zone and night zone, depending on the location, orientation, window size and use of these rooms. Figure 6 (Left) shows the box plots for the exceedance hours in the day zone in relation to the different applied cooling systems for all the dwelling configurations without any anti-heating strategies present. Figure 6 (Right) does the same for the night zone. Although the maximum temperature limit for the day zone is much higher (28 °C) compared to that of the night zone (26 °C), the exceeding hours seem to be higher in the day zone. This is mainly the case for the apartments and the free-standing dwelling where most of the window area is situated in the living room, while the bedrooms usually receive less solar gains. It is the living room in the apartment with 3 facades and the largest window-to-floor ratio that requires more than the maximum applied 50 W/m² resulting in comfort issues. The terraced house used as example in Figure 3 shows a different layout and more comfort problems at the highest levels, caused by the solar gains through the roof windows, which cannot be fully solved without the use of any passive anti-heating strategies.

From Figure 6 it is clear that cooling systems have a large impact on comfort levels: **if no cooling system is applied (blue bars), half of the dwelling combinations show serious comfort problems** in day and/or night zone when subjected to successive heat waves. Only 15 % of these combinations are sufficiently comfortable. The cooling systems applied in the ventilation system (indirect adiabatic cooling and cooling coils) can *improve* comfort. I.e. with a cooling coil at low regime temperatures almost 30 % of the cases show good comfort – but still 40 % of the cases show a bad thermal comfort in the day and/or night zones. In those cases, the available cooling capacity provided by these systems (below 1 kW) is insufficient to cool away all heat gains. On the right-hand side of the graphs, the **hydronic cooling systems show good and remarkably homogeneous comfort**

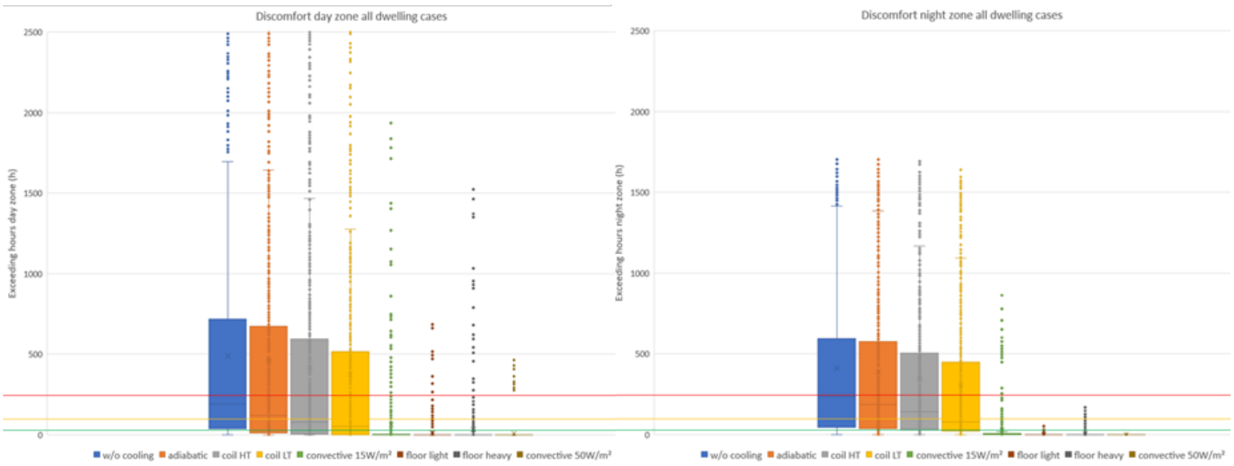

Figure 6. Discomfort results of all simulated cases for the day zone (left) and night zone (right) for all cases without any anti-heating strategies.

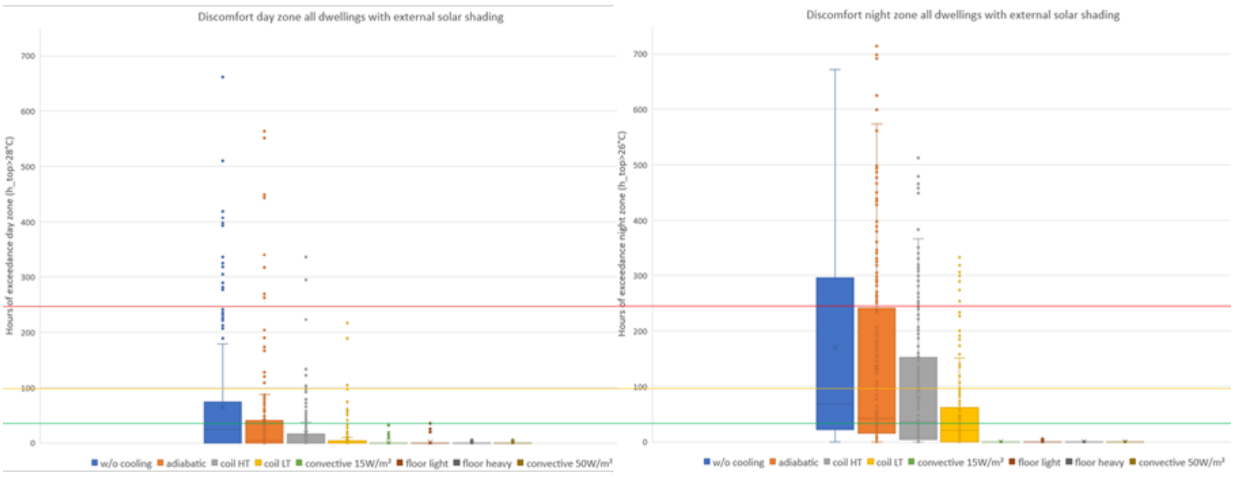

Figure 7. Discomfort results of all simulated cases with external solar shading for day zone (left) and night zone (right).

results, with the ventilo-convectors (dimensioned for heating purposes), underfloor cooling and active air-cooling systems respectively providing up to 15 W/m², 30–40 W/m² and 50 W/m². As expected, the active air-cooling systems can provide 'good comfort' in 98 % of all studied cases. At 15 W/m² the sustainable systems can however also provide similar comfort for 80 % of the combinations and only in 8 % of cases there is 'bad comfort'. The latter result is remarkable because for 75 % of these cases the calculated cooling power ranges between 20 and 40 W/m² with an average of 30 W/m². This effect can be explained by the difference in control assumptions between the calculation (fixed temperature at 25 °C and variable (unlimited) capacity) and this paper's simulations (fixed capacity at 15 W/m², setpoint temperature 24 °C and variability allowed up to 26 °C in the night zone and 28 °C in the day zone). **This allowance for (a limited) setpoint-temperature variance proves to be very important to lower the necessary cooling capacity**. This result is particularly interesting for (hydronic) sustainable cooling systems: **they can make up for their limited cooling capacity by running longer cycles.**

When_other dwelling parameters are studied, solar shading appears to have the highest impact on the comfort (and energy use). Figure 7 shows the results for all cases with external solar shading. The comfort of the dwellings without any cooling systems or only with a very limited capacity system (ventilation based) greatly improves: for the day zone in 55 % of the cases without any cooling system, screen use can still provide good comfort. Only 6 % of these cases are found to be uncomfortable. E.g. the combination of cooling coils at higher temperatures and the use of solar shading results in good comfort in up to 81 % of cases. Only 1 % is still at risk of bad comfort. In the bedrooms, where the influence of solar gains is less pronounced and the temperature limit is 2 degrees lower, the comfort assessment is somewhat different. 30 % of the configurations without cooling systems, 24 % for the adiabatic systems and 13 % for cooling at higher temperatures, are still assessed as 'bad comfort'.

The combination of external solar shading and hydronic cooling system (with at least 15 W/m² cooling capacity) provides good comfort for all combinations. Solar shading also has a large impact on the energy use: without solar shading the demand for cooling energy averages 1,500 kWh/y for the hydronic cooling systems (at 15 W/m²), 1,700 kWh/y for underfloor cooling and 2,150 kWh/y for active air-cooling (at 50 W/m²). These demands are roughly reduced to a third to respectively 550, 600 and 700 kWh/y with solar shading.

When ventilative cooling (night cooling by window opening) is added to the equation, also the low power aeraulic systems provide good results. This can be seen in Figure 8. Practically all combinations, even without cooling system, show an acceptable comfort. However, in the bedrooms a cooling coil is at least needed to guarantee good comfort. For the hydronic cooling systems the comfort was already good, but the cooling energy demand drops even further to respectively 400, 450 and 635 kWh/y.

Other building parameters such as orientation, insulation and inertia also have some impact on the results, but to a much lesser degree. (Users of the online decision support tool can witness the specific impact of these parameters by altering them individually.) Of course orientation is important: day zones oriented towards the south-east and night zones oriented towards the west provide the worst comfort results, given the timing of their usage and the solar energy they absorb. This issue can only be solved architecturally. Passive anti-heating strategies like solar shading and free ventilative cooling prove to be much more important than the degree of building insulation. Inertia is mainly notable in combination with the free ventilative cooling strategies or in cases where the cooling system is slightly under dimensioned and the inertia can help to spread out the heat gains over the day. However, if heat gains are far higher than the cooling energy that can be delivered, inertia not only dampens the heat peaks but also results in longer periods of overheating, since heavy dwellings cool down much slower. With the rising amount of (successive) heat waves the resulting impact of higher inertia can go both ways.

VALIDATION OF SIMULATION RESULTS THROUGH IN SITU MEASUREMENTS

Supplemental to the computer-generated building simulations, In Situ measurements were performed on two recent residential buildings in Belgium during the summers of 2019 and 2020. Both buildings are equipped with a geothermal heat pump system with 'free cooling' abilities coupled to underfloor cooling, a high temperature cooling coil and indirect adiabatic cooling (the latter system is only present in one of the 2 residences). The results of these measurements can be discussed entirely on their own when discussing the thermal comfort and performance of sustainable cooling systems, but for this paper they are only considered as a support for the computer simulations (inputs & results).

As discussed above, certain simulation inputs were derived from these measurements, like cooling coil efficiency and also substantiating the claims that a well-dimensioned cooling source can provide a constant supply temperature of 16 °C (this was not further simulated).

In general, these two specific cases corroborate the claims made during the building simulations, verifying these results to a limited degree. This will now be discussed, yet only briefly. The 'Holven case' best fits the description of the row housing topology. The 'Mol case' best fits the description of the architectural residence.

Figure 9 shows indoor and outdoor temperatures over time (1 summer period) for the Holven case. For day zones (grey) good comfort is always maintained. For night zones (yellow) in two instances only 'average' or 'possible' comfort is achieved. This can be directly attributed to non-ideal occupant behavior with respect to screen- and ventilation usage and due to the very unfavorable location of the bedroom directly under the roof.

The Mol case specifically shows the limited capacity of adiabatic cooling within residential buildings. A claim that was also made in simulation results. Figure 10 shows the measured cooling capacity of adiabatic cooling and underfloor cooling during the heat wave period of 2020 (July 16th–August 8th, underfloor cooling was disabled from 24–07 until 2–08). Cooling power is limited to an absolute maximum of 450 W, which was proven to be insufficient for good comfort. This is also confirmed by the average indoor temperature, rapidly exceeding the 26 °C limit.

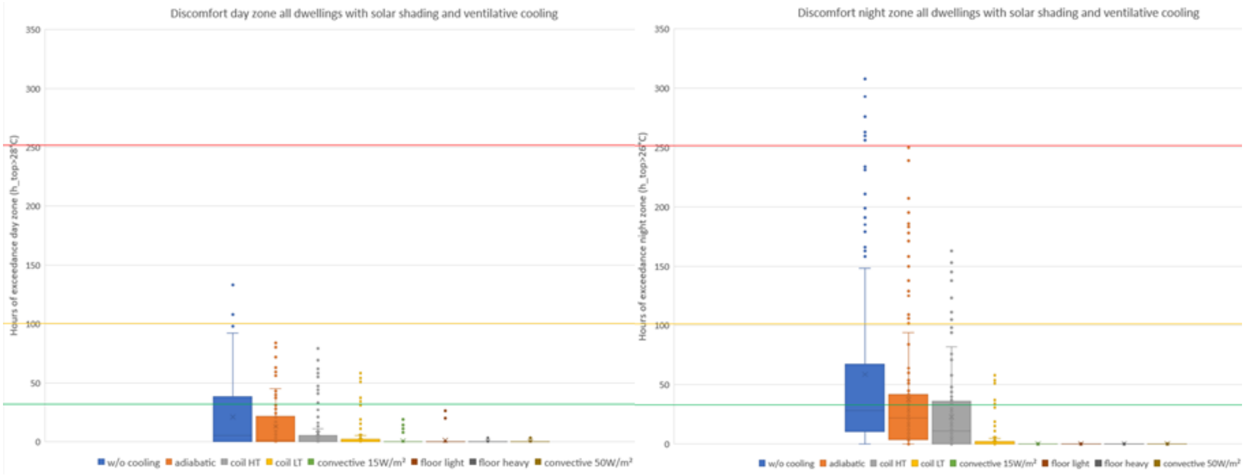

Figure 8. Discomfort results of all simulated cases with external solar shading and ventilative cooling for the day zone (left) and night zone (right).

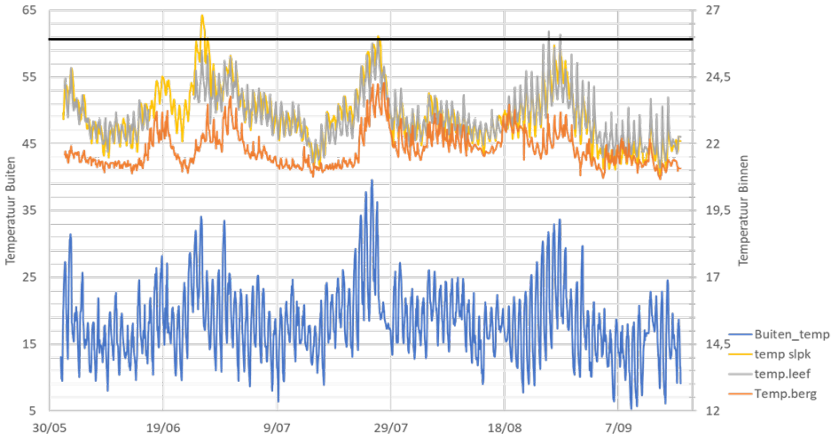

Figure 9. Indoor (right y-axis) and outdoor (Blue, left y-axis) temperatures of a row housing residence with passive anti-heating measures and sustainable cooling systems. Yellow = bedroom; Grey = living room; Orange = storage room; Blue = outdoor temperature.

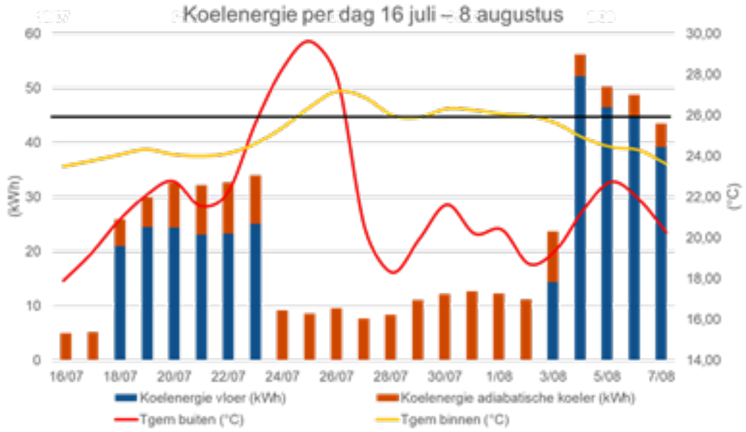

Figure 10. Adiabatic and underfloor cooling power over time (underfloor cooling disabled 24/07–3/08). Adiabatic cooling power is limited to 450 W.

SUSTAINABLE COOLING SYSTEMS AND (FUTURE) LEGISLATION

The premise of this study and paper was two-fold: we are witnessing a rapid change in our climate, but increased building insulation also has its effect on indoor summer comfort. Since this second factor is set in legislation and EPBD requirements, one could argue that these specific regulations complicate the large scale rollout of sustainable cooling systems. Is this so? Or more importantly, will future legislation be advantageous or disadvantageous to sustainable cooling? While this question is subject for a completely separate study, it is interesting to very briefly touch upon this issue (according to this paper's authors). Within EPBD requirements there is a notable evolution towards the promotion of passive anti-heating strategies and sustainable cooling systems. I.e., recently passive underfloor cooling coupled to a geothermal heat source was added to the software. However, it is still unclear whether or not these calculations are detailed enough to truly factor in the real value of these systems. This analysis is still work in progress, performed by KCE Thomas More. What is clear, however, is the increased penalization of active cooling solutions within the EPB software, creating an obvious and ever increasing incentive for installing passive anti-heating measures and sustainable cooling systems. In short: the authors of this article do see legislation as a support to passive systems, rather than a detriment, though much depends on the exact implementation of these requirements.

Online decision support tool

The goal of the dynamic building simulations in this study was to evaluate the performance of sustainable cooling systems with respect to thermal comfort and energy usage in a wide variety of settings. A user-friendly web tool (Figure 11) was derived from this simulation packet which allows each user to make their own analysis, based on a personalized combination of building parameters. It can be used to decide which sustainable cooling system is 'best' for a specific situation and overall it serves as a promotional tool for sustainable cooling systems.

On the left-hand side **(1)** the building parameters can be selected, using the drop-down menus [building type (5 variants), inertia (2), insulation level (2), glass surface (2), orientation (4)], as well as passive cooling strategies for solar shading (3) and ventilative cooling (3).

In the low left corner **(2)**, the SEER (Seasonal Energy Efficiency Rating) of a possible (free) cooling system can be selected if connected to a high temperature or a low temperature emitter system.

When these parameters are selected, on the right-hand side **(3)** the energy consumption (height of the columns) and resulting comfort for the day zone and night zone are given for the different simulated systems (colors of the columns). From left to right these systems are 'no heating system', indirect adiabatic cooling, cooling coil at high temperature, cooling coil at low temperature, convective cooling at 15 W/m², floor cooling heavy and light variants and finally active convective cooling at 50 W/m². In the lower right corner **(4)** the maximum specific cooling capacity of the convective cooling system is shown for the different cooling zones.

Conclusion

To facilitate the overall assessment of thermal summer comfort in residential buildings in a rapidly changing climate and to provide a new 'decision support tool' with an intuitive and easy to use color-coded interface, the authors of this paper studied the different applicable comfort standards and proposed an updated method to define 4 different comfort levels (good, acceptable, possible or no comfort). Through extensive computer simulations, the effects of heat waves on indoor thermal summer comfort were analyzed, introducing different cooling systems and passive anti-heating strategies. Results show that passive cooling strategies, like solar screens and free ventilative cooling, can already drastically improve thermal comfort, reducing the hours of exceedance by tenfold or more. They reduce the necessary cooling capacity of any cooling system combined with them, making it easier to reach comfort goals. These passive anti-heating measures allow for the implementation of a wider variety of sustainable cooling systems such as top cooling with a cooling coil in the ventilation system connected to a sustainable cooling source. Indirect adiabatic cooling can also help, but its cooling power is often limited to 500 W or even less when ventilation rates drop or when indoor humidity raises. These passive anti-heating strategies rely on a very strict and consistent control by building occupants, or automated control. Real-life occupant operation will likely be less strict, causing these strategies to be less effective and causing cooling needs to rise again. In some cases window opening may not even be possible due to noise or air quality issues. However, even without any passive measures, certain sustainable cooling systems with sufficient cooling power prove to be proficient. I.e. underfloor cooling or fan coil units on high regime temperatures can still do the trick on their own when control is adapted and when a large enough margin is available between the set-point and the lower comfort temperature band, so the highest capacity demands can be buffered in the system and in the building. Aeraulic systems such as cooling coils and adiabatic cooling prove to be insufficient for this purpose when used on their own. **Simulation results also show that energy usage is drastically reduced when compared to 'classic active cooling', as was expected**. In situ measurements in actual residential buildings in Belgium were performed to substantiate the claims made from these simulation results and to provide the computer models with certain inputs. A user-friendly decision support tool for the selection of sustainable cooling systems in residential buildings was further elaborated from the simulation model (see acknowledgements).

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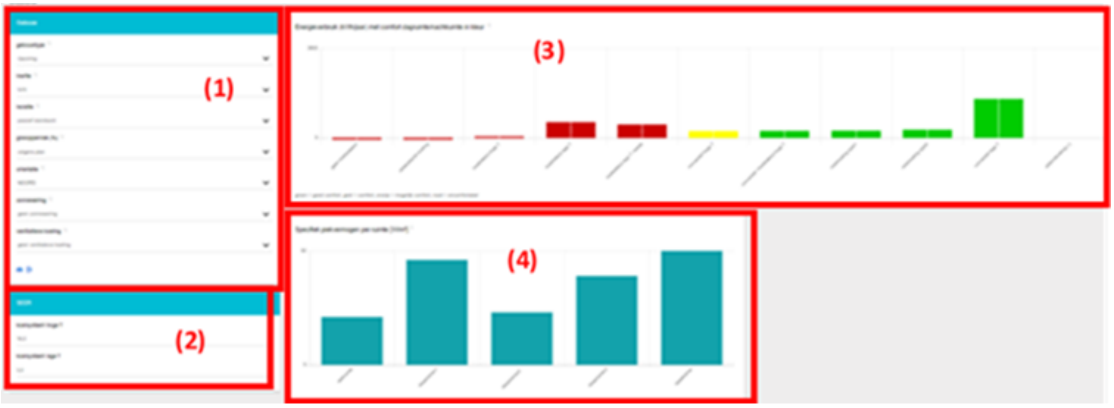

Figure 11. Graphic representation of the SCoolS evaluation and selection tool.

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