Overheating Indicator and Calculation Method for Walloon Buildings

WP3 Report: Building Overheating Concepts and Weather Patterns in Belgium

Version: Final

ISBN: 978-2-930909-22-6

Orbi Link: https://orbi.uliege.be/handle/2268/263959

Author: Deepak Amaripadath[1]

[1] Sustainable Building Design (SBD) Lab, Dept. UEE, Faculty of Applied Science, University of Liege, Belgium

E-mail: deepak.amaripadath@uliege.be

Summary

This report is prepared as a deliverable in the framework of Project SurChauffe, which is part of BEWARE Fellowship funded by the Service Public de Wallonie (SPW) and co-funded by Marie Skłodowska-Curie Actions (MSCA) of the European Commission (EC) and MK Engineering, Belgium. The project is carried out in collaboration between Sustainable Building Design (SBD) Lab, Liege, and MK Engineering, Brussels. The main aim of the project is to increase the competitiveness of the Walloon building services sector. The main project objectives and deliverables are as follows:

- WP3: Overview and database for the important concepts relevant to overheating. The main deliverable is this report, which includes thermal comfort principles, a cooling technology database, and weather and climate pattern studies.
- WP4: Design of climate change-sensitive overheating indicator. The main deliverable of this work package will include a climate change-sensitive overheating indicator and a journal paper based on this design.
- WP5: Modeling framework and protocol with low input uncertainty and high-risk assessment. In addition to the framework and protocol, the work package will also deliver a journal paper.
- WP6: Low-cost in-situ measurement methods, monitoring protocols, and field measurement kit. In addition to the developed methodology and measurement kit, there will be a probable journal paper based on the studies.

The report emphasizes the importance of thermal comfort in the growing influence of climate change. Extreme events like, heatwaves and power outages associated with it are going to become more frequent in the upcoming decades. The studies on HDD and CDD indicate a future weather scenario with warm winters and hot summers. This points to the selection of appropriate cooling technologies for existing and new buildings to counter these scenarios and to be resilient to climate change. The cooling database introduced in the report provides a knowledge base to existing cooling technologies and their applications in different types of residential buildings. However, there is a scope to expand this database to include cooling technologies relevant to commercial buildings.

The report discusses thermal comfort in the scope of European standards like EN 16798, and regional standards like ISSO 74. These studies can be further elaborated by including more international and ASHRAE standards. We have analyzed 3 different definitions of heatwaves in the report. RMI definition considers the maximum daily temperature, and the federal heat plan definition considers both maximum and minimum daily temperature, whereas Meteo France defines a heatwave based on the average daily temperature. The building sector plays a major role in energy demand and consumption for space heating and cooling. To ensure lower CO_2 emissions and better energy savings, it is important to improve the energy efficiency in the buildings. The report analyzes the different cooling technologies for residential buildings. The report also studies design day calculations and extreme events like heatwaves, power outages, etc.

Acknowledgments

I appreciate the financial support of the Service Public de Wallonie, Belgium, for funding this project through BElgian WAllonia Research (BEWARE) project and European Union (EU) framework program for research and innovation, Marie Skłodowska-Curie Actions for co-funding me through contract 847587, during my postdoctoral research, and the Sustainable Building Design (SBD) Lab, ULiege, for hiring me as an employee during the project. The project duration spans from April 01, 2021, to March 31, 2024. I would like to thank, Prof. Shady ATTIA for accepting to review this report, despite his active working schedules, and for his helpful comments. I would also like to address special thanks to Dr. Mirjana VELICKOVIC for collaborating with me on this project. I would also like to thank my colleagues from SBD Lab, MK Engineering, Project OCCuPANt consortium, and IEA Annex 80 - Resilient Cooling of Buildings for their constant support. I would like to acknowledge the Sustainable Building Design Lab for the use of lab facilities in this research and the valuable support during the experiments and the analysis of data.

Table of Contents

Abbreviations

AC - Air Conditioner
ASHP - Air Source Heat Pump
ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATM - Automated Teller Machine
BEWARE - BElgian WAllonia Research
CDD - Cooling Degree Days
EER - Energy Efficiency Ratio
EN - European Norms
EPBD - Energy Performance of Buildings Directive
ERA5 - ECMWF Reanalysis 5th Generation
EU - European Union
HDD - Heating Degree Days
IEA - International Energy Agency
ISO - International Organization for Standardization
MAR - Modèle Atmosphérique Régional
PMV - Predicted Mean Vote
PPD - Predicted Percentage Dissatisfied
RELi - REsilience action List
RMI - Royal Meteorological Institute
SBD - Sustainable Building Design
VRF - Variable Refrigerant Flow
WSHP - Water Source Heat Pump

List of Figures

List of Tables

1. Introduction

Overheating in buildings is expected to be more intense and prolonged due to the current rate of climate change and global warming. Indoor overheating significantly deteriorates the occupants' comfort, productivity, well-being, and health. Other factors like urbanization, urban densification, and urban heat island effect intensify the effects of overheating. There is a significant need for resilient building design and therefore it is mandatory to develop calculation methods and indicators to avoid overheating and invest in carbon-neutral cooling technologies and sustainable solutions. There is still a challenge of keeping the occupants safe, comfortable, and productive in an affordable way despite the rising temperatures and changes in the rainfall and solar irradiance.

Since the exceptional summer of 2003, extreme events like heatwaves are likely to become more frequent by the end of this century and there is a growing opportunity for the building designers to improve the thermal comfort and resilience of the buildings in Belgium. Considerations of the impacts of future climate are new territory for both clients and the construction sector. This framework has the potential to radically alter the way we design, construct, use, and adapt our buildings. As such, it could be a rich source of design inspiration as we develop elegant approaches to produce buildings that will be resilient in future that is both certain (change is inevitable) and uncertain (unclear rate and magnitude of change), as well as meeting challenging mitigation targets necessary to avoid the catastrophic events, such as climate change. In addition, the solutions to improve the resilience of buildings should be in a way that minimizes the future maintenance and operational costs of the buildings. As a result, the Belgian construction business can generate new income streams by providing much-needed climate adaptation expertise, frameworks, and solutions by developing strategies specific for the Belgian retrofit and construction projects.

Extreme climatic events like heatwaves are foreseen to become more frequent, intense, and longer in the future due to climate change. Recent studies have shown that the frequency and duration of heatwaves have increased in every region of the world, since the 1950s [1], [2]. In this scenario, the cooling system plays an important role in future building resilience [3] against climate change and other extreme weather events. Hence, it is an urgent need to implement resilient cooling technologies in existing and new buildings. The main objective of this report is to analyze the principles of thermal comfort in the buildings. The report is organized as follows:

- Chapter 2 describes the thermal comfort principles, including PMV/PPD and the adaptive thermal comfort model. Various standards like EN 16798 are also discussed in this chapter.
- Chapter 3 explains various overheating concepts like extreme events, such as heatwaves, power outages, urban heat island effects, etc.
- Chapter 4 introduces a cooling technology database that includes design day calculations for sizing and the most prominent residential cooling systems.
- Chapter 5 studies the weather and climatic patterns in Liege, Belgium, and identifies extreme events like heatwaves that occurred in Liege during 2020.
- Chapter 6 to 9 describes the discussions, conclusions, publications, and references of the report.
- The report also contains 5 different annexes, which add clarifications to different questions raised during project meetings, thermal comfort visualization, and project poster.

2. Thermal comfort

Thermal comfort is defined by ASHRAE 55 [4] as “the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation”. Thermal comfort can be assessed in two ways:

- steady-state or PMV/PPD
- adaptive or dynamic

Several international and national standards have been established with the purpose of “specifying the combinations of indoor thermal environmental factors that will produce thermal environmental conditions acceptable to a majority of the occupants within the space.” Those leading standards include ASHRAE 55 (2020) [4], EN 16798 (2019) [5], and ISO 7730 (2005) [6]. While these standards are primarily designed to define the thermal comfort conditions for spaces that are mostly consumed in sedentary positions like offices, theaters, lecture halls, etc. the application is not limited to only spaces as such. However, it is worth noting that the empirical foundation of those standards does not include any data for spaces used for sleeping, medical care/nursing, or heightened levels of physical activity. According to the standards listed above, occupant thermal comfort can be predicted based on air temperature, thermal radiation, humidity, air speed, as well as personal factors such as physical activity and the degree of clothing insulation. Numerical simulation helps predict those conditions already in the early stage of conceptualization.

2.1 PMV/PPD thermal comfort model

The applicability of the comfort models in different types of buildings is under debate to date. Initially, PMV/PPD models were suggested by the standards for the evaluation of thermal comfort. PMV/PPD models are aimed at determining the thermal comfort in steady-state conditions like in a climate chamber by assuming fixed values for the personal variables, such as clothing insulation or metabolic rate. The desired thermal conditions are assessed by regulating the environmental parameters, such as the temperature, velocity, humidity, and radiant temperature, and neglecting the adaptive opportunities taken by the occupants [7] in this methodology. These PMV/PPD models consequently led to the definition of the limits and ranges for the evaluation of thermal comfort. A widely accepted heat balance thermal comfort model that is referred to as Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) was developed by (Fanger, 1970) [8]. In Fanger’s model, PMV corresponds to the thermal sensation scale and PPD corresponds to the percentage of people who are likely to be dissatisfied in an environment. PMV index can be calculated through:

- 4 environmental parameters - air temperature, air velocity, radiant temperature, and humidity.
- 2 personal parameters - occupant activity and clothing.

According to this model, the requirements for PMV/PPD thermal comfort [9] are:

- the body is in heat balance.
- mean skin temperature and sweat rate, influencing the heat balance, are in prescribed limits.
- there are no local discomforts, such as draughts, radiant asymmetry, or temperature gradients.

In addition, the high frequency of temperature fluctuation should be minimized as well. According to Fanger’s model, PMV is given as follows:

$$PMV = \left(0.352 \times e^{-0.42\left(\frac{M}{A_{Du}}\right)} + 0.032\right) \times [\frac{M}{A_{Du}} \times (1-\eta) - 0.35 \times \Big[43 -$$

$$0.061 \times \frac{M}{A_{Du}} \times (1-\eta) - p_a \Big] - 0.42 \times \left[\frac{M}{A_{Du}} \times (1-\eta) - 50\right] - 0.023 \times \frac{M}{A_{Du}} (44 - p_a) - 0.0014 \times \frac{M}{A_{Du}} \times (34 - T_a) - 3.4 \times 10^{-8} \times f_{cl} \times [(T_{cl} + 273)^4 - (T_{mrt} + 273)^4 - f_{cl} \times h_{cl} \times (T_{cl} - T_a)] \tag{1}$$

Where, M is the metabolic rate production $[met]$, A_{Du} is the surface area of the human body $[m^2]$, η is the mechanic efficiency, p_a is the ambient vapor pressure $[\mathrm{Pa}]$, T_a is the ambient air temperature $[℃]$, f_{cl} is the clothing insulation factor $[\mathrm{clo}]$, T_{cl} is the surface temperature of clothing $[℃]$, T_{mrt} is the mean radiant temperature $[℃]$, h_c is the convective heat transfer coefficient $[W/m^2℃]$. The correlation between PMV and PPD is as given below:

$$PPD = 100 - \left(95 \times e^{-\left(0.03353 \times PMV^4 + 0.2179 \times PMV^2\right)}\right) \tag{2}$$

The operative temperature as defined in various international standards [4]-[6] is the uniform temperature of an imaginary black enclosure wherein a body would exchange the same amount of heat by convection and radiation as in the real non-uniform environment. It is defined as the average ambient air and mean radiant temperature weighted by corresponding heat transfer coefficients. The operative temperature can be derived as follows:

$$T_{op} = \frac{(h_r T_{mrt} + h_c T_a)}{h_r + h_c} \tag{3}$$

Where, h_r is the linear radiative heat transfer coefficient $[W/m^2℃]$.

ASHRAE 55 [4] defines the methods for calculating these important parameters. ISO 7730 [6] and EN 16798 [5] follows a similar method as suggested in ASHRAE 55. The ASHRAE 55 guidelines for the measurements are as follows:

- Through surveys of occupant responses to the environment with a survey response rate of greater than 35% for more than 45 participants, between 20 to 45 participants, at least 15 responses are required and for less than 20 participants, a response rate of 80% is required. These surveys could be either:
    - Satisfaction surveys: Thermal satisfaction surveys with diagnostic questions to identify the causes of thermal dissatisfaction and a scale with the choices from very satisfied to dissatisfied.
    - Point in time surveys: Thermal acceptability questions with a continuous or seven-point scale from very unacceptable and very acceptable.
    - Thermal sensation questions with the ASHRAE seven-point thermal sensation scale are subdivided as cold, cool, slightly cool, neutral, slightly warm, warm, and hot.
- Through physical measurement positions including the floor plan, height above the floor, timing, and device criteria:
    - Air temperature is measured at the center of the room or 1m inward of each wall, and at a height of 0.1, 0.6, and 1.1 m levels for seated occupants and at the 0.1, 1.1, and 1.7 m levels for the standing occupants for a period of 5 mins or more for a total time span of 2 hours or more.
    - Operative temperature shall be measured or calculated the center of the room or 1m inward of each wall or space and at the height of 0.6 m level for seated occupants and the 1.1 m level for standing occupants for a time of 5 mins or more for a total period of 2 hours or more.

- Floor temperature can be measured at the surface by a contact thermometer or infrared thermometer.
- Average air speed is measured at the 0.1, 0.6, and 1.1 m levels for seated occupants and at the 0.1, 1.1, and 1.7 m levels for the standing occupants for a time of 3 mins or more for a total period of 2 hours or more.
- Radiant temperature is measured in the affected occupants' location, with the sensor oriented towards the greatest surface temperature difference for a time of 3 mins or more for a total period of 2 hours or more.
- As for the device criteria:
    a. Air temperature is measured using a thermometer at a range of 10 °C to 40 °C with an accuracy of ± 0.2 °C.
    b. Mean radiant temperature is measured using a globe thermometer at a range of 10 °C to 40 °C with an accuracy of ± 1 °C.
    c. Relative humidity is measured using a hygrometer at a range of 25% to 95% with an accuracy of ± 5 %.
    d. Air speed is measured using an anemometer at a range of 0.05 m/s to 2 m/s with an accuracy of ± 0.05 m/s.
- Fixed values for different types of clothing are defined in ISO 7730 Annex C - Table C.1 [6]. These values vary from 0.70 clo to 2.55 clo for work clothing and 0.30 clo to 1.50 clo for daily wear clothing.
- Similarly, for metabolic activity values are given in ISO 7730 Annex B - Table B.1 [6]. The values vary from 0,8 met to 3,4 clo depending on the type of activity.

However, the overheating incidents seem to be overestimated in the PMV/PPD model, which considers the human body as a passive recipient of surrounding temperature and neglects its ability to adapt to the surrounding environment. This in turn predicts a higher cooling load to provide a thermally comfortable environment [10]. This creates an additional burden to the countries that are prone to fuel poverty. However, this approach is important for buildings, such as blood banks, museums, seed vaults, etc., where the indoor thermal conditions should not vary depending on the outdoor thermal environment.

2.2 Adaptive thermal comfort model

In the 1970s [11], stated that the human body is not a passive recipient of heat exposure. In contrast, it reacts through feedback between the thermal perception and occupant behavior in the buildings. Thus, they can tolerate a wider range of temperatures compared to the limits set by the PMV/PPD model. A Human body adapts to elevated temperatures through three different mechanisms:

- Physiological: physiological adaptation is the automatic response of the human body to the perceived thermal environment to reach thermally comfortable conditions [12].
- Psychological: psychological adaptation is an important factor when humans are exposed to thermal fluctuations in the environment to avoid discomfort through correlated factors such as naturalness, expectation, experience, time of exposure, environmental simulation, and perceived control [13].
- Behavioral: Behavioral adaptation in indoor spaces is the human conscious or unconscious attempt to create or maintain a favorable environment in case of stressful thermal conditions [14].

Since the year 2004, there is a growing trend towards the application of adaptive or dynamic models for the evaluation of thermal comfort. An adaptive approach to the thermal comfort questioning the validity of the steady-state model through several field studies was introduced in [11]. Adaptive models are based on surveys and monitoring data collected in real buildings. A direct correlation between indoor comfort temperature (T_{CO}) and outdoor temperature (T_{out}) in naturally ventilated buildings is explained in [15] and suggested the following linear equation,

$$T_{CO} = a.T_{out} + b \tag{4}$$

Where a, b are constants that are determined through regression methods applied to the results of the field studies [11]. There is a source of uncertainty in the determination of (T_{out}), where Humphreys initially suggested the use of monthly mean outdoor temperature. Subsequently, [16], [17], indicated that exponentially weighted running mean outdoor temperature leads to higher accuracy,

$$\theta_{rm} = (1-\alpha)(\theta_{ed-1} + \alpha.\theta_{ed-2} + \alpha^2.\theta_{ed-3}) \tag{5}$$

θ_{ed-1} & θ_{ed-i} is the daily mean outdoor air temperature for the previous day & i_{th} previous day $[°C]$,
α is the weighing factor $(0 \le \alpha \le 1)$, with a recommended value of 0.8.
Moreover, EN 16798 (2019) [5] followed the suit by introducing a factor for calculating approximate values, where daily running mean outdoor temperatures are not available. This factor is the arithmetic average of mean daily outdoor temperature over a certain period of days. When records of daily mean outdoor temperatures are not available:

$$\theta_m = \frac{(\theta_{ed-1} + 0.8\theta_{ed-2} + 0.6\theta_{ed-3} + 0.5\theta_{ed-4} + 0.4\theta_{ed-5} + 0.3\theta_{ed-6} + 0.2\theta_{ed-7})}{3.8} \tag{6}$$

Limits for different categories for Indoor operative temperature, θ_O:

Category I: upper limit: $\theta_O = 0.33\theta_{rm} + 18.8 + 2$
lower limit: $\theta_O = 0.33\theta_{rm} + 18.8 - 3$

Category II: upper limit: $\theta_O = 0.33\theta_{rm} + 18.8 + 3$
lower limit: $\theta_O = 0.33\theta_{rm} + 18.8 - 4$

Category III: upper limit: $\theta_O = 0.33\theta_{rm} + 18.8 + 4$
lower limit: $\theta_O = 0.33\theta_{rm} + 18.8 - 5$

Optimal operational temperature, $\theta_c = 0.33\theta_{rm} + 18.8$

The limits only apply when $10 \le \theta_{rm} \le 30\ °C$

Based on the outdoor running mean temperature, θ_{rm} & weighting factor, α. The standard implies that to use a value of $\alpha = 0.8$ only 3 days of data is required. This results in considering 48% of the temperatures measured on the previous days. This implementation has the consequence of giving false results for the evaluation of adaptive thermal comfort. According to our observations, if we want to use a value of $\alpha = 0.8$ then more than 25 days of data are needed. For $\alpha = 0.3$ at least 13 days of data is required. Unfortunately, the standard implies that the formula can be used with 3 days of data for an $\alpha = 0.8$ and this results in considering 48% of the temperatures measured on the previous days. This implementation has the consequence of giving false results for the evaluation of adaptive thermal comfort in the buildings.
The buildings are differentiated into categories I, II, and III in EN 16798. Category I includes the buildings such as senior houses and hospitals, where vulnerable age groups influence and people are present. Category II applies to all new residential buildings. Category III corresponds to the existing and old residential buildings. The main thermal comfort parameters are shown in Fig. 1. The figure

illustrates the external and internal parameters that influences indoor thermal comfort and the respective measurement devices. The figure considers both PMV/PPD thermal comfort model and adaptive thermal comfort model parameters.

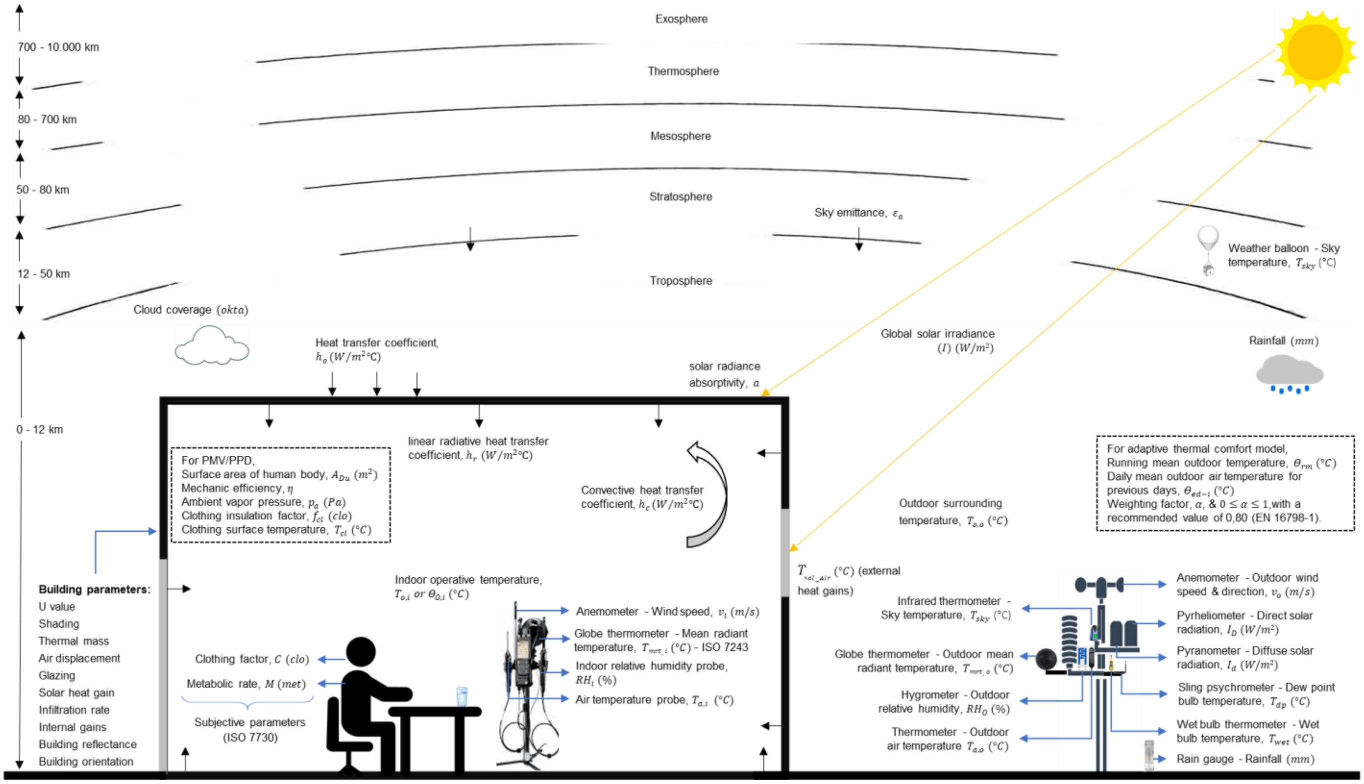


Figure 1. Thermal comfort parameters.

The main overheating concepts, such as heatwaves, power outages, and urban heat island effects are explained in the next chapter.

3. Overheating concepts

The main overheating concepts like extreme events, e.g., heatwaves, power outages, and urban heat island effects are detailed in the following sections.

3.1 Heatwaves

In Belgium, two different definitions of heatwaves exist. Royal Meteorological Institute (RMI) defines heatwaves as a period of 5 consecutive days with maximum daily temp. of 25 °C or more (summer days), including a 3 day-period of 30 °C or higher (tropical days) measured in Uccle [18], whereas the federal heat plan “heatwaves and ozone peaks” defines heatwaves as a period with a predicted minimum temperature of 18.2 °C or more for 3 days and a maximum temperature of 29.6 °C or higher [18]. IEA Annex 80 Resilient Cooling of Buildings has set different criteria for defining heatwaves. Heatwave criteria as per the Euro-Cordex [19] are:

- Intensity - Maximum temperature (°C)
- Duration - Number of days (days)
- Severity - Aggregated temperatures (°C.days)

These criteria are defined by Meteo France [19] as follows:

- A heatwave is detected when the daily temperature reaches at least once the S_{pic} value.
- The start of this heatwave is the first day on which the daily temperature is above S_{deb} value.

The heatwave is interrupted if:

- The daily temperature is below S_{deb} for at least 3 consecutive days, (or)
- The daily temperature falls back (even occasionally) to values below S_{int}.

According to S_{pic}, S_{deb}, and S_{int} values are defined as percentiles of the daily mean temperature distribution over several years to make the method accessible to any dataset.

- S_{pic} is the threshold for detection of the event = 26 °C
- S_{deb} is the threshold for beginning and end of the event = 23 °C
- S_{int} is the threshold for merging two consecutive events = 20 °C

S_{pic} (99.5 percentile), S_{deb} (97.5 percentile), and S_{int} (95 percentile) values are depicted in Fig. 2.

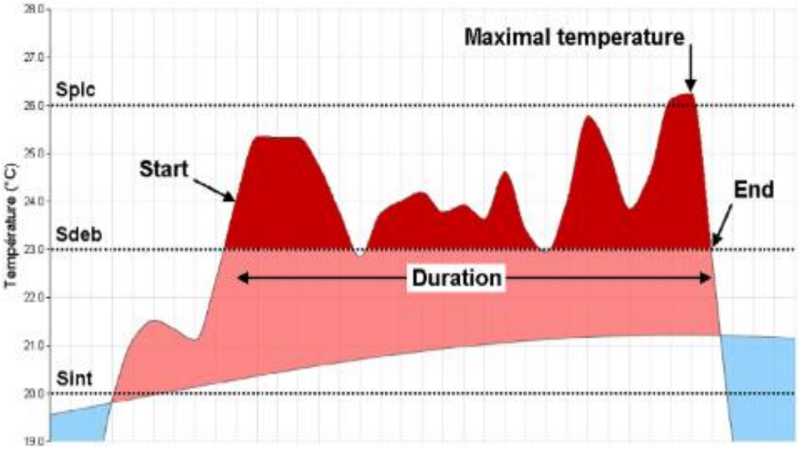


Figure 2. Heatwave definition [19].

In this report, we consider the method used by IEA Annex 80 - Resilient Cooling of Buildings [19], [20]. The weather patterns in Liège, Belgium, is analyzed in Chapter 5 using this methodology. Overheating in buildings is one of the major adverse impacts of heatwaves. The Belgian EPBD calculation method for dwellings is based on a quasi-steady-state calculation method of the overheating risk is used for calculations in Belgium [21]. The overheating indicator currently used in Belgium is based on the German research, which was performed in the 1990s and presented by the Czech Society of Environmental Engineering during the REHVA World Congress and International Conference on Indoor Air Quality in 2013 [22]. The overheating calculation uses the input and calculation parameters that are part of the ISO 13790 [23] and CEN 15251 [24] calculation method for heating. The method defines the overheating indicator as to the sum of the monthly normalized excess heat gains.

$$I_{overh} = \sum_{m=1}^{12} \frac{(1-\eta_{C\cdot gn})\cdot Q_{C\cdot gn}}{H_{tr,adj}+H_{ve,adj,ext}+H_{ve,adj,hyg}} \cdot \frac{1000}{3.6} \tag{7}$$

Where, I_{overh} is the overheating indicator (Kh), $\eta_{C\cdot gn}$ is the utilization factor for heat gains in case of cooling, possibly taking also passive cooling techniques into account (-), $Q_{C\cdot gn}$ is the monthly internal and solar heat gains (MJ), $H_{tr,adj}$ is the heat transfer coefficient for transmission (W/K), $H_{ve,adj,ext}$ is the heat transfer coefficient for ventilation with outside air (W/K), $H_{ve,adj,hyg}$ is the heat transfer coefficient for ventilation with preconditioned air (W/K). An overheating indicator of 11000 Kh/year would correspond to temperatures higher than 23°C. The use of the limit value allows adopting fictitious cooling in dwellings without mechanical cooling. A fictitious cooling demand calculates if mechanical cooling was installed, and a probability $p_{cool,seci}$ (-), which depends on the overheating risk [25]. This intervention penalizes the contingent installment of mechanical cooling after completing the dwelling as described in [22].

$$p_{cool,seci} = max\left\{0, min\left(\frac{I_{overh,seci}-I_{overh,tresh}}{I_{overh,max}-I_{over,tresh}}, 1\right)\right\} \tag{8}$$

Where $p_{cool,seci}$ is the probability that mechanical cooling is installed in energy sector I (-),$I_{overh,seci}$ is the overheating indicator of energy sector I (Kh), $I_{overh,tresh}$ is the minimum overheating indicator above which mechanical cooling possibly is installed in energy sector I (Kh), set equal to 8000 Kh, $I_{overh,max}$ is the maximum overheating indicator in energy sector I (Kh), set equal to 17500 Kh. The power outages associated with heatwave events are described in the next section.

3.2 Power outages

A power outage is an event, where there is a loss of electric power network supply to the end-user. RELi 2.0 Rating guidelines [26] for resilient design and construction provide guidelines for mitigating power outages during extreme events like heatwaves. The RELi 2.0 is a rating system, which is holistic, resilience-based, and combines innovative design criteria for next-generation homes, buildings, neighborhoods, and infrastructure with novel integrative design processes. Hazard mitigation and adaptation guidelines for protection against power outages from the grid during heatwave events are included in this rating system. Some of the guidelines [26] include:

- Critical utilities such as HVAC and boilers must be provided with permanent backup power, switching gear, and/or power hook-ups, and infrastructure for temporary generators to provide power in extreme scenarios.
- Equipment and infrastructure should be located above the 500-year floodplain.

- Develop a detailed flood protection plan, and provide on-site supplies, and infrastructure for protecting existing facilities with switchgear, infrastructure, and/or fuel storage, which are located below the 500-year floodplain elevation.
- If necessary, to ensure protection, modify the existing infrastructure according to the guidelines.

The rating system also provides guidelines for the duration over which backup power [26] should be provided in case of extreme events like heatwaves. Either these guidelines or local guidelines should be met, depending on which one is more stringent.

- For residential Buildings, lodging, hospitals, nursing homes, emergency shelters, and emergency facilities like fire stations, 911 call centers, police stations, etc., backup power should be provided for 4 consecutive days, 24 hours per day.
- For establishments, such as pharmacies, convenience stores, grocery stores, and facilities with significant stocks of refrigerated or frozen food and Automated Teller Machines (ATMs) at these facilities should have backup power for 4 consecutive days, with 8 hours each during the day for general operations. For refrigeration and freezers, 4 consecutive days with 24 hours of backup power.
- For establishments like gas stations, 4 consecutive days with 12 hours each day or until the stocks are depleted preferably during daylight hours. These should also have backup power or built-in handpumps for fuel distribution.
- ATMs at facilities like banks, credit unions, malls, etc., should have backup power during normal business hours.

For all facilities above except hospitals, nursing homes, and emergency services, backup power for one-half of the duration identified excluding elevators, for solar or wind electric systems and battery storage. The maximum and minimum indoor temperatures that should be maintained during a power outage are as follows [26]:

- Mission-critical or fundamental community service organizations: ≤ 39.44 °C during hot seasons, ≥ 10 °C for cold seasons.
- Hospitals and nursing homes: ≤ 27.22 °C during hot seasons, ≥ 21.67 °C for cold seasons.
- General residential buildings, facilities, and areas: ≤ 32.22 °C during hot seasons.
- Commercial buildings: ≤ 39.44 °C during hot seasons, unless external temperature exceeds 39.44 °C.

Urban heat island effect is another important extreme event that adds to thermal discomfort in urban areas. This is discussed in the following section.

3.3 Urban heat island effects

Urban heat island effect occurs when cities replace the natural land cover with dense concentrations of buildings, pavement, & other surfaces that absorbs & retains heat. The main effects of urban heat islands are increasing energy costs, air pollution levels, heat-related illness & mortality [27]. A typical comparison of rural areas and urban areas with heat island effect are shown in Fig. 3. Various factors that contribute to urban heat island effects are illustrated in Fig. 3.

Urban weather generator (UWG) is a software that can model multiple typologies & visualize the simulation results [28]. The output of this generator is a morphed EnergyPlus Weather file (epw) that captures the urban heat island effect. This output file is compatible with many building performance simulation programs, like EnergyPlus.

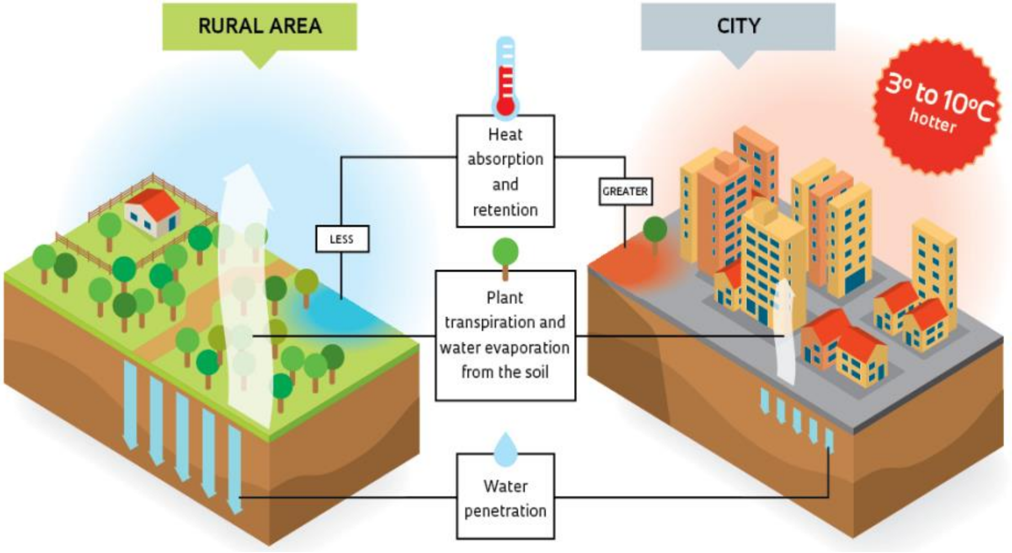


Figure 3. Urban heat island effect [2929].

The main steps of developing a UWG file [28] is as follows:

- Obtain a weather file in epw format for the reference site.
- Create a custom input file considering the important parameters, such as meteorological parameters, reference site parameters, etc., for the studied city.
- Run UWG with your epw and xml (or xlsm) files.
- The resulting epw file captures the urban heat island effect.

Efficient and sustainable cooling technologies are one of the solutions to tackle overheating in buildings. The cooling technologies and their sizing methodology are explained in the following chapter.

4. Cooling technology database

This chapter explains the sizing of cooling technologies and the most prominent cooling systems used in the residential sector.

4.1 Design day calculations

Design day calculations are used for sizing a cooling system or a heating system based on the location of the analysis. Summer design days are used for sizing a cooling system and Winter design days are used for sizing a heating system. Design day calculations should be performed in compliance with standards, such as ISO 15927-2 (2009) [30] and ASHRAE handbook (2017) [31]. The design day calculations according to ISO 15927-2 is as follows.

- Identify the parameters to be used to construct the design days.
- For each calendar month, calculate:
  - The daily mean dry-bulb temp., daily total global solar radiation exceeded 1%, 2%, or 5%.
  - If relevant, the daily mean dew point temp. exceeded 1%, 2%, or 5%.
  - The daily mean wind speed & daily change in dry-bulb temp. exceeded 99%, 98%, and 95%.
- These percentiles are the confidence levels as suggested by the standard.
- Define intervals for each parameter and identify the risk levels.
- For each calendar month and each of the 3 risk levels, identify the days for which the daily means of all the parameters used to fall within the error bands.
- The 3 possibilities include:
  - One day is identified, this is the design day.
  - More than 1 day is identified, progressively reduce the intervals, one at a time.
  - No days are identified, progressively increase the intervals, one at a time.
- This procedure is repeated until a day is identified and is provided in ISO 15927-2 Annex A [30].

Design day calculation can be also performed using DesignBuilder software. The conditions for using DesignBuilder to perform design day calculations are as follows [32].

- The thermal comfort criteria must be maintained for a confidence level of 99.6% of the whole year.
- Design day calculation is based on effectively the worst-case day for cooling or heating loads.
- These calculations determine the equipment capacity, fan sizes, the duct sizes and impact the peak KW demand of the building.
- Design day calculations depend on the location & solar angle of the building.
- ASHRAE Handbook (2017) [31] gives a detailed procedure on how to perform these calculations.
- With DesignBuilder, summer design day calculations are made for the month of July for the northern hemisphere and January for the southern hemisphere.

Since the project focuses on the overheating and thermal comfort in the buildings, summer design day calculations are given more priority.

a. Heating degree days

Heating degree days (HDD) is an indicator, which is a measure of amplitude in degrees, and the duration, outside air temperature, was lower than a specific base temperature. They are used to calculate the energy consumption required to heat the buildings [33], [34]. The HDD values are calculated as follows:

Example 1: The high temperature for a particular day was 12 °C and the low temperature was 8 °C. The mean temperature for that day was:

$$\frac{(12\,°C\ +\ 8\,°C)}{2} = 10\,°C$$

Since the result is less than the threshold of 15 °C:

$$15\,°C - 10\,°C\ =\ 5\,°C\ (HDD/day)$$

b. Cooling degree days

Cooling degree days (CDD) is an indicator, which is a measure of amplitude in degrees, and the duration, outside air temperature, was higher than a specific base temperature. They are used to calculate the energy consumption required to cool the buildings [33], [34]. The CDD values are calculated as follows:

Example 2: The high temperature for a particular day was 35 °C and the low temperature was 25 °C. The mean temperature for that day was:

$$\frac{(35\,°C\ +\ 25\,°C)}{2} = 30\,°C$$

Since the result is greater than the threshold of 24 °C:

$$30\,°C - 24\,°C\ =\ 6\,°C\ (CDD/day)$$

The residential cooling systems, which are used to avoid overheating in residential buildings are detailed in the next section.

4.2 Residential cooling systems

Cooling technologies can be differentiated into passive and active cooling technologies. Passive cooling technologies use an approach with zero to low energy sources to control the heat gain and dissipation to maintain and improve the thermal comfort in the building. Passive cooling technologies [35] either use prevention designs, such as shading, glazing, etc., or modification designs, such as thermal storage, night cooling, etc., or dissipation designs, such as natural ventilation, evaporative cooling, earth cooling, etc.

With recent environmental awareness, there is an increased interest in the implementation of effective passive cooling technologies in the new and existing building stock. In certain conditions like the location and design of the buildings, passive cooling technologies might not be fully efficient to ensure the desired rate of thermal comfort. Thus, we go for active cooling systems. The active cooling technologies use an approach with an energy source to control the heat gain and dissipation to improve the thermal comfort in the building. An active cooling system may include fans, chillers, air conditioners like split systems, and these vary in size, energy consumption, and cost. An active cooling system needs to be properly sized in the beginning stages of designing a building to ensure effective cooling in the building. Active cooling system relies on either electricity or other forms of fuel, which makes it less carbon neutral compared to passive cooling technologies. Therefore, the cooling technologies used in a building depend on the factors, such as the building function, cooling demand, and financial resources. A detailed database on different residential cooling systems is listed in Table 1. A list of the most prominent cooling systems used in the residential sector is shown in Fig. 4.

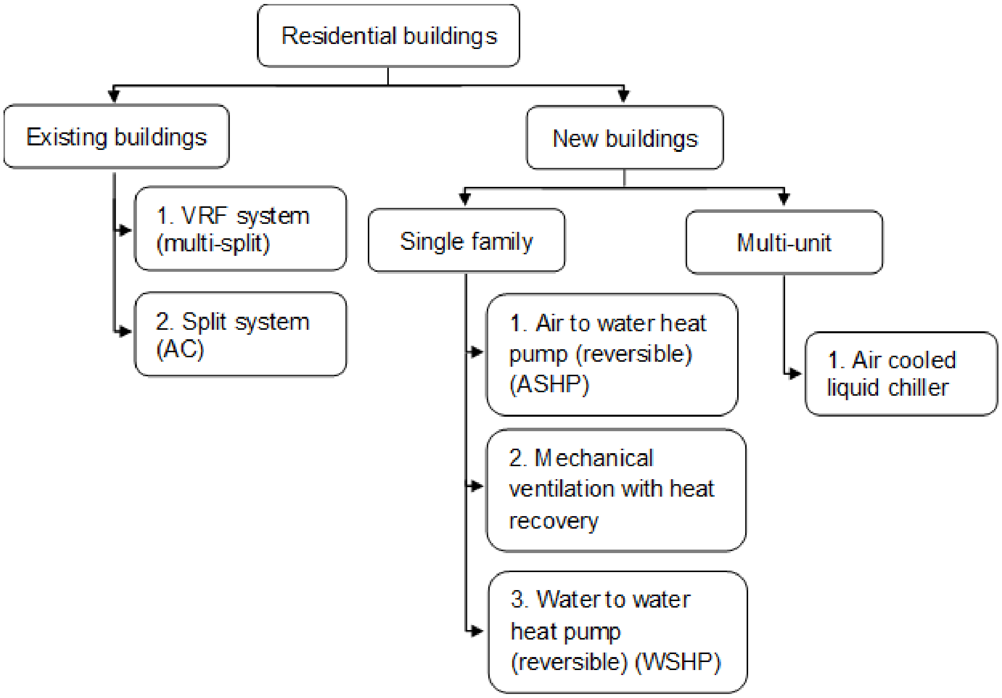


Figure 4. Prominent cooling systems for residential buildings.

Table 1 lists the different cooling systems based on their manufacturer, production side, distribution side, etc.

Table 1. Cooling system details for residential buildings.

Existing residential buildings		
1. VRF system (multi-split)		
a. Manufacturer		Hitachi (a)
b. Production side		Refrigeration compressor
c. Distribution side		Fan coils
d. Humidity control		No
e. Storage characteristics		Cooling towers
f. EER		4,24 - 5,75 (b)
g. Cost	System	3.850 - 47.000 € (b)
	Running cost per year (a small residential unit)	582 € (c)
h. Total sales		100.000 (d)
i. Market penetration		5,11 (d) (in EU per 100 households)
2. Split systems (AC)		
a. Manufacturer		Daikin (e)
b. Production side		Heat exchanger

c. Distribution side		Fan coils		
d. Humidity control		Yes		
e. Storage characteristics		External environment		
f. EER		3,59 - 4,53 (e)		
g. Cost	System	1.100 - 1.900 € (f)		
	Running cost per year (a small residential unit)	142,60 - 369,20 € (g)		
h. Total sales				
i. Market penetration				
New residential buildings				
Single family detached houses				
1. Air to water heat pump (reversible) (ASHP)				
a. Manufacturer		Mitsubishi (h)	Daikin (i)	Panasonic (j)
b. Production side		Outdoor coil with refrigeration compressor		
c. Distribution side		Floor cooling & ventilo-convector		
d. Humidity control		No		
e. Storage characteristics		Hydronic tanks		
f. EER		3,14 - 3,84 (k)	4,05 - 4,56 (l)	4,74 (j)
g. Cost	System	7.000 - 14.000 € (m)	7.000 - 14.000 € (n)	3.000 - 10.000 € (o)
	Running cost per year (single family detached house)	1.016 € (p)		
h. Total sales		121.586 (q)		
i. Market penetration		22,55 (q) (Heat pumps in EU per 100 households)		
2. Mechanical ventilation with heat recovery				
a. Manufacturer		Zehnder (r)	Mitsubishi (s)	Brink (t)
b. Production side		Fan coils		
c. Distribution side		Fan coils		
d. Humidity control		No		
e. Storage characteristics		External environment		
f. Heat recovery performance		96% (s)	73% (u)	91% (t)
g. Cost	System	6.700 € (v)	16.768 - 42.784 € (w)	2.860 € (x)
	Running cost per year (single family detached house)			

h. Total sales				
i. Market penetration				
3. Water to water heat pump (reversible) (WSHP)				
a. Manufacturer		Mitsubishi (y)		
b. Production side		Groundwater, e.g., borewells		
c. Distribution side		Floor cooling & ventilo-convector		
d. Humidity control		No		
e. Storage characteristics		Bore wells		
f. EER		4,50 (y)		
g. Cost	System	21.000 € (z)		
	Running cost per year (single family detached house)	650 € (aa)		
h. Total sales		94.480 (q)		
i. Market penetration		22,55 (q) (Heat pumps in EU per 100 households)		
Multi-unit residential buildings				
1. Air cooled liquid chiller				
a. Manufacturer		Toshiba (ab)	Carrier (ac)	
b. Production side		Cooling tower with refrigeration compressor		
c. Distribution side		Heat absorber		
d. Humidity control		No		
e. Storage characteristics		Cooling water tower		
f. EER		2,83 - 4,72 (ab)	2,90 - 4,11 (ac)	
g. Cost	System		6.400 € (ad)	
	Running cost per year (150kW capacity)	31.468 € (ae)		
h. Total sales		1034.8 M€ (af)		
i. Market penetration				

Table 1 references:

[a]https://www.jci-hitachi.com/outdoor/hptypes_ns-npseries/pdf/brochure.pdf

[b]https://www.hawco.co.uk/media/pdf/Hitachi_2018_Price_List.pdf

[c]https://modbs.co.uk/news/fullstory.php/aid/6030/VRF_systems_that_are_truly_energy_efficient.html

[d]https://www.applia-europe.eu/images/Library/Review_Study_on_Airco_05-2018.pdf

[e]https://www.daikin.co.uk/content/dam/dauk/document-library/data-sheet/ac/split_skyair_r410a/split/Emura_UKEPLEN15-201_LR.pdf

[f]https://www.orionairsales.co.uk/daikin-air-conditioning-emura-aluminium-or-white-casing-wall-mounted-ftxg--ftxj-using-r32-374-c.asp

[g]https://www.topten.eu/private/products/air_conditioners?filters%5Bbrand%5D%5B%5D=Daikin&filters%5Btype_of_air_conditioner%5D%5B%5D=split&sort_attribute=cost_electricity_10yrs&sort_direction=4

[h]https://planetaklimata.com.ua/instr/Mitsubishi_Electric/Mitsubishi_Electric_Ecodan_Data_Book_Eng.pdf

[i]https://www.daikin.eu/content/dam/internet-denv/catalogues_brochures/residential/Daikin%20Altherma%203%20M_Product%20catalogue_ECPEN20-756_English.pdf

[j]https://www.panasonicproclub.com/uploads/HR/catalogues/EU_AQUAREA_231211.pdf

[k]https://termo-plus.com/products/hybrid-air-source-heat-pumps/#specifications

[l]https://www.daikin.eu/content/dam/document-library/catalogues/heat/air-to-water-heat-pump-high-temperature/ekhbh-a/Altherma%20technical%20catalogue%20for%20installers_EPCEN08-721_Catalogues _English.pdf

[m]https://www.boilerguide.co.uk/air-source/mitsubishi

[n]https://www.boilerguide.co.uk/air-source/daikin

[o]https://www.panasonicproclub.com/uploads/IE/catalogues/IRE%20A2W%20PRICE%20LIST%2019% 20LR.pdf

[p]https://www.edfenergy.com/heating/advice/air-source-heat-pump-guide

[q]http://www.stats.ehpa.org/hp_sales/story_sales/

[r]https://www.international.zehnder-systems.com/products-and-systems/comfosystems/zehnder-comfoair-350

[s]https://www.zehnder.co.uk/download/29630/118734/en_uk-72926.pdf

[t]https://www.brinkclimatesystems.nl/documenten/technical-sheet-flair-325.pdf

[u]https://www.coolingpost.com/products/mitsubishi-conjures-the-wizard-ahu/

[v]https://www.buildinggreen.com/blog/how-we-chose-our-heat-recovery-ventilator

[w]https://qualcomfort.ro/catalog-preturi-produse-mitsubishi-electric.pdf

[x]https://boutique.brinkclimatesystems.fr/flair-325/567-flair-325-40-r-fr.html

[y]https://www.deltatechniki.gr/wp-content/uploads/2019/02/WWH-HT_0071-0302.pdf

[z]https://www.boilerguide.co.uk/ground-source/mitsubishi-ground-source-heat-pumps

[aa]https://www.viessmann.co.uk/heating-advice/Do-heat-pumps-use-a-lot-of-electricity

[ab]https://www.carrier.com.hk/comm/comm_new2010/Toshiba%20USX%20EDGE.pdf

[ac]https://www.shareddocs.com/hvac/docs/1001/Public/0A/Carrier-Catalogue-2018-2019/1/Carrier-Catalogue-2018-2019.pdf

[ad]https://www.andrianos.gr/en/eshop/heat-pumps/heat-pump-carrier-aqua-snap-plus-30awh-015-3ph

[ae]https://www.euroheat.org/wp-content/uploads/2016/04/SUMMERHEAT_Report.pdf

[af]https://refindustry.com/articles/mart-research/the-hvac-r-market-in-the-emea-region-in-2018/

Terminology:

A. REHVA (https://www.rehva.eu/fileadmin/HVAC_Terminology /4th_Draft_2012.0 5.02_-_HVAC_ Terminology.pdf)

B. EHPA (https://www.ehpa.org/technology/glossary/)

5. Climate data - Belgium

The weather patterns in Liège, Belgium is studied for a time frame of 2015 - 2020, using weather files developed using Modèle Atmosphérique Régional (MAR) for outdoor thermal conditions and monitored data for indoor thermal conditions. The analysis and validation of weather files are described in the following sections.

5.1 MAR modeling

The weather files were developed in compliance with ISO 15927-4 (2005) [36] based on the MAR forced by the reanalysis model ERA5 based on the real observation [37]. The location of the study is Liege in Belgium, with a coordinate of 50.6326° N, 5.5797° E. MAR can effectively represent variability in the Belgian climate and is shown in Fig. 5. This model was developed at the end of the 1990s to study the polar regions especially melting Greenland and on which the University of Liege's Climate Laboratory is actively working, e.g., to study floods in the Ardennes. The model works effectively in the context of Belgium. The forecasts are updated automatically every 12 hours at 08h00 and 20h00 in the climato database.

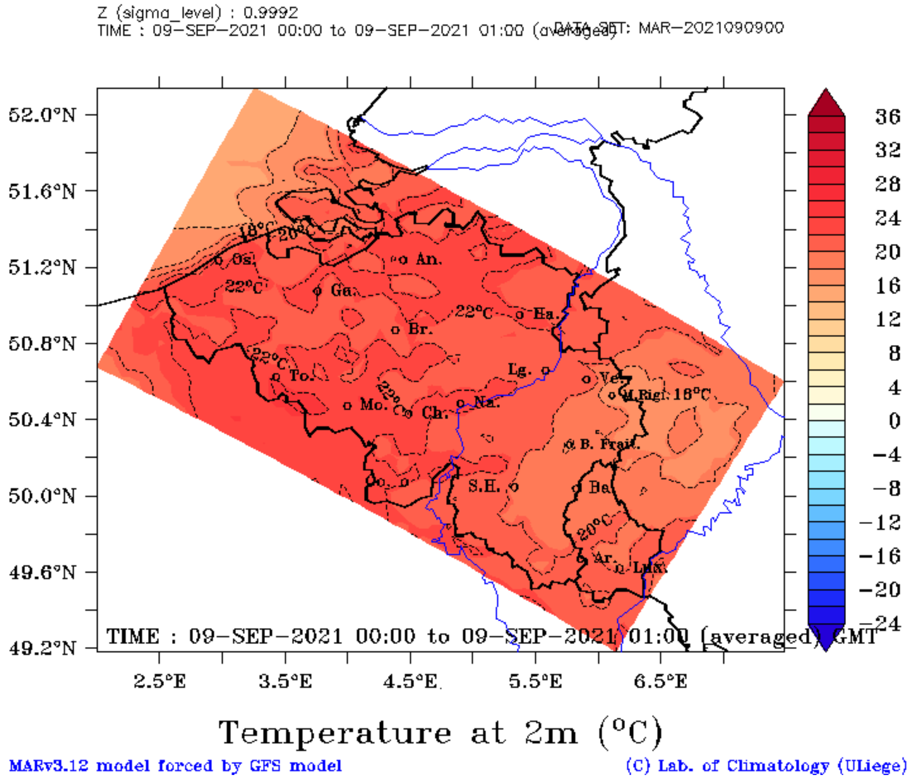


Figure 5. Temperature readings from MAR [37].

The analysis of annual weather patterns and heatwaves using this model is explained in the next section.

5.2 Data analysis

HDD and CDD are obtained from the Eurostat application [33], where HDD and CDD are derived from meteorological observations of parameters, such as air temperature, interpolated to regular grids at 25 km resolution for Europe. HDD index is a weather-based technical index that describes the heating energy requirements of buildings and CDD index is a weather-based technical index that describes the cooling (air-conditioning) requirements of buildings [33].

HDD comparisons for Liege and Belgium from the years 1980 - 2020 are shown in Fig. 6. The figure shows a decreasing trend in HDDs from 2015 to 2020. In addition, the HDD value for Liege is lower compared to the average value for the whole of Belgium indicating warmer winter seasons.

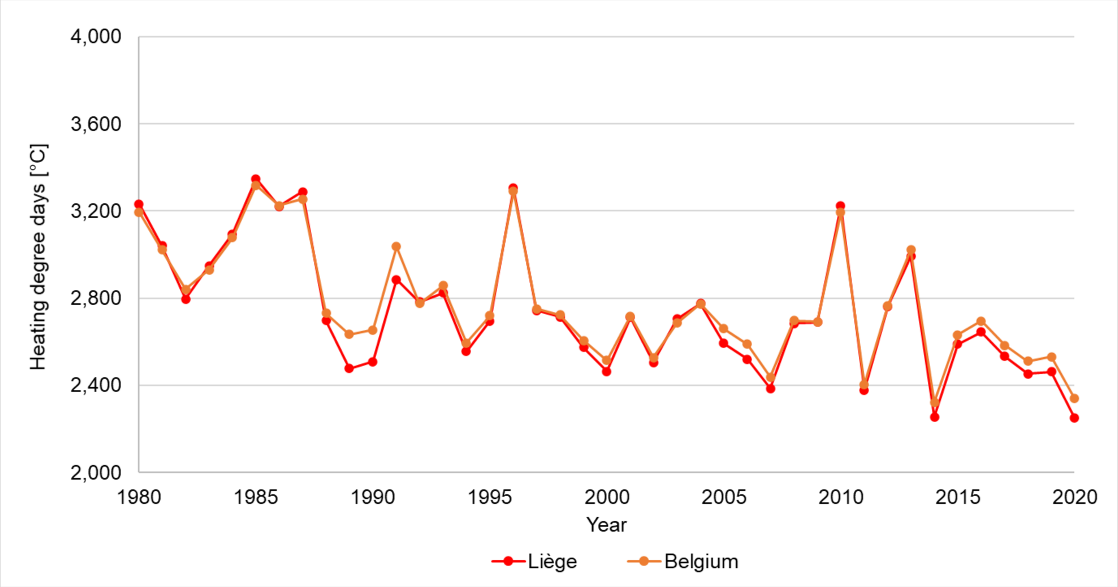


Figure 6. Heating degree days comparison between Liege and Belgium.

CDD comparisons for Liege and Belgium from the years 1980 - 2020 are shown in Fig. 7. The figure shows an increasing trend in CDDs from 2015 to 2020. In addition, CDD value for Liege is much higher compared to the average value for whole of Belgium indicating to hot summer seasons.

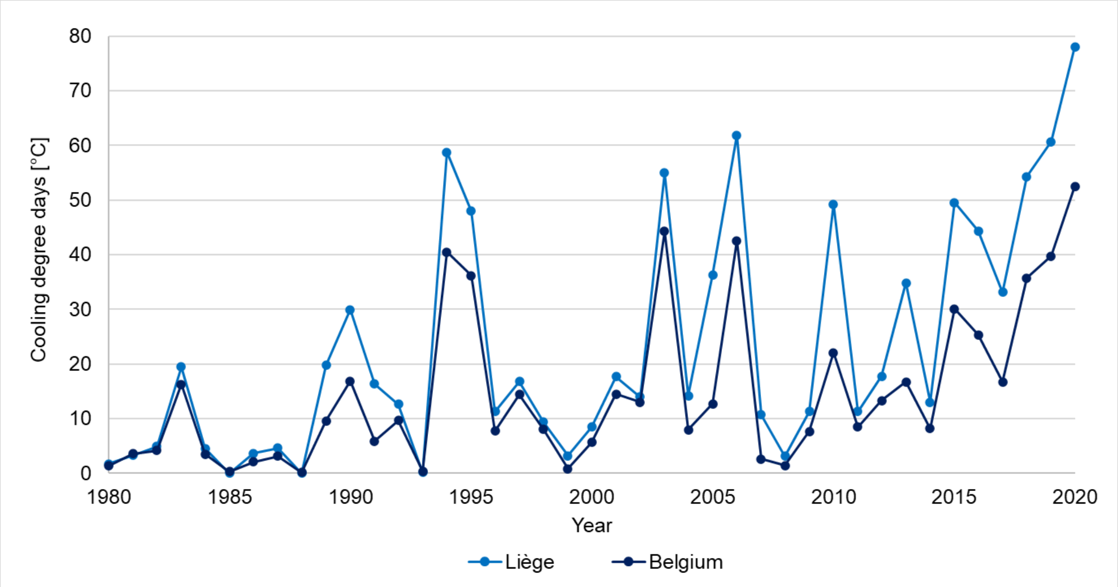


Figure 7. Cooling degree days comparison between Liege and Belgium.

The CDD values from the years 2015 - 2020 indicate that 2020 was the worst year in terms of cooling requirements in this time frame. Therefore, both HDD and CDD values point towards an increase in air temperature in Liege and legitimize the need for the implementation of sustainable cooling technologies. Hence, we will analyze the presence of heatwaves according to definitions of RMI [1818], Federal heat plan [18], and Meteo France [19], for the year 2020.

The following criteria are used for the analysis of weather data in Liege, Belgium. Weather files from MAR forced by the reanalysis model ERA5 based on the real observation are used here for the year 2015 - 2020. Since we already know that 2020 was the worst year in this time frame, indoor operative temperature and outdoor air temperature are overlaid on EN16798 (2019) [5], upper and lower limits of category I and category II. This is done for both PMV/PPD and adaptive thermal comfort models and is shown in Fig. 8. The remaining years only overlay external air temperature and is added in Annex C.

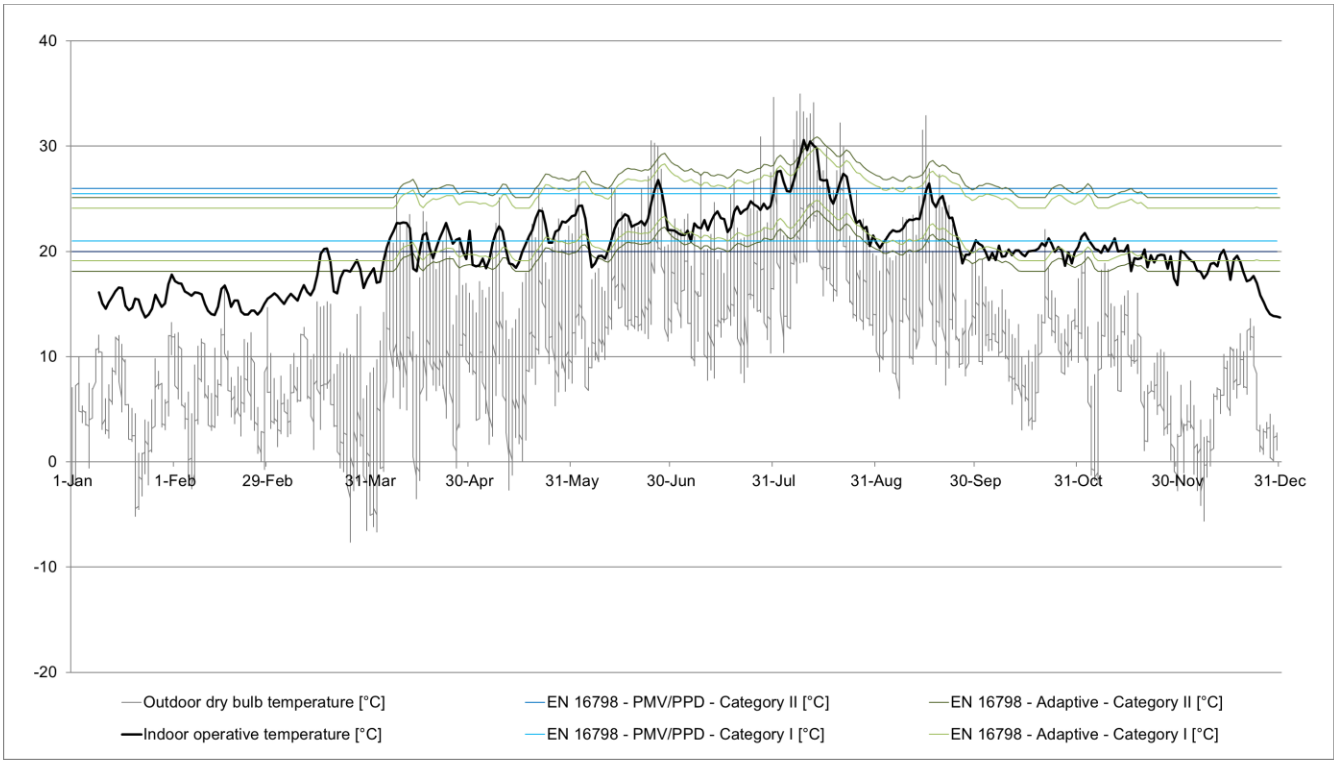
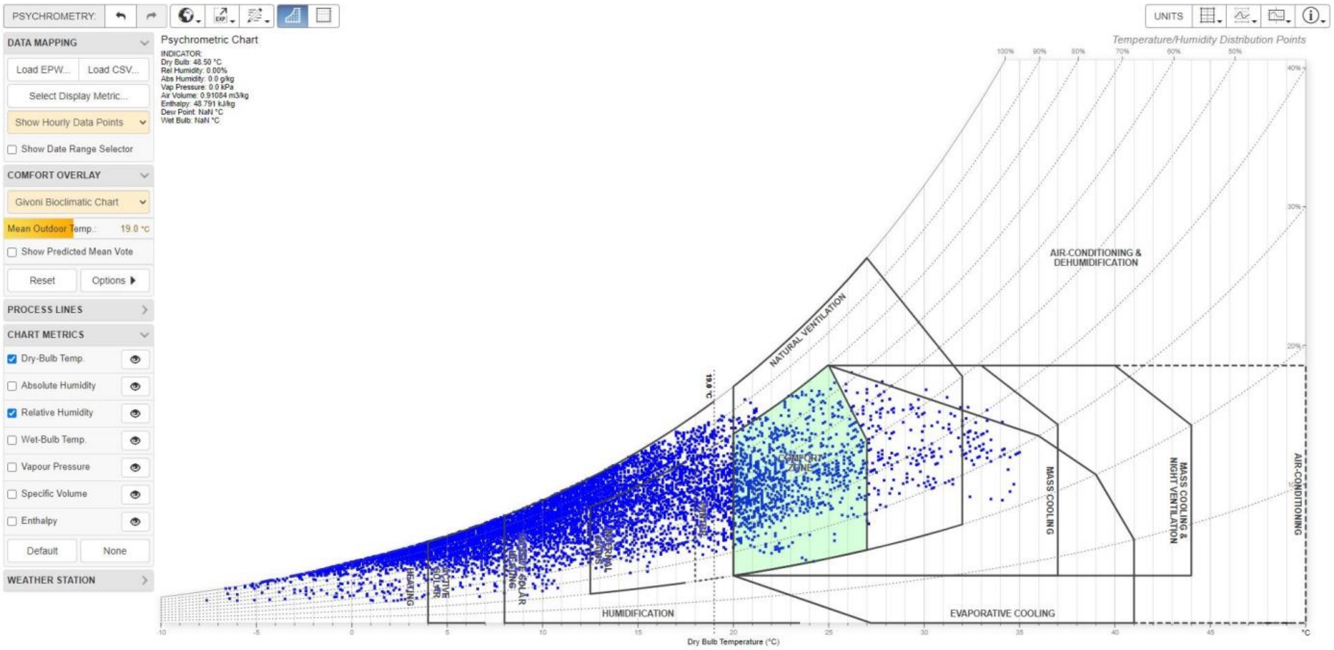


Figure 8. Annual outdoor air temperature distribution (MAR-ERA5) for 2020.

Indoor operative temperature range is outside both PMV/PPD and adaptive thermal comfort limits during the first weeks of August 2020. Another important criterion to be noted here is that when we calculate the adaptive model to running mean outdoor temperature, the limits tend to exceed 30 °C and more. These limits in real scenarios might not be considered as comfortable. This is to be noted for future standard developments.

The outdoor air temperature points are overlaid on a psychrometric graph with Givoni bioclimatic overlay in Fig. 9. This is a representation of limits for different technologies like humidification, natural ventilation, evaporative cooling, etc. In addition, indoor thermal comfort to different standards like EN 16798 (2019) - PMV/PPD [5], and adaptive thermal comfort model [5], ISSO 74 (2014) [38], Passive house (2016) [39] based on EN 15251 (2007) - PMV/PPD model [24], and psychrometric chart for 2020 outdoor air temperature to relative humidity overlaid on Givoni bioclimatic model [40]. The location of study is an apartment located in Outremeuse, Liege, Belgium for 2020.



Psychrometric Chart

INDICATOR:
Dry Bulb: 48.50 °C
Rel Humidity: 0.00%
Abs Humidity: 0.0 g/kg
Vap Pressure: 0.0 kPa
Air Volume: 0.91084 m3/kg
Enthalpy: 48.791 kJ/kg
Dew Point: NaN °C
Wet Bulb: NaN °C

Show Hourly Data Points
☐ Show Date Range Selector
Givoni Bioclimatic Chart
Mean Outdoor Temp.: 19.0 °C
☐ Show Predicted Mean Vote
☑ Dry-Bulb Temp.
☐ Absolute Humidity
☑ Relative Humidity
☐ Wet-Bulb Temp.
☐ Vapour Pressure
☐ Specific Volume
☐ Enthalpy

Figure 9. Givoni bioclimatic overlay for outdoor air temperature for 2020.

Indoor thermal comfort as per EN 16798 - PMV/PPD thermal comfort model for categories I, II, III, and IV is shown in Fig. 10 [5]. The daily indoor operative temperature values are calculated and mapped to outdoor mean running temperature.

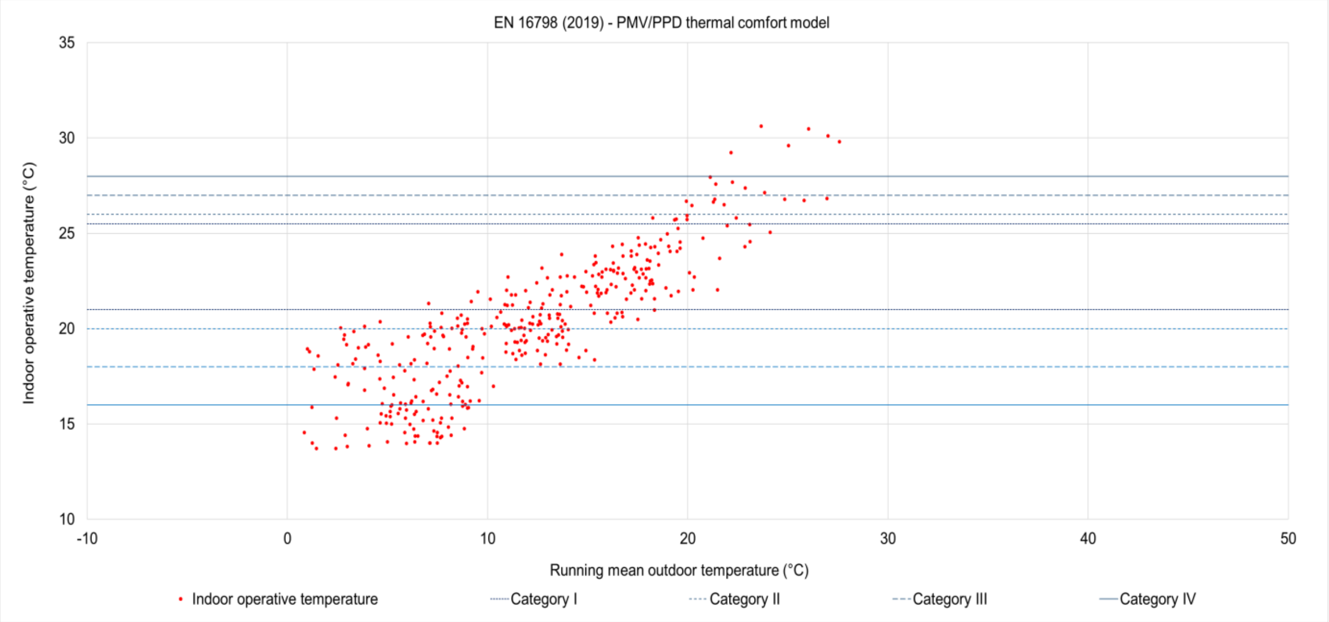


Figure 10. Indoor temperature distribution wrt PMV/PPD model for 2020.

Indoor thermal comfort as per EN 16798 (2019) - Adaptive thermal comfort model for categories I, II, and III is shown in Fig. 11 [5].

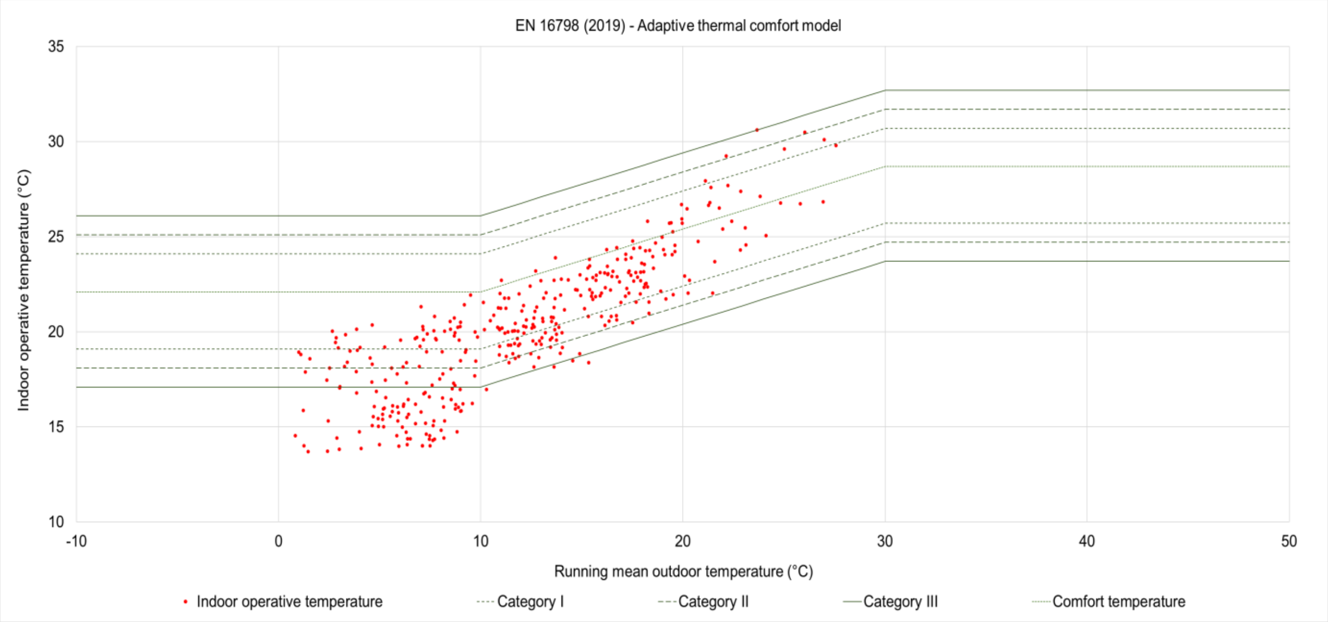


Figure 11. Indoor temperature distribution wrt adaptive model for 2020.

Indoor thermal comfort as per ISSO 74 (2014) - Adaptive thermal comfort model for Class B, C, and D for building type α and β is shown in Fig. 12 [38].

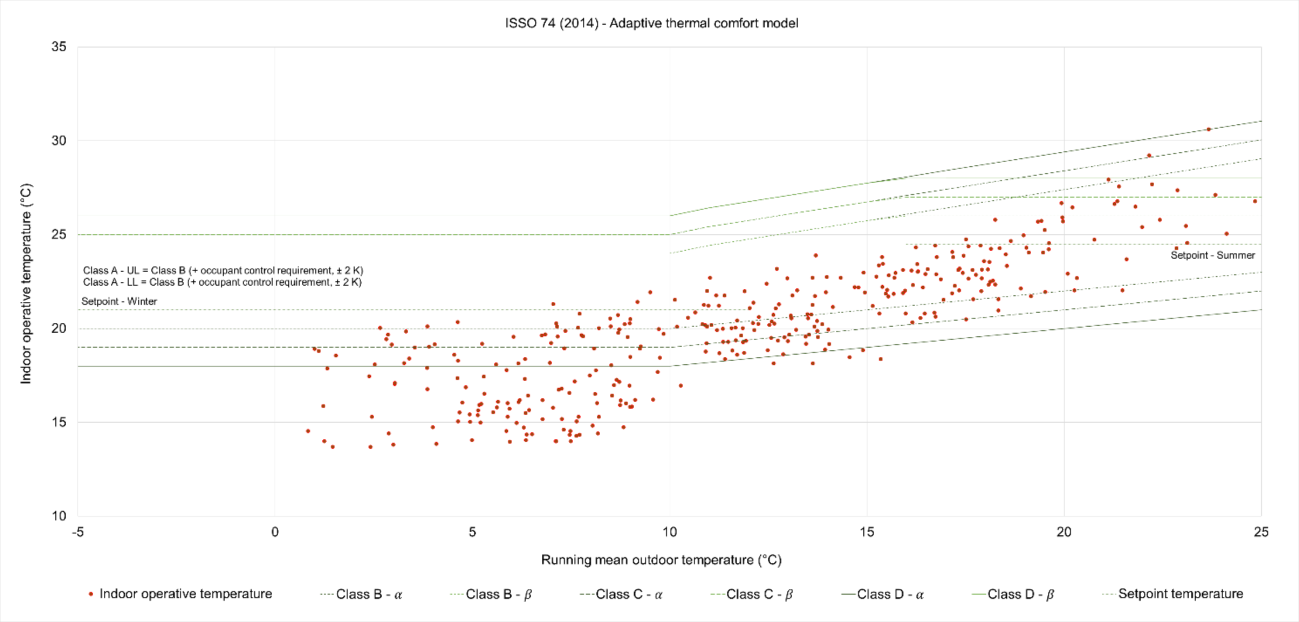


Figure 12. Indoor temperature distribution wrt adaptive model for 2020.

Indoor thermal comfort as per passive house (2016) [39] based on EN 15251 (2007) - PMV/PPD thermal comfort model [24] to relative humidity is shown in Fig. 13. The figure consists of a comfort area and an extended comfort area. The y axis contains the relative humidity values (%) and x-axis contains indoor operative temperature (°C).

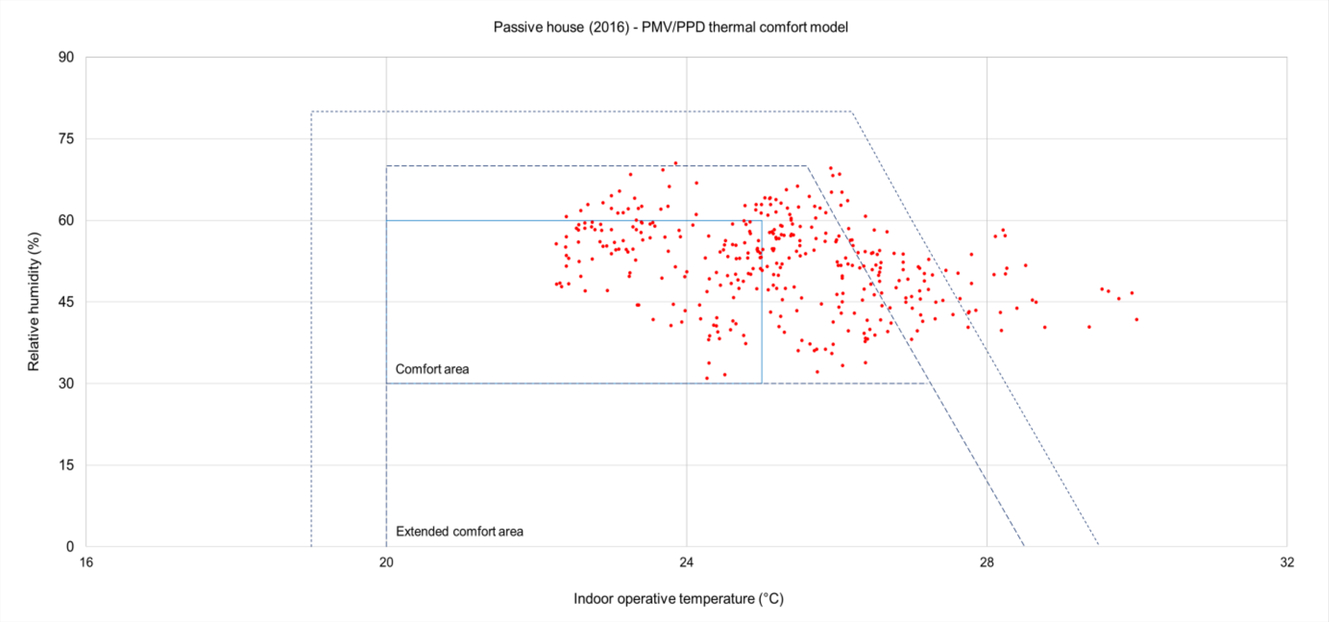


Figure 13. Indoor temperature distribution wrt PMV/PPD model for 2020.

Indoor thermal comfort as per EN 16798 (2019) - PMV/PPD comfort model [5] to relative humidity is shown in Fig. 14. Categories I, II, III, and relative humidity limits are considered here.

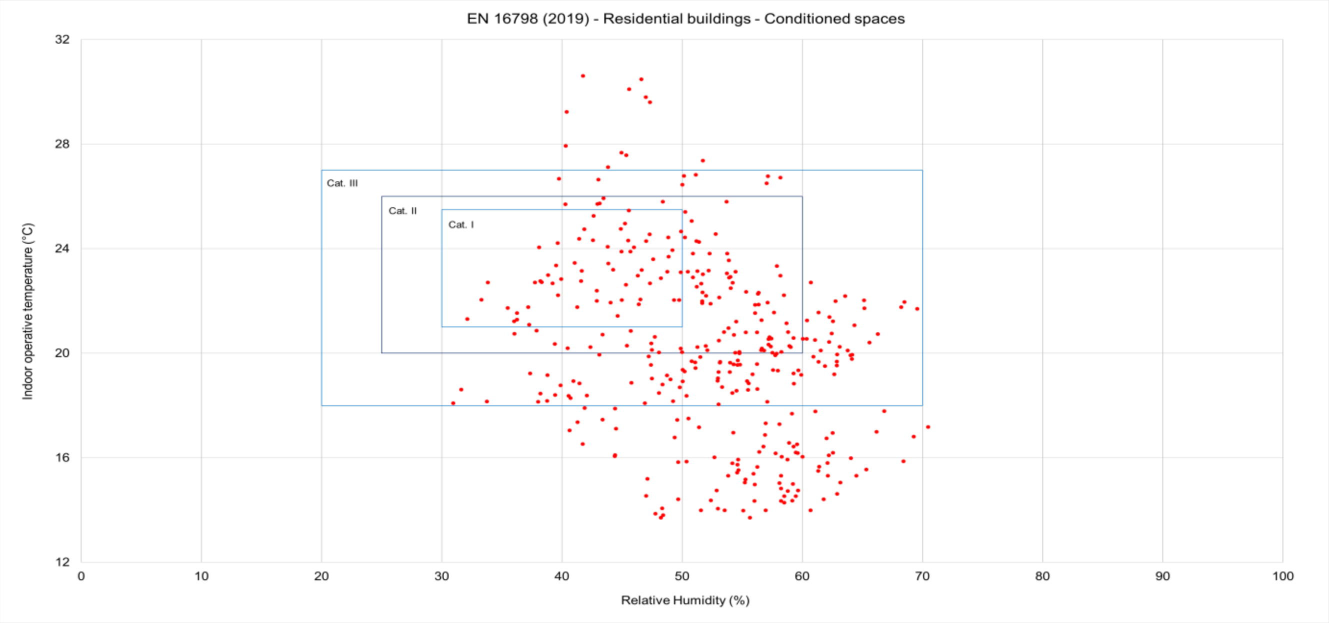


Figure 14. Indoor temperature distribution wrt PMV/PPD model for 2020.

A commonality in all these figures is that it points to overheating in residential buildings in Liege, Belgium. In addition, it also points out the importance of sustainable cooling systems to ensure thermal comfort future scenarios influenced by climate change. Another important effect of climate change is extreme events like heatwaves. Heatwaves determined according to the RMI of Belgium [18], Federal heat plan "heatwaves and ozone peaks" [18], and Meteo France [19] are shown in Fig. 15. One heatwave was detected for all definitions in Liege, Belgium during 2020. Meteo France identifies this heatwave as the most severe heatwave in the period 2015 - 2020. Severe is the cumulative difference between the daily temperature and S_{deb} during the event, divided by the difference between S_{pic} and S_{deb} [19]. The parameters considered are:

- RMI - Maximum daily temperature (°C)
- Federal heat plan - Maximum and minimum daily temperature (°C)
- Meteo France - Daily mean temperature (°C)

The data compiled to determine the heatwave event are listed in Table 2 [37], [41].

Table 2. Heatwave data from Liege for 2020.

RMI		**Federal heat plan**			**Meteo France**	
Date	**Max. (°C)**	**Date**	**Max. (°C)**	**Min. (°C)**	**Date**	**Avg. (°C)**
05/08/2020	29	07/08/2020	34	20	06/08/2020	24.82
06/08/2020	31	08/08/2020	36	22	07/08/2020	26.11
07/08/2020	34	09/08/2020	32	23	08/08/2020	28.08
08/08/2020	36	10/08/2020	34	21	09/08/2020	27.63
09/08/2020	32	11/08/2020	33	23	10/08/2020	27.19
10/08/2020	34	12/08/2020	33	21	11/08/2020	28.06
11/08/2020	33	13/08/2020	31	21	12/08/2020	28.18
12/08/2020	33					
13/08/2020	31					
14/08/2020	28					
15/08/2020	25					
16/08/2020	29					
17/08/2020	26					

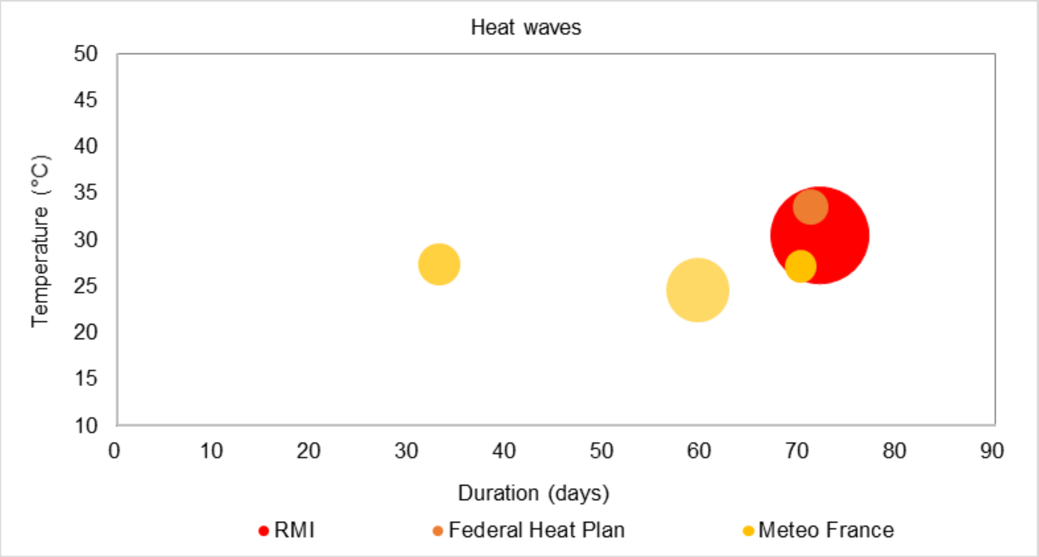


Figure 15. Heatwaves in Liege for 2020.

For the complete definition of heatwaves [20], the most intense heatwave in the time frame 2015 to2020, with a daily mean temperature 29.66 °C from 01/07/2015 to 05/07/2015, and the longest heatwave of duration 12 days from 24/07/2018 to 04/08/2018 are added to Fig. 15. Since the three definitions consider different parameters, like temperature, duration, beginning and end of the event, etc., the scope of heatwaves in terms of duration and intensity varies with the considered definition.

6. Discussions

The main findings of the report are:

1. The HDD values from Liege, Belgium, for the last 40 years indicate a decreasing trend in numbers, implying warmer winters in the future.
2. The HDD values in Liege are lower compared to the average value of the whole of Belgium indicating higher rate of heating needs in the future.
3. The CDD values from Liege, Belgium, for the last 40 years indicate an increasing trend in numbers, implying hotter summers in the future.
4. The CDD values in Liege are much higher compared to the average value of the whole of Belgium indicating higher rate of cooling needs in the future.
5. For adaptive thermal comfort model, the indoor operative temperature tends to go over the higher limits of EN 16798 category I and II for summer months, which makes sustainable cooling necessary.
6. In addition, during hot summers, the limits of the adaptive thermal comfort model go above 30 °C, which might not be a suitable environment for thermal comfort. In most cases, thermal comfort limits are not respected during the hot summers in Liege, Belgium.
7. The comparison of heatwave definitions shows that the RMI definition has a broader scope in defining the heatwaves, whereas Meteo France and Machard definitions provide a better classification in terms of duration, intensity, and severity of the heatwaves.

The main recommendations of the report are:

1. The findings from 1 to 4 point towards the need for efficient sizing of building for heating and cooling loads, considering future climate scenarios.
2. These findings suggests that there will be lower heating demand in future and thus, the heating load can be lower.
3. In addition, there will be higher cooling demand and thus, the cooling load should be higher.
4. The failure of existing residential buildings to achieve thermal comfort during the summer months shows the importance of the implementation of sustainable cooling solutions in the buildings.
5. The higher limits of adaptive thermal comfort models according to EN 16798 indicate to need to develop the standard further, keeping in mind the current climate change scenarios.
6. The increasing intensity, duration, and number of heatwaves are a matter of great concern for the future. This reiterates the need for the implementation of sustainable and carbon-neutral cooling systems.
7. The existing cooling technologies can be used for retrofits and new constructions, but these databases should be updated regularly considering recent developments in the field of cooling technologies.

The main implications on the practice of building design consultancies and industries are the need to focus more on sustainable and carbon neutral cooling technology to ensure proper resilience of the buildings during extreme events like heatwaves and to ensure occupants' safety and well-being through proper thermal comfort. Future work in the upcoming work package 4 deals with the development of climate change-sensitive overheating indicators, taking into consideration various parameters, such as air temperature (°C) and relative humidity (%). Further down the road a Modeling framework and protocol with low input uncertainty and high-risk assessment in the Belgian context will be developed based on [42].

7. Conclusions

The report is prepared as a deliverable to work package 3, which is focused on the development of a knowledge base on overheating in buildings. The work package report seeks to evaluate the thermal comfort models, different cooling technologies and analyzes weather patterns in Liège, Belgium, for a defined time frame of 2015 - 2020. Therefore, a literature base was developed in this context, considering various thermal comfort models, such as PMV/PPD and adaptive models and extreme weather events, such as heatwaves studied according to different definitions from RMI, federal heat plan, and Meteo France. The comfort analysis was developed representing different standards, European, international, and regional. This report also compares different cooling technologies to the different parameters like humidity control, EER, storage characteristics, etc. The selection of worst weather data and the calculation of thermal comfort are based on CDD values and weather data from MAR. The report consists of a detailed study of thermal comfort principles, a cooling technology database, extreme events due to climate change, and weather pattern modeling for Liège, Belgium. One of the key findings of the report is the higher adaptive thermal comfort limit during hot summer months, which might not be considered as ideal. This opens an avenue for future development in standards.

8. Publications

Rahif, R., Amaripadath, D., & Attia, S. (2021). Review on time-integrated overheating evaluation methods for residential buildings in temperate climates of Europe. *Energy and Buildings*, 111463. https://doi.org/10.1016/j.enbuild.2021.111463

9. References

1. Coumou, D., & Rahmstorf, S. (2012). A decade of weather extremes. *Nature climate change, 2*(7), 491-496.
2. Wilby, R. L., & Perry, G. L. (2006). Climate change, biodiversity and the urban environment: A critical review based on London, UK. *Progress in physical geography, 30*(1), 73-98.
3. Attia, S., et al. (2021). Resilient cooling of buildings to protect against heat waves and power outages: Key concepts and definition. *Energy and Buildings, 239*, 110869. https://doi.org/10.1016/j.enbuild.2021.110869
4. ASHRAE. (2020). Thermal environmental conditions for human occupancy. ASHRAE, Atlanta, USA. https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy
5. CEN. (2019). EN 16798-1 - Energy performance of buildings - Ventilation for buildings part 1. CEN, Brussels, Belgium. https://www. nbn.be/shop/en/standard/nbn-en-16798-1-2019_8687/
6. ISO. (2005). ISO 7730:2005 - Ergonomics of the thermal environment. ISO, Geneva, Switzerland. https://www.iso.org/standard/39155.html
7. Carlucci, S., et al. (2018). Review of adaptive thermal comfort models in built environmental regulatory documents. *Building and Environment*, *137*, 73-89. https://doi.org/10.1016/j.buildenv.2018.03.053
8. Fanger, P. (1970). Thermal comfort. Analysis and applications in environmental engineering. *Thermal comfort. Analysis and applications in environmental engineering*.
9. Van Hoof, J. (2008). Forty years of Fanger's model of thermal comfort: comfort for all?. *Indoor air, 18*(3), 182-201.
10. Nicol, J. F., & Humphreys, M. A. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and buildings, 34*(6), 563-572.
11. Nicol, J. F., & Humphreys, M. A. (1973). Thermal comfort as part of a self-regulating system.
12. Nicol, J. F., & Roaf, S. (2017). Rethinking thermal comfort.
13. Nikolopoulou, M., & Steemers, K. (2003). Thermal comfort and psychological adaptation as a guide for designing urban spaces. *Energy and Buildings, 35*(1), 95-101.
14. Périard, J. D., et al. (2015). Adaptations and mechanisms of human heat acclimation: applications for competitive athletes and sports*. Scandinavian journal of medicine & science in sports*, 25, 20-38.
15. M. A. Humphreys, “The variation of comfortable temperatures,” *Int. J. Energy Res.*, vol. 3, no. 1, pp. 13-18, 1979. doi: 10.1002/er.4440030103.
16. Nicol, F., Humphreys, M., & Roaf, S. (2012). Adaptive thermal comfort: Principles and practice (1st ed.). Routledge. https://doi.org/10.4324/9780203123010
17. S. Roaf, et al, “Twentieth century standards for thermal comfort: promoting high energy buildings,” *Archit. Sci. Rev.*, vol. 53, no. 1, pp. 65–77, 2010, doi: 10.376nicol
18. Brits, E., et al. (2009). Climate change and health - Set-up of monitoring of potential effects of climate change on human health and on the health of animals in Belgium. Scientific Institute of Public Health. www.belspo.be/belspo/organisation/Publ/pub_ostc/agora/ragjj146_en.pdf
19. Ouzeau, G., et al. (2016). Heat waves analysis over France in present and future climate: Application of a new method on the EURO-CORDEX ensemble. *Climate Services, 4*, 1-12.

20. Machard, A., et al. (2020). A methodology for assembling future weather files including heatwaves for building thermal simulations from the European coordinated regional downscaling experiment (EURO-CORDEX) climate data. *Energies, 13*(13), 3424.
21. Attia, S., et al. (2021). Comparison of overheating risk in nearly zero-energy dwelling based on three different overheating calculation methods. In *Proceeding of the International Building Simulation Conference,* pp. 30147-30153, KU Leuven.
22. Czech Society of Environmental Engineering, Clima 2013 11th REHVA World Congress & 8th International Conference on IAQVEC: energy, efficient, smart & healthy buildings: proceedings. Prague: Society of Environmental Engineering.
23. ISO 13790. (2008). Energy performance of buildings - Calculation of energy use for space heating and cooling. ISO, Geneva, Switzerland. https://www.iso.org/standard/41974.html
24. EN 15251. (2007). Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. CEN, Brussels, Belgium. https://www.nbn.be/shop/en/standard/nbn-en-15251-2007_12248/
25. Attia, S. et al. (2019) 'Analysis tool for bioclimatic design strategies in hot humid climates', Sustainable Cities and Society, 45, pp. 8-24. doi: 10.1016/j.scs.2018.11.025.
26. RELi (2020). Rating Guidelines for resilient design + construction. U.S. Green Building Council. https://www.usgbc.org/sites/default/files/2021-02/RELi%20_05_2020.pdf
27. EPA. (2020). Heat island effect. https://www.epa.gov/heatislands
28. Nakano, A., Bueno, B., Norford, L., & Reinhart, C. F. (2015). Urban Weather Generator-A novel workflow for integrating urban heat island effect within urban design process.
29. JolmaArchitects. (2018). *How landscape architecture mitigates the urban heat island effect*. www.land8.com/how-landscape-architecture-mitigates-the-urban-heat-island-effect/
30. ISO. (2009). ISO 15927-2: Hygrothermal performance of buildings - Calculation and presentation of climatic data - Part 2: Hourly data for design cooling load. ISO, Geneva, Switzerland. https://www.iso.org/ standard/44282.html
31. ASHRAE. (2017). ASHRAE handbook of fundamentals. ASHRAE, Atlanta, USA. www.ashrae.org/technical-resources/ashrae-handbook/description-2017-ashrae-handbook-fundamentals
32. DesignBuilder. Cooling Design Calculation. https://designbuilder.co.uk/helpv5.5/Content/_Cooling_design_simulation.htm
33. Eurostat metadata. (2019). Energy statistics - cooling and heating degree days. Eurostat, EU. https://ec. europa.eu/eurostat/cache/metadata/en/nrg_chdd_esms.htm
34. NWS. What are "Heating Degree Days" and "Cooling Degree Days"?. NOAA, USA. https://www.weather.gov/ffc/degdays
35. Limb, M. J. (1998). Passive Cooling Technologies for office buildings. *An Annotated Bibliography. Air Infiltration and Ventilation Centre (AIVC)*.
36. ISO. (2005). ISO 15927-4: Hygrothermal performance of buildings - Calculation and presentation of climatic data - Part 4: Hourly data for assessing the annual energy use for heating and cooling. ISO, Geneva, Switzerland. www.iso.org/standard/41371.html
37. Laboratory of Climatology. Modèle Atmosphérique Régional (MAR). ULiège, Belgium. https://www.climato.uliege.be/c m/c_5626456/fr/climato-temperatures
38. ISSO Publication 74. (2014). Thermal Comfort. ISSO, Rotterdam, Netherlands. https://open.isso.nl/publicatie/isso-publicatie-74-thermische-behaaglijkheid/2014?query=ISSO-publicatie+74

39. Passive House. (2016). Criteria for the passive house, EnerPHit and PHI low energy building standard. PHI, Darmstadt, Germany. https://passipedia.org/_media/picopen/9f_160815_phi_building_criteria_en. pdf
40. Marsh, A. (2018). Psychrometric chart. http://andrewmarsh.com/software/psychro-chart-web/
41. Wunderground. (2020). Liege weather history. https://www.wunderground.com/
42. Attia, S., et al. (2021). *Framework to evaluate the resilience of different cooling technologies*. Sustainable Building Design Lab.

Annex A

1. Why are we using PMV/PPD thermal comfort model and adaptive thermal comfort model?

PMV/PPD thermal comfort model:

- An experimental approach was performed in thermal chambers, disconnected from the outside world.
- PMV/PPD model has a human adaptability range based on clothing and metabolic activity.
- This approach is important for buildings, such as blood banks, museums, seed vaults, etc., where the indoor thermal conditions should not vary depending on the outdoor thermal environment.
- PMV/PPD model standardized thermal comfort in buildings.

Adaptive thermal comfort model:

- This approach defines that a threshold of 10 - 30 °C, the indoor and outdoor temperatures are relative to each other.
- This makes the adaptive model more energy efficient.
- The adaptive model allows people to adapt to a wider range based on indoor and outdoor temperature compared to the Fangers model.

Some of the main differences between PMV/PPD and adaptive thermal comfort models are given in the following table.

Table 3. Differences between PMV/PPD and adaptive thermal comfort models.

Parameter	PMV/PPD thermal comfort model	Adaptive thermal comfort model
Buildings	Air-conditioned buildings	Free running buildings
Factors	Environmental factors: • Air temperature • Radiant temperature • Air velocity • Humidity Personal factors: • Clothing Insulation • Metabolic heat	Based on the outdoor running mean temperature, θ_{rm} & weighting factor, α. According to our observations, if we want to use a value of $\alpha = 0{,}8$ then more than 25 days of data are needed. For $\alpha = 0{,}3$ at least 13 days of data is required. Unfortunately, the standard implies that the formula can be used with 3 days of data for an $\alpha = 0{,}8$ & this results in considering 48% of the temperatures measured on the previous days. This implementation has the consequence of giving totally false results for the evaluation of adaptive comfort.
Equations	PMV & PPD equations [8]	Indoor operative temperature based on outdoor running mean temperature, θ_{rm} & weighting factor, α [5].
Observations	Views the occupants as passive	The adaptive hypothesis predicts that

	recipients of thermal stimuli driven by the physics of the body's thermal balance with its immediate environment & mediated by autonomic physiological responses.	contextual factors, such as having access to environmental controls, and past thermal history can influence the occupants' thermal expectations and preferences.
Developed on	Built on experiments involving the exposure of subjects to steady-state conditions in thermal chambers.	Built on abundant field studies that were conducted in different climate zones.
Limits	Limits based on maximum operative temperature [℃].	Limits based on an upper limit [℃] & a lower limit [℃].
Standards	EN 16798 (2019) ISO 7730 (2005) ISO 17772 (2017) ASHRAE 55 (2020) CIBSE Guide A (2015) CIBSE TM52 (2013) CIBSE TM59 (2017) Passive House (2016)	EN 16798 (2019) ISO 7730 (2005) ISO 17772 (2017) ASHRAE 55 (2017)

2. What is the use of $T_{\text{sol-air}}$ parameter? Isn't it like a correction factor applied during calculating IOD?

- $T_{\text{sol-air}}$ provides a realistic interface between the external conditions and indoor thermal conditions, taking into consideration factors, such as global solar irradiance.
- Sol-air parameter contains the effects of solar radiation in specifying the building's outdoor thermal environment.
- If we consider only the air temperature, we will have same temperature for a sunny and cloudy day, and thermal comfort criteria will remain the same. This will be far away from the real scenario resulting in improper energy use.

Therefore, sol-air parameter ($T_{\text{sol-air}}$) is a variable used to calculate the cooling load of a building and determine the total heat gain through the exterior surfaces.

$$T_{Sol-Air} = T_O + \frac{(a \cdot I - \Delta Q_{ir})}{h_o}$$

a is the solar radiance absorptivity, I is the global solar irradiance $[\mathrm{W/m^2}]$,
$\mathrm{h_o}$ is the heat transfer coefficient for radiation (long wave) and convection $[\mathrm{W/m^2{}^\circ C}]$,
$\Delta \mathrm{T_{O-sky}}$ is the difference between outdoor air temperature and sky temperature $[^\circ\mathrm{C}]$,
$\mathrm{T_O}$ is the outdoor surrounding temperature $[^\circ\mathrm{C}]$,

$$T_O = \frac{t_{mrt} + \left(t_a \cdot \sqrt{10v}\right)}{1 + \sqrt{10v}}$$

$\mathrm{t_{mrt}}$ is the mean radiant temperature $[^\circ\mathrm{C}]$, $\mathrm{t_a}$ is air temperature, & v is the air velocity $(\mathrm{m/s})$.
$\Delta \mathrm{Q_{ir}}$ is the extra infrared radiation due to the difference between external air temperature and apparent sky temperature.

$$\Delta Q_{ir} = F_r \cdot h_r \cdot \Delta T_{o-sky} \ [W/m^2]$$

$\mathrm{F_r}$ is the form factor between element & sky (1 for unshaded horizontal roof & 0.5 for unshaded vertical wall), $\mathrm{h_r}$ is the external heat transfer coefficient $[\mathrm{W/m^2 \cdot {}^{\circ}C}]$.

Annex B

1. Question: Mirjana enquired about finding reliable values for clothing, metabolic rates, and air velocity.

Comments: Clothing values, metabolic rates, and air velocity can be determined from reliable standards like ISO 7730 (2005), which is an international standard. More details on thermal insulation for a typical combination of garments and garments are given in Annex C, Tables C.1 and C.2. Metabolic rates are given in Annex A, Table A.5.
Clothing patterns in Belgian residential sectors was also studied in the following master thesis:
De Ceuster, E., & Laverge, J. (2019). Clothing behavior and its relation to comfort and residential energy use.

2. Question: Mirjana does not feel confident in PMV/PPD comfort model.

Comments: The PMV/PPD and adaptive comfort models used to determine thermal comfort as per standard EN 16798 are explained in chapter 1.

3. Question: Power outage: How do we prepare to counter events like power outages in Belgium.

Comments: You can find relevant information regarding this in the guide ‘RELi Rating Guidelines for Resilient Design + Construction'. In the section 'Hazard Mitigation + Adaptation'. The guide gives detailed solutions based on the category and vulnerability of the concerned building.
https://www.usgbc.org/sites/default/files/2021-02/RELi%20_05_2020.pdf

Corentin also suggested that in the case of senior houses like Kain, they use cool rooms and plug panels for energy generation.

4. Question: Accuracy of design day calculation to size the cooling systems. Mirjana used half the sizing recommended by design day calculation and surprisingly there was no overheating in the building. They used the weather files from the previous year for the comparison. The sizing was performed using VES.

Comments: Based on the description of design day calculations, it is a very rough estimation of sizing a cooling system and we do not recommend this method. This method only considers the hottest day of the year from the past. We recommend selecting and sizing the cooling systems based on annual dynamic simulation coupled with future weather files.

5. Question: Mirjana is currently working on a case study using the weather files from Jade Deltour (BBRI). She uses this file to perform sensitivity analysis considering internal equipment gains to calculate the heating and cooling load in the building. She asked if the weather files in SBD Lab consider rainwater levels. She is also interested in calculating the diffuse and direct radiation from global solar radiation and sky coverage, so she can use this in DesignBuilder simulations.

Comments: The new weather files in SBD Lab consider rainwater level in mm. The direct and diffuse radiation levels are also separately specified in the weather files. The weather files prepared in the Project OCCuPANt have compliance with DesignBuilder. Sky coverage will be added later. Global solar radiation can be also used to calculate direct and diffuse radiation separately.

6. Question: Urban heat island effect.

Comment: Mirjana thinks it is an interesting topic and she tried to model and study it for a year. Separate modeling of weather files is required since most of the weather stations are in the suburbs and do not represent urban weather. The software for this calculation is Urban Weather Generator developed by MIT. There is a lot of parameters to be calculated to find this effect. We might investigate the possibility of integrating it with MAR weather files.

7. Question: Top residential cooling system used in Belgium.

Comments: Corentin suggested that reversible air to water heat pumps with hydronic loops for floor cooling for ground floor and ventiloconvector for top floors with bedrooms.

Annex C

The outdoor air temperature patterns in Liège from 2015 -2019 is presented here. The external weather files are based on the Modèle Atmosphérique Régional (MAR) forced by the reanalysis model ERA5 based on the real observation. These are overlaid on EN 16798 PMV/PPD and adaptive thermal comfort models - Category I and II - upper and lower limits. The adaptive thermal comfort limits are calculated based on running mean outdoor temperature as in EN 16798.

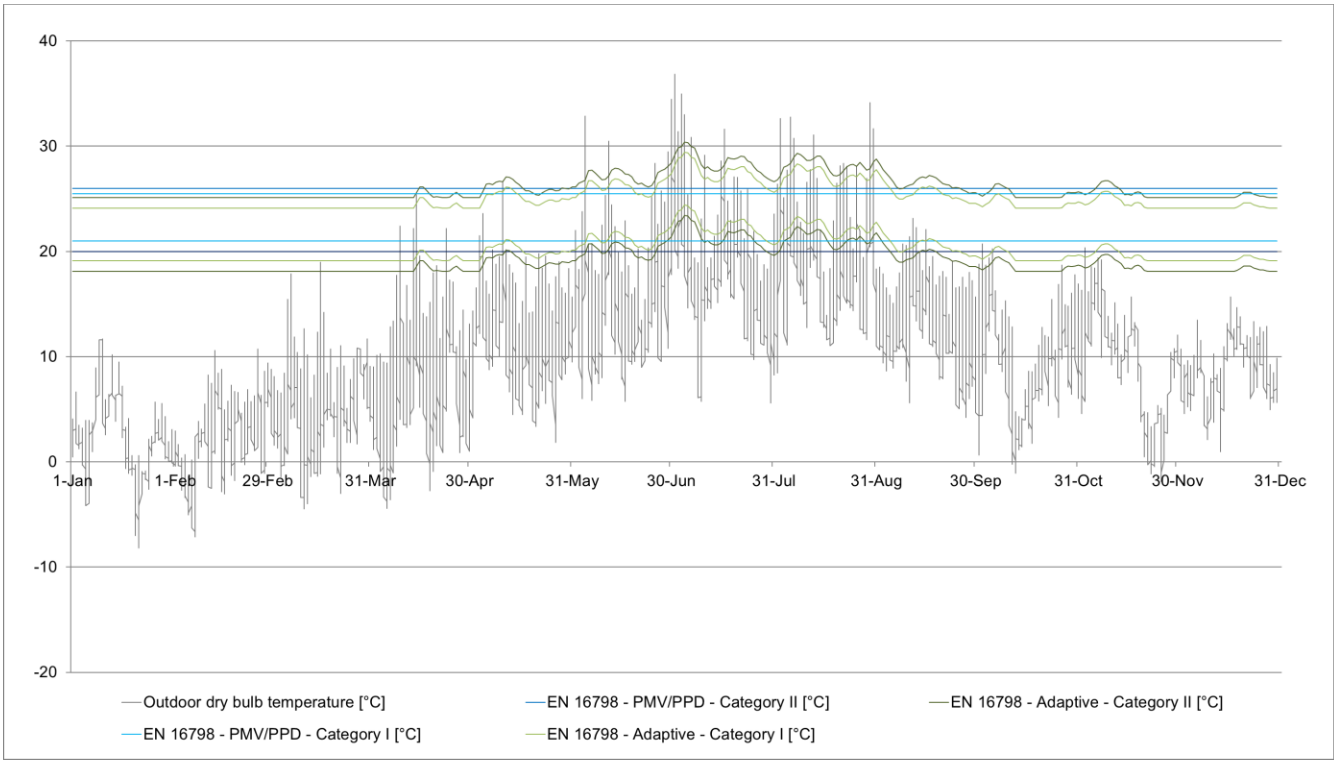


Figure 16. Annual outdoor air temperature distribution (MAR-ERA5) for 2015.

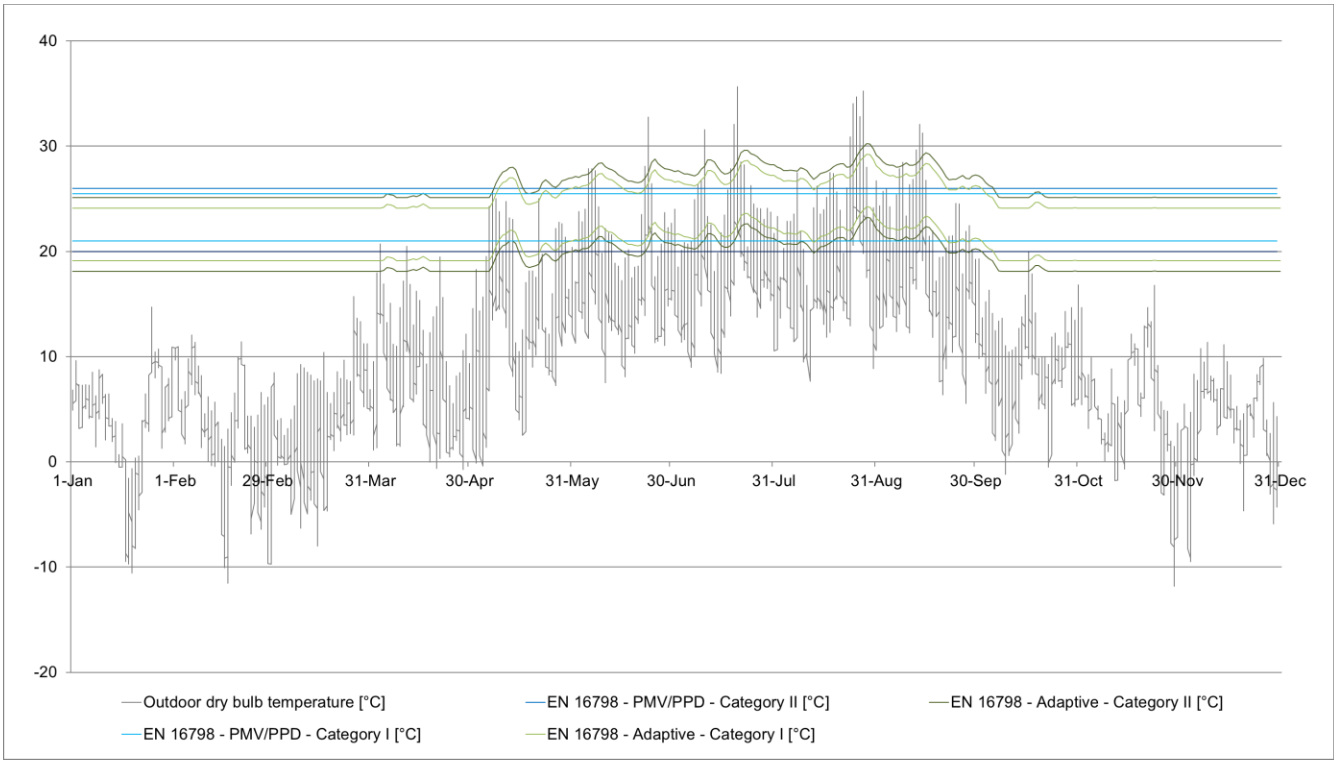


Figure 17. Annual outdoor air temperature distribution (MAR-ERA5) for 2016.

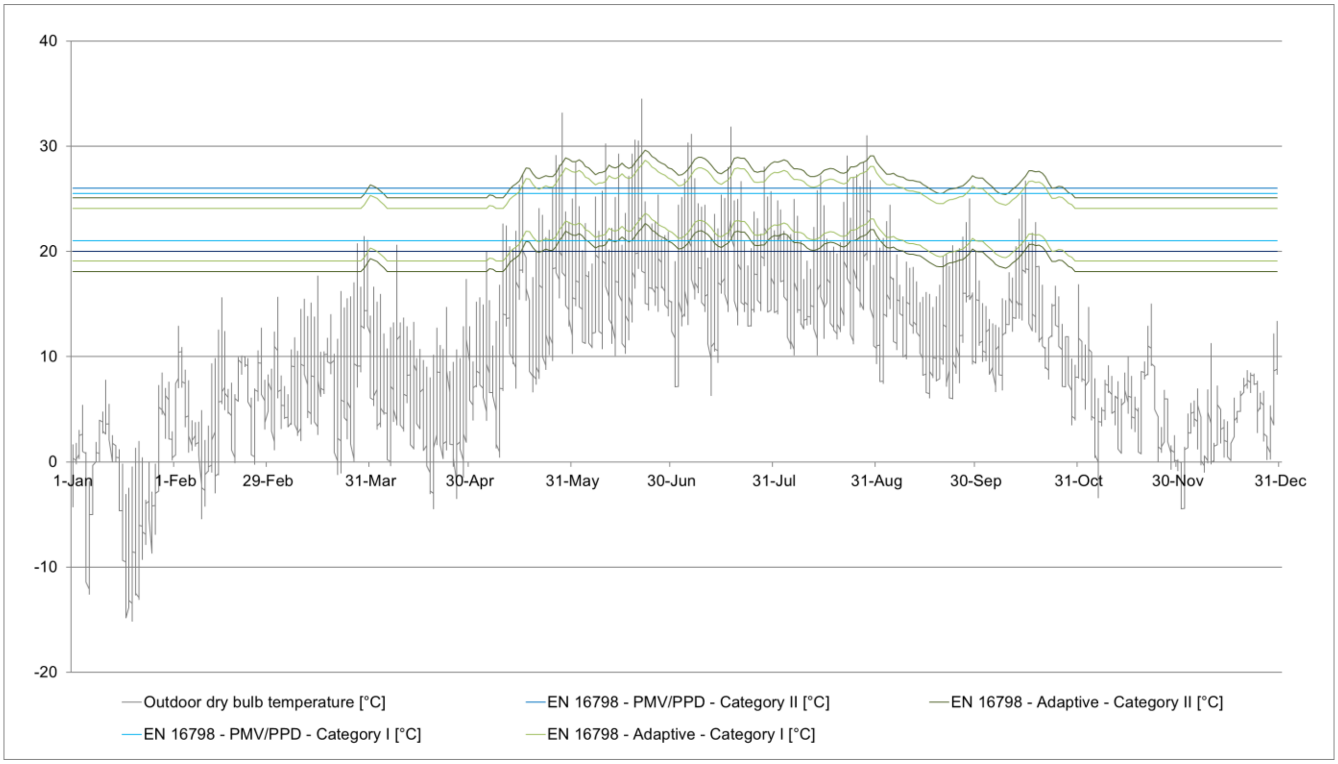


Figure 18. Annual outdoor air temperature distribution (MAR-ERA5) for 2017.

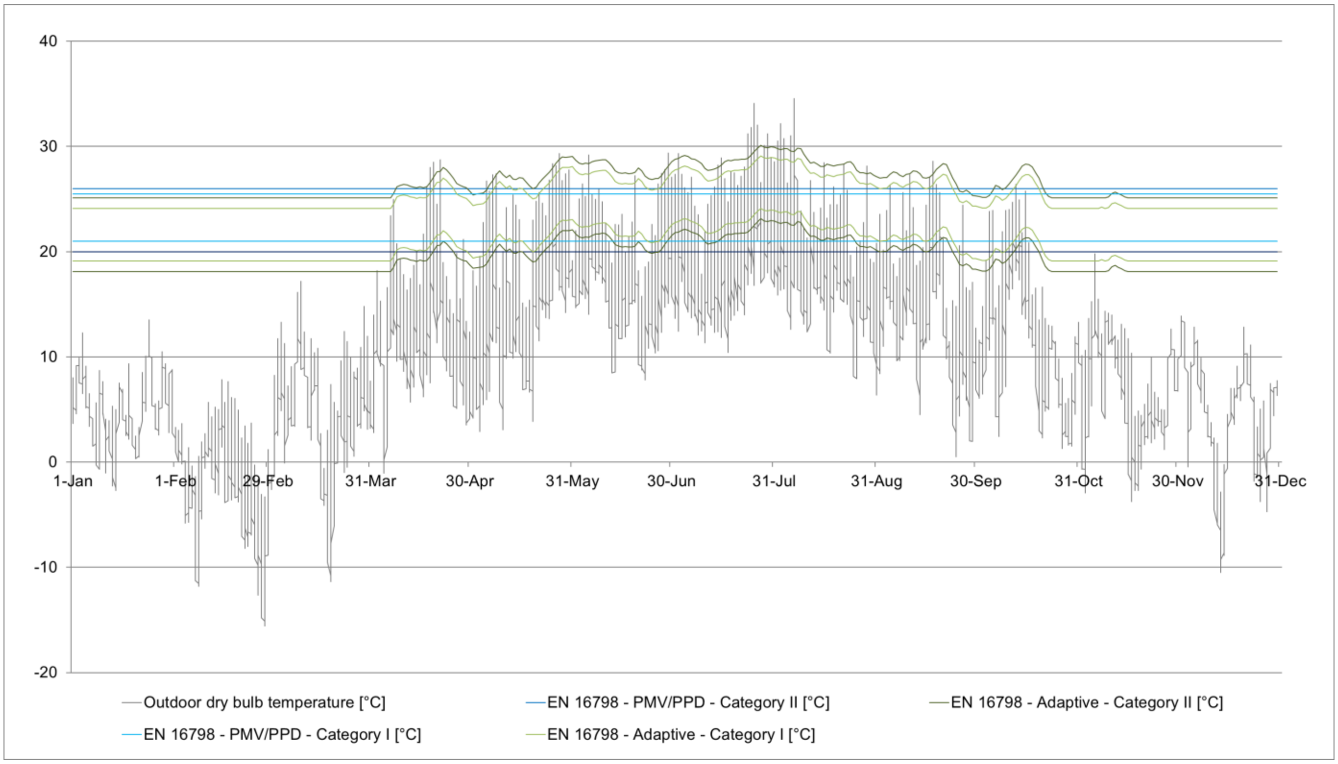


Figure 19. Annual outdoor air temperature distribution (MAR-ERA5) for 2018.

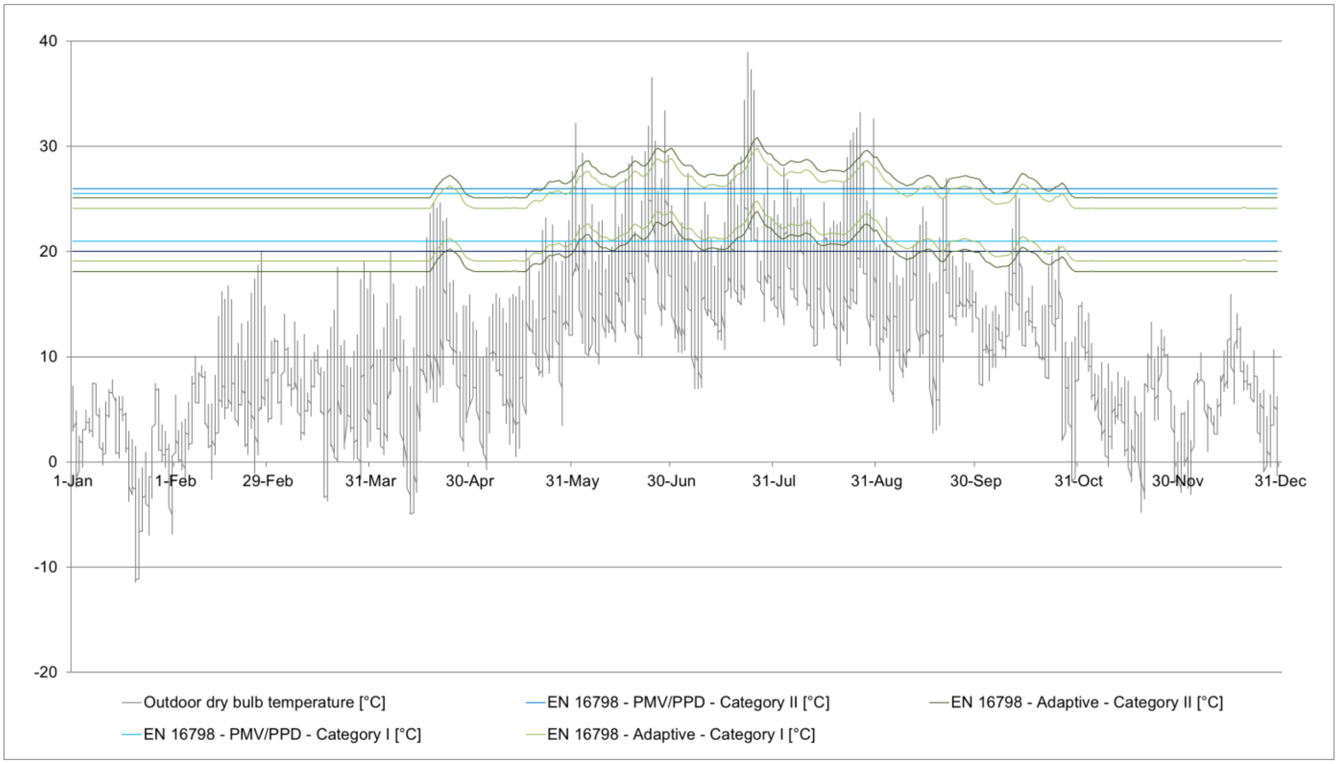
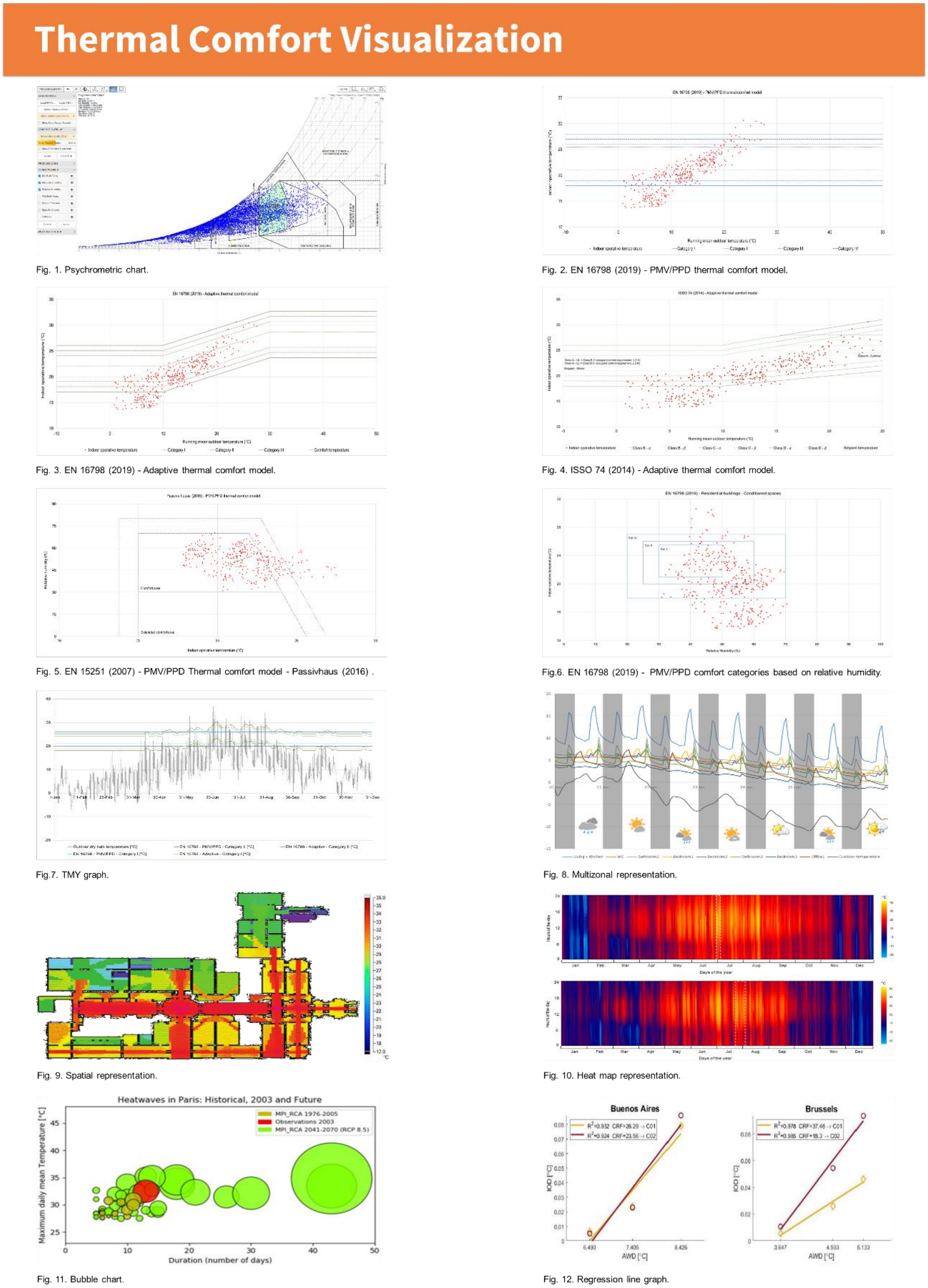


Figure 20. Annual outdoor air temperature distribution (MAR-ERA5) for 2019.

Annex D



Thermal Comfort Visualization

Fig. 1. Psychrometric chart.

Fig. 2. EN 16798 (2019) - PMV/PPD thermal comfort model.

Fig. 3. EN 16798 (2019) - Adaptive thermal comfort model.

Fig. 4. ISSO 74 (2014) - Adaptive thermal comfort model.

Fig. 5. EN 15251 (2007) - PMV/PPD Thermal comfort model - Passivhaus (2016) .

Fig.6. EN 16798 (2019) - PMV/PPD comfort categories based on relative humidity.

Fig.7. TMY graph.

Fig. 8. Multizonal representation.

Fig. 9. Spatial representation.

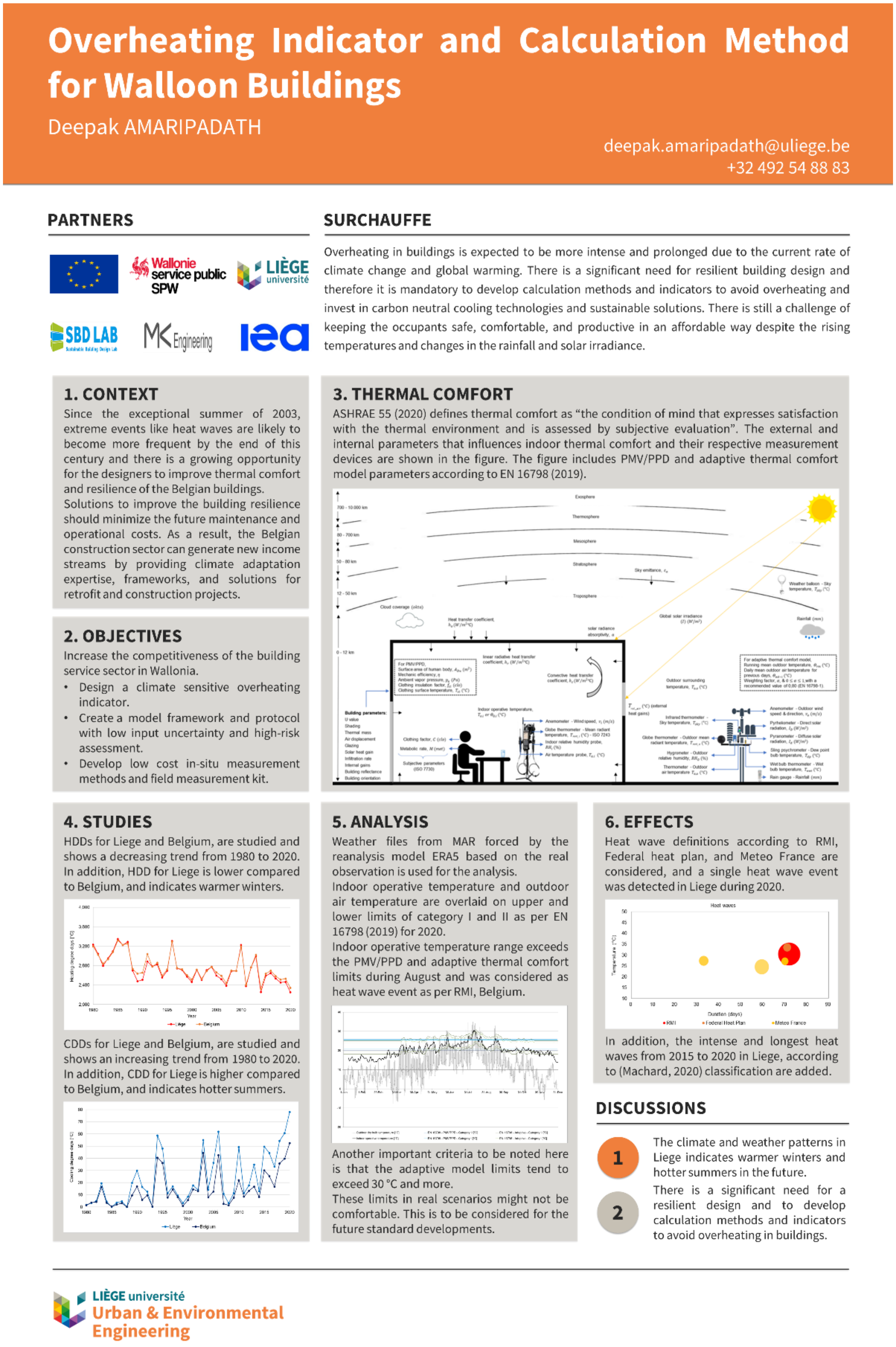
Fig. 10. Heat map representation.

Fig. 11. Bubble chart.

Fig. 12. Regression line graph.

Figure 21. Thermal comfort visualization techniques.

Annex E



Overheating Indicator and Calculation Method for Walloon Buildings

Deepak AMARIPADATH

deepak.amaripadath@uliege.be
+32 492 54 88 83

PARTNERS

SURCHAUFFE

Overheating in buildings is expected to be more intense and prolonged due to the current rate of climate change and global warming. There is a significant need for resilient building design and therefore it is mandatory to develop calculation methods and indicators to avoid overheating and invest in carbon neutral cooling technologies and sustainable solutions. There is still a challenge of keeping the occupants safe, comfortable, and productive in an affordable way despite the rising temperatures and changes in the rainfall and solar irradiance.

1. CONTEXT

Since the exceptional summer of 2003, extreme events like heat waves are likely to become more frequent by the end of this century and there is a growing opportunity for the designers to improve thermal comfort and resilience of the Belgian buildings. Solutions to improve the building resilience should minimize the future maintenance and operational costs. As a result, the Belgian construction sector can generate new income streams by providing climate adaptation expertise, frameworks, and solutions for retrofit and construction projects.

2. OBJECTIVES

Increase the competitiveness of the building service sector in Wallonia.

- Design a climate sensitive overheating indicator.
- Create a model framework and protocol with low input uncertainty and high-risk assessment.
- Develop low cost in-situ measurement methods and field measurement kit.

3. THERMAL COMFORT

ASHRAE 55 (2020) defines thermal comfort as "the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation". The external and internal parameters that influences indoor thermal comfort and their respective measurement devices are shown in the figure. The figure includes PMV/PPD and adaptive thermal comfort model parameters according to EN 16798 (2019).

4. STUDIES

HDDs for Liege and Belgium, are studied and shows a decreasing trend from 1980 to 2020. In addition, HDD for Liege is lower compared to Belgium, and indicates warmer winters.

CDDs for Liege and Belgium, are studied and shows an increasing trend from 1980 to 2020. In addition, CDD for Liege is higher compared to Belgium, and indicates hotter summers.

5. ANALYSIS

Weather files from MAR forced by the reanalysis model ERA5 based on the real observation is used for the analysis.

Indoor operative temperature and outdoor air temperature are overlaid on upper and lower limits of category I and II as per EN 16798 (2019) for 2020.

Indoor operative temperature range exceeds the PMV/PPD and adaptive thermal comfort limits during August and was considered as heat wave event as per RMI, Belgium.

Another important criteria to be noted here is that the adaptive model limits tend to exceed 30 °C and more.

These limits in real scenarios might not be comfortable. This is to be considered for the future standard developments.

6. EFFECTS

Heat wave definitions according to RMI, Federal heat plan, and Meteo France are considered, and a single heat wave event was detected in Liege during 2020.

In addition, the intense and longest heat waves from 2015 to 2020 in Liege, according to (Machard, 2020) classification are added.

DISCUSSIONS

① The climate and weather patterns in Liege indicates warmer winters and hotter summers in the future.

② There is a significant need for a resilient design and to develop calculation methods and indicators to avoid overheating in buildings.

LIÈGE université
Urban & Environmental Engineering

Figure 22. Project poster - UEE day.