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Contents

1. Executive Summary

As part of the EBC Annex 80 - Resilient cooling of buildings activities, the Thermal Condition Taskforce was created, in April 2020. In coordination with all other groups and the Weather Data Taskforce, two objectives were set by the Annex leader Dr. Peter Holzer. Firstly, to define common thermal conditions to assess different cooling technologies. Secondly, define a standard benchmark that can allow comparing the different cooling technologies worldwide. Several meetings and discussions took place between May and November 2020 to identify a systematic methodology for assessing the overheating risk in buildings and enable the comparative evaluation of resilient cooling technologies. The taskforce succeeded to identify common comfort criteria based on an existing overheating calculation method. Also, reference simulation models for benchmarking were identified. This report presents the outcome of the Thermal Condition Taskforce in the form of a methodological framework that can allow performing a comparative evaluation of cooling technologies. The framework is meant to provide a consistent and structured approach to evaluate and relatively compare different cooling technologies on the building scale, taking into account comfort and not only energy efficiency. Therefore, the framework was designed and tested in line with the Weather Data taskforce choice of sixteen cities worldwide and involving IPCC climate change scenarios. The framework is flexible and open, allowing building simulation modellers to run comparative simulations in different climates and evaluating the Technologies investigated by the Annex.

2. Introduction

The world is facing a rapid increase of air conditioning of buildings. This is driven by multiple factors, such as urbanization and densification, climate change and elevated comfort expectations together with economic growth in hot and densely populated climate regions of the world. The trend towards Cooling seems inexorable. Therefore it is mandatory to guide this development towards sustainable solutions.

Against this background, it is the motivation of Annex 80 to assess solutions of resilient Cooling and overheating protection. Resilient Cooling is used to denote low energy and low carbon cooling solutions that strengthen the ability of individuals and our community as a whole to withstand, and also prevent, thermal and other impacts of changes in global and local climates. It encompasses the assessment of both active and passive cooling technologies of the following four groups (Zhang, 2021):

1. Reduce externally induced heat gains to indoor environments;
2. Enhance personal comfort apart from cooling whole spaces;
3. Remove sensible heat from indoor environments;
4. Control latent heat (humidity) of indoor environments.

Therefore, the Annex 80's main aim is to support a rapid transition to an environment where resilient, low energy and low carbon cooling systems are the mainstream and preferred solutions for cooling and overheating issues in buildings. In this context, as part of the activities of Group A, the Thermal Conditions Taskforce developed a framework to assess and compare different cooling technologies. The framework can determine the overheating risk in a building and the potential of comfort improvement of various active and passive cooling technologies. The boundary conditions for the framework include the use of existing international standards and overheating risk assessment methodologies that are already published. The framework had to enable the choices made by the Weather Data Taskforce to generate future weather files for 16 cities. The cities were selected based on their high demographic population increase potential and representation of different climate conditions. The cities had to represent major climates worldwide based on the ASHRAE heating degree day and cooling degree day classification system described in ASHRAE Handbook Chapter 14.

A literature review was conducted, and four focus group discussions took place in 2020. The methodological approach to establish the framework opted to select a reference building, which is an ideal building model, defined based on experts' inquiries and assumptions. Also the evaluation of resilience should comply with the resilience definition developed by Group A (Attia et al., 2021) (Attia et al. 2021). Therefore, we avoided a real existing building with average characteristics concerning a specific building category due to the difficulty to find a universal building that can be representing eight climates and to avoid the overlap with Group C activities. However, the developed framework allows to model single or packaged cooling technologies in a single zone and multiple zone building models. To test and validate the framework, a comparative performance analysis of three cooling technologies was conducted. The validation activities are not described in this report but can be found in the study of (Rahif et al., 2021) Rahif et al. (2021a). Thus the framework is novel and comprehensive, allowing comparing different cooling technologies according to various resilience indicators, building functions and archetypes. The framework can be used by building energy modellers who wish to assess the resilience of cooling technologies concerning comfort or energy/carbon efficiency.

3. Methodology

A literature review was conducted, and four focus group discussions took place in 2020:

1. 20200528 Meeting 01 Thermal Comfort Conditions
2. 20200619 Meeting 02 Thermal Comfort Conditions
3. 20201009 Meeting 03 Benchmark Model
4. 20201104 Meeting 04 Benchmark Model

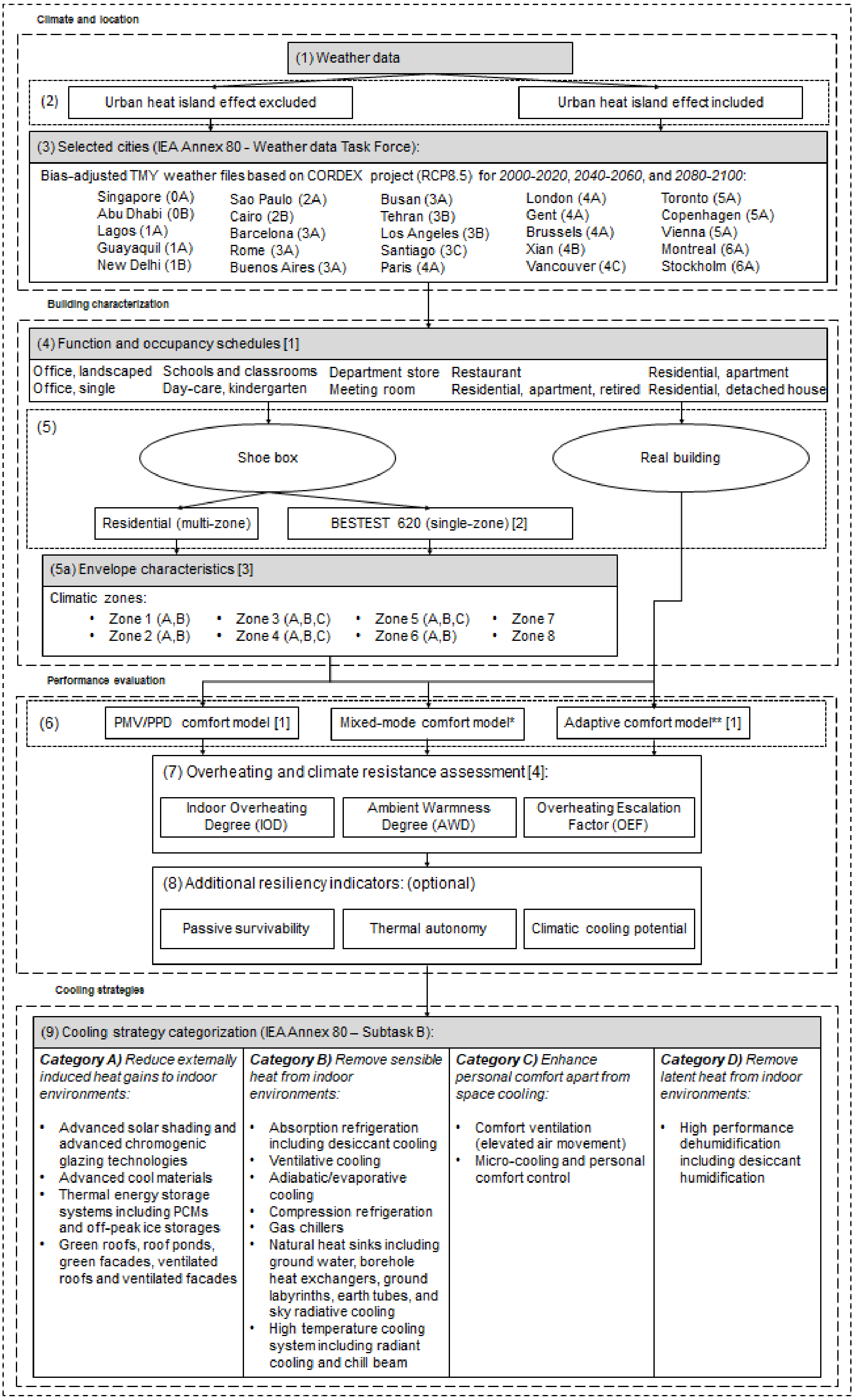
The methodological approach to establish the framework opted to select a reference building, which is an ideal building model, defined based on experts' inquiries and assumptions. Therefore, we avoided a real existing building with average characteristics concerning a specific building category due to the difficulty to find a universal building that can be representing eight climates and to avoid the overlap with Group C activities. However, the developed framework allows to model single or packaged cooling technologies in a single zone and multiple zone building models. To test and validate the framework, a comparative performance analysis of three cooling technologies was conducted. The validation activities are not described in this report but can be found in the study of (Rahif & Attia, 2021) Rahif et al. (2021a).

4. **Results: Framework** (v.01)

The decision making flow chart illustrated in Figure 01 is grouping nine key decisions that need to be made to perform any comparative building simulation analysis. The key decisions to run relative comparative simulations for different cooling technologies must address the following items:

1. Weather data and urban heat island effect
2. Selected cities based on the Weather Data Taskforce
3. Building function and occupancy
4. Envelope characteristics
5. Thermal comfort model
6. Overheating and climate resistance model
7. Resilience indicators (optional)
8. Cooling technologies

Figure 1: Framework to define common thermal conditions and reference benchmark model to evaluate different cooling technologies



* The selection of mixed/hybrid mode comfort model is optional.
** In case of adaptive thermal comfort model no mechanical cooling system should be in operation and occupants should have mainly sedentary activities and have access to operable openings and can freely adapt their clothing to indoor/outdoor environments [1].

[1] ISO 2017, DS/ISO 17772-1:2017 Energy performance of buildings – Indoor environmental quality – Part 1: Indoor environmental input parameters for the design and assessment of energy performance of buildings, ISO, 2017. Geneva, Switzerland.
[2] Judkoff, R., & Neymark, J. (1995). International Energy Agency building energy simulation test (BESTEST) and diagnostic method (No. NREL/TP--472-6231). National Renewable Energy Lab. Colorado, United States.
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5. Climate data and location

The Weather Data Taskforce developed a weather datasets covering all ASHRAE 169 (2013) climatic zones. Climate zone representative cities are selected (see Table 1). The Typical Meteorological Year (TMY) (ISO/TR 15927-4, 2005) weather data are generated for the periods of 2000-2020 (2010s), 2040-2060 (2050s), and 2080-2100 (2090s) including heatwave data for overheating assessments. The task is done in three main steps:

1) downloading CORDEX weather data for IPCC RCP8.5 scenario in.NetCDF format and extracting the required parameters (i.e. air temperature, relative humidity, specific humidity, wind speed, air pressure, downwelling shortwave radiation, and total cloud fraction) in .csv format for the specified cities (coordinates) (Machard et al., 2020),

2) bias-adjustment of the extracted data using the real historical weather data (Cannon, 2018; Cannon et al., 2015).

3) generation of TMY weather data from multi-year hourly datasets and characterization of heatwave events (Machard et al., 2020; Ouzeau et al., 2016). The resulted weather data does not include the urban heat island effect.

Table 1. Representative cities [IEA Annex 80 - weather data task force]

Selected cities				
Singapore (0A)	Sao Paulo (2A)	Busan (3A)	London (4A)	Toronto (5A)
Abu Dhabi (0B)	Cairo (2B)	Tehran (3B)	Gent (4A)	Copenhagen (5A)
Lagos (1A)	Barcelona (3A)	Los Angeles (3B)	Brussels (4A)	Vienna (5A)
Guayaquil (1A)	Rome (3A)	Santiago (3C)	Xian (4B)	Montreal (6A)
New Delhi (1B)	Buenos Aires (3A)	Paris (4A)	Vancouver (4C)	Stockholm (6A)

The Weather Data Task Force proposed a methodology that allows using the same data source and time periods (baseline-historical and future) for different cities and climate zones. It allows detecting future extreme events such as heat waves too.

The framework is open to any other validated approach to generate weather files as long a city can be represented through three periods 1) historical period, 2) short term future period and 3) long term future period. The representation of heat waves shall be introduced in all periods.

6. Function, vintage and occupancy schedules

The framework allows for modelling different building functions, including nursing homes commercial buildings and educational buildings. For occupancy schedules, ISO 17772.P1-P2 must be used for all types of residential buildings. ISO 18523.P1-P2 can be used as a complementary standard.

Modellers will need to define the building vintage. The framework allows comparing different cooling technologies in new construction or existing buildings and high-performance and low-performance buildings.

Overall, the reference building should be tested with no shading and no natural ventilation to test those passive strategies as cooling technologies.

Any reference model must comply with ISO 17772.P1-P2 ventilation requirements regarding the air quality and minimum ventilation requirements.

7. Building geometry and envelope

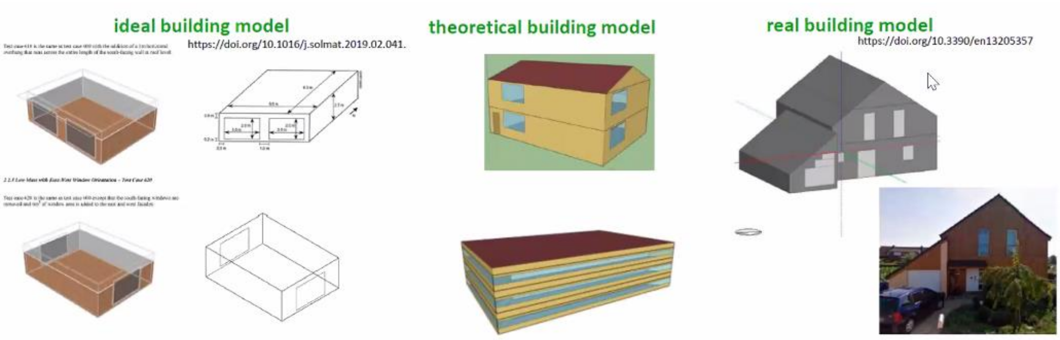
A prototype or reference model must be representative and linked to building energy codes and standards. These reference buildings play a critical role in the comparative studies and technologies benchmarking. They provide a consistent baseline of comparison and improve the value of building performance simulations outcomes. For example, the U.S. Department of Energy's Building Energy Codes Program published prototypes for residential buildings (single-family detached house and multi-family low-rise apartment building) and commercial buildings (US DOE, 2020b, 2020a). Similarly, the European Projects TABULA & EPISCOPE aimed to monitor progress towards climate targets in European Housing Stocks (IWU, 2016). As shown in Figure 2, the framework allows to propose any reference model whether it is (Attia et al., 2020; Corgnati et al., 2013; de Vasconcelos et al., 2015), see Figure 2:

1, an ideal building model**, defined based on experts' inquiries and assumptions;**

2, a theoretical building model, **ideal building model defined by processing statistical data.**

3, real building model, **real existing building with average characteristics concerning a specific building category;**

Figure 2: The three modelling approaches discussed during the 4th meeting of the Thermal Conditions Task Force.

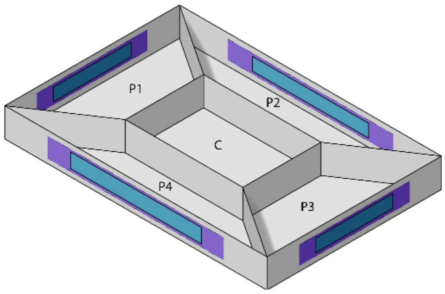


The framework allows comparing cooling technologies in buildings with multiple zones. But the energy modeller must choose zonal configurations that correspond to the cooling technology. Some cooling technologies can be assessed in buildings with identical zoning configurations, such as personal comfort systems. Other cooling technologies, such as packaged systems, can only be evaluated in building with non-identical zones (e.g., corridors).

The modeller can use two identical office spaces for typical closed office layouts but change the function/activity or occupancy schedule. For residential buildings or commercial building with a different team or individual spaces, simulation modellers are free to define the thermal zone(s) dimensions. Zone adjacencies (adjacent walls and floor has a standard heating setpoint) and orientations need to be fixed (worst case, e.g., in Europe: south oriented with top roof are preferred.

The reader should be reminded that the framework, is based on the work of (Hamdy et al., 2017) and aims to represent the real situation in buildings including zones with variable thermal comfort requirements (Peeters et al., 2009).

Figure 3: An example of a multizone model representing geometry. Modellers are free to define any other geometry with a minimum of two zones.



Regarding thermal proprieties of the envelope ASHRAE 189.1-2017 must be used for new constructions. The standard defines, the conductivity, infiltration, heat capacity etc. values.

We advise that building modeller who wishes to compare cooling technologies in existing buildings, should come up with thermal properties that cover the eight climatic zones worldwide and represent a specific time vintage.

8. Performance evaluation

8.1. Thermal comfort models

PMV/PPD model and adaptive thermal comfort model based on ISO/TR 17772-1 (2017) and ISO/TR 17772-2 (2018) must be used for air-conditioned and free-running buildings. Occupants should be free to adjust their clothing to adapt to indoor/outdoor environment (ISO/TR 17772-1, 2017). The comfort category (I, II, III, and IV) should be selected considering the building typology and occupant expectation.

There should be no mechanical cooling system in operation for the adaptive thermal comfort model, and occupants should have mainly sedentary activities (~1.2 met) and access to operable openings (e.g. windows and doors).

The choice of mixed/hybrid comfort models is subjective and up to the building energy modeller's assumption. For this framework, we did not explore how to investigate this option.

8.2. Overheating and climate resistance assessment

Based on the literature review (Rahif et al. 2021b), the task force members agreed to carry out the overheating risk assessment using the methodology proposed by (Hamdy et al., 2017). The method is based on four significant steps:

Step 1: Identify *the design* and *minimum* thermal condition, according to introduced methodology

Step 2: Quantify the *severity of foreseeable events* (i.e., heatwave and electricity cut) by using introduced index (AWD)

Step 3: Quantify the impact of the *foreseeable events* by using the introduced index (*IOD)*

Step 4: Assess the *resistance (IOD\AWD),* according to the presented method (escalation factor)

The method consist of three metrics called Indoor Overheating Degree (IOD), Ambient Warmness Degree (AWD), and Overheating Escalation Factor (α). IOD is a multizonal metric which quantifies the severity and frequency of indoor overheating risk, Indoor overheating degree (IOD) is introduced so that different thermal comfort limits for different dwelling zones can be considered; taking into account the particular occupant's behaviour and the adaptation opportunity he/she has in each identified zone. Furthermore, the IOD quantifies the overheating risk, taking into account the intensity and the frequency of indoor overheating. The intensity is quantified by the temperature difference (DT) between the free-running indoor operative temperature (Tfr) and a chosen thermal comfort temperature limit (TLcomf). In contrast, the frequency is calculated by integrating the intensity of overheating during the occupied period (Nocc) into the different building zones (z) to present the overall overheating in a building.

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

Where t is the time step, i is occupied hour counter, Z is total building zones, N_{occ} is the total number of occupied hours, $T_{fr,i,z}$ is the free-running indoor operative temperature in zone z at time step i [℃], $T_{i,o,comf,z}$ is the comfort temperature in zone z at time step i [℃]. Only positive values of $\left(T_{fr,i,z} - T_{i,o,comf,z}\right)^{+}$ are considered.

AWD is used to assess the severity of outdoor air temperature over a reference temperature T_b. The reference temperature T_b should be selected based on building typology and climate.

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

α is the slope of the regression line between IOD and AWD. It shows the resistance of the building toward the increasing outdoor air temperature because of global warming.

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

$\alpha_{IOD} < 1$ shows the ability of the building to resist climate change impacts. And, $\alpha_{IOD} > 1$ shows that the building is unable to resist climate change impacts.

The methodology is applicable for short- (daily/weekly) and long-term (monthly) heatwaves and annual overheating assessment. However, the results of identical time-periods are comparable.

8.3. Additional resiliency indicators

Additional cooling resiliency indicators can be used to test the resilience of the cooling technologies. The evaluation of resilience should comply with the resilience definition developed by Group A (Attia et al., 2021) and can address the following aspects:

- Passive Survivability: the ability to maintain safe indoor thermal conditions in the absence of function air conditioning.
- Thermal Autonomy: the fraction of time a building can passively maintain comfort conditions without active systems.
- Climatic Cooling Potential

The simulation outputs can be based on choosing universal metrics such as the:

- Annual cooling load per conditioned floor area [kWh/m^2]
- Annual heating load per conditioned floor area [kWh/m^2]
- Annual cooling source energy per conditioned floor area [kWh/m^2]
- Annual heating source energy per conditioned floor area [kWh/m^2]
- Annual overheating hours [h]
- Annual cold discomfort degree hours [^{o}C·h]
- Hourly summer operative temperature [^{o}C]
- Summer minimum, maximum, and average indoor operative temperature [^{o}C]
- Peak load [kW]

9. Cooling technologies

The framework allows modellers to compare different cooling technologies. However, building energy modellers need to be aware of different cooling technologies' spatial implications and especially personal cooling systems. The framework allows evaluating and comparing single cooling technologies or multiple cooling technologies. The framework allows focusing on the distribution side of cooling technologies and the generation side of cooling technologies. However, we advise modellers to focus on the distribution side if they seek to assess indoor thermal comfort quality. Detailed modelling that involve the input parameters of the production side including chillers and cooling towers or even renewables and grid interaction can be modelled if modellers seek to assess the energy efficiency and grid management. IEA Annex 80 Group B developed the technology sheets and reports that list more than 15 cooling technologies. A summary of the investigated technologies with Annex 80 are listed below (Zhang, 2021):

- Advanced window/glazing and shading
- Cool envelope technologies
- Evaporative envelope surface
- Ventilative envelope surfaces
- Heat release and storage
- Sensible heat removal
- Personal cooling systems

10. Conclusion

Comparative building performance simulations seek to evaluate different technologies or measures in buildings with identical boundary conditions. Therefore, we developed a framework that allows performing a relative comparison of individual or multiple cooling technologies as part of the IEA Annex 80. The framework was developed representing different climates, building users and comfort expectations. The strength of this framework is that it allows comparing different cooling technologies under future climate change conditions. The selection of weather data and the calculation of overheating risk are based on unique approaches for resilience evaluation in buildings. The framework consist of three metrics called Indoor Overheating Degree (IOD), Ambient Warmness Degree (AWD), and Overheating Escalation Factor (α). IOD is a multizonal metric which quantifies the severity and frequency of indoor overheating risk. The multizonal modelling approach can represent the real situations in buildings including zones with variable thermal comfort requirements and comfort models (PMV/PPD and adaptive models). The framework is flexible and allows for personalisation to evaluate cooling technologies under real and artificial conditions.

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