Testing architectural quality Key Performance Indicators for Climate Positive Circular Communities in a new highly efficient residential building

Iuliia Maskova[1[0000-0002-2712-7277]], Joana Ortiz[1[0000-0002-2236-154X]], Óscar Negre Moreno[2] and Jaume Salom[1[0000-0001-7035-3248]]

[1] Thermal Energy and Building Performance Group, the Catalonia Institute for Energy Research (IREC), Jardins de les Dones de Negre 1, 2ª pl., 08930 Sant Adrià del Besòs, Barcelona, Spain
[2] Metrovacesa, Puerto de Somport 23, pl. 1, 28050, Madrid, Spain
imaskova@irec.cat

Abstract. This article aims to test the architectural quality indicators defined for the ARV project assessment framework in a new highly efficient residential building. The main categories of Key Performance Indicators (KPIs) are energy, environment, social, architecture, circularity, and economics. Some of the architectural quality indicators relate to the assessment of the building design concepts (e.g., Aesthetics and Visual Qualities, Flexibility and Adaptability, Sufficiency and Adequacy of Space, and others). The other indicators are intended to evaluate the Indoor Environmental Quality (IEQ) conditions of the building's occupants. The methodology applied included a design team survey to assess how architectural quality concepts were considered in the design phase of the building. In addition, a monitoring campaign and a Post Occupancy Evaluation (POE) were performed to determine the occupants' comfort conditions. It was demonstrated that the architectural quality aspects were considered during the design phase, which contributed to the high architectural performance of the building. In addition, the results of the monitoring campaign have shown that the IEQ indicators of the demonstration project are mostly in the high and medium comfort categories based on the European standard EN16798-1:2019, as expected by the ambitions set during the design phase. The proposed methodology was successfully applied in the real case study and proved to be a useful framework for evaluating the design concepts of the building and the IEQ of the occupants.

Keywords: Climate Positive Circular Communities, Indoor Environmental Quality, Architectural Quality Indicators, Post Occupancy Evaluation, Assessment Framework, Highly Efficient Residential Buildings.

1 Introduction

Indoor Environmental Quality (IEQ) is a fundamental component in the construction and renovation process, as the comfort, efficiency, and well-being of building occupants can be significantly impacted by the IEQ conditions. To achieve a high IEQ, it is crucial to design buildings with effective ventilation systems, eco-friendly materials, and consideration for air pollution. To evaluate the IEQ of the built environment, post-occupancy evaluation (POE) is required. The goal of POE is to assess the building's physical performance and occupant satisfaction in relation to the goals set during the design and construction phases [1]. It typically uses subjective surveys for acoustic, visual, thermal, and air quality. These surveys can be combined with the qualitative evaluation conducted during the monitoring process. Another objective of a POE is finding any issues affecting occupants' capacity to live and work efficiently in the space [2]. It offers information to help comprehend how buildings are functioning in relation to their intended use. With the correct combination of aesthetics, design, technology, building techniques, and materials, good architecture can improve the quality of life for the occupants beyond just meeting their basic needs. Additionally, by considering the needs of users who might have limited mobility or other impairments, good design can improve accessibility and enhance the way that people interact with a building. In addition, the physical aspects of a building, including lighting, windows placement, heating, and ventilation, contribute significantly to the well-being of its occupants. Although these aspects are frequently considered in terms of sustainability and energy consumption, making a cozy, well-lit space can also save energy and have a positive psychological effect on users.

One of the objectives of the EU-funded ARV project (ARV is the Norwegian word for "heritage" or "legacy") [3] is to establish a high level of IEQ conditions in addition to high architectural quality of the buildings. The ultimate objective is to present and validate appealing, robust, and cost-effective solutions that greatly accelerate the implementation of energy and climate measures in the building and energy sectors. With a focus on zero-emission buildings and neighbourhoods, the project aims to establish Climate Positive Circular Communities (CPCCs) throughout Europe. A CPCC is an urban area, which aims to achieve net zero greenhouse gas emissions, enables energy flexibility, and promotes a circular economy and social sustainability [4]. To characterize the impacts of CPCCs, the ARV project assessment framework [4] offers a multi-dimensional perspective to the defined Key Performance Indicators (KPIs). By emphasizing the value of the community-based approach, the proposed assessment framework seeks to go beyond the conventional sustainability assessment of buildings, which focuses primarily on environmental, economic, and social impacts. With considering factors at both the building and neighbourhood levels, the KPI categories chosen for the ARV assessment framework are energy, environment, social, architecture, circularity, and economics. The purpose of this article is to test architectural quality indicators, aimed at evaluating the design concepts of the building and the IEQ conditions of its occupants at a new highly efficient residential building located in Palma, Spain, one of the demonstration sites of the ARV project.

Following the introduction, a general overview of the building is provided, along with technical details about building components and energy systems. The methodology section describes architectural quality KPIs and explains the two methods used in the demo site to calculate them: the design team survey and the IEQ monitoring campaign with an analysis of the results obtained. The feasibility of implementing the suggested architectural quality KPIs in the actual case study and the key research findings are covered in the conclusion section.

2 Demonstration site

This article focuses on a new highly efficient residential building constructed by the Metrovacesa company in the Llevant Innovation District in Palma (**Fig. 1** left). The residential building consists of 114 flats distributed in one- to four-bedroom apartments. The building consists of 2 blocks, of which block 1 has a north-east (NE) orientation (**Fig. 1** middle) and block 2 a south-west (SW) orientation (**Fig. 1** right).

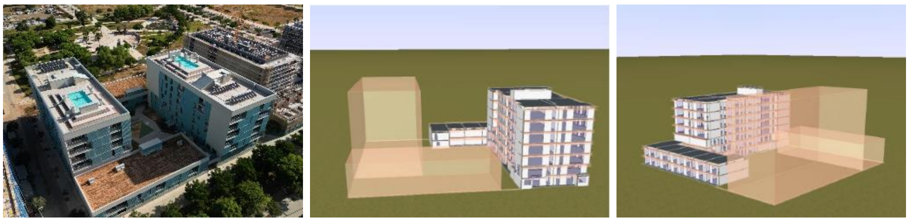

Fig. 1. The Metrovacesa highly efficient multi-family residential building (left) (source: Metrovacesa). Block 1 with NE orientation (middle) and block 2 with SW orientation (right).

The building received the A-energy certificate and was designed to the highest standards of efficiency and sustainability. Building blocks 1 and 2 have non-renewable primary energy values of 13.25 kWh/m^{2}y and 14.06 kWh/m^{2}y, respectively. **Table 1** provides a summary of the building envelope's characteristics.

Table 1. Envelope properties of the building.

Parameter	Value	Unit
External wall, U-value	0.29	W/m²K
Roof, U-value	0.17-0.24	W/m²K
Floor, U-value	0.48	W/m²K
Window, U-value	1.36	W/m²K
Window, SHGC	0.31	-

The building's energy systems include photovoltaic panels in the communal areas and a centralized air-to-water heat pump system for domestic hot water. At household level, the heating and cooling demand is covered by air-to-air heat pumps, combined with a mechanical ventilation system with double flow and heat recovery system. The technical characteristics of the energy systems are summarised in **Table 2**.

Table 2. Configuration of energy systems.

Energy system	Parameters
PV production	PV production: 17 060 kWh/y, 36 PV panels (78.2 m^2), total power: 15.84 kWp, slope: 30º (South oriented panels with 10º towards West).
Heating and cooling: air-to-air heat pumps multi-split in each apartment	Coefficient of performance (COP): 4.1 to 4.84. Energy efficiency ratio (EER): 3.24 to 4.82.

	Capacity: 2 to 5.6 kW (bedroom or living room) in heating mode, 2 to 5.3 kW in cooling mode.
Domestic hot water (DHW): centralized air-to-water heat pump system	COP: 3.44. Capacity: 2 x 39.2 = 78.4 kW.
Ventilation: individual mechanical ventilation in each apartment	Crossflow with heat recovery. Ventilation flow from 60 m^3/h to 120 m^3/h.

3 Methodology

3.1 Architectural Quality Key Performance Indicators

The ARV project’s objective is to design and demonstrate integrated circular buildings of high architectural quality. The term "architectural quality" is broad and encompasses many different criteria and qualities that overlap with other general terms [5]. It is claimed that high architectural quality is the overarching goal for good buildings, integrating all criteria related to economic, ecological, social, functional, and cultural values. In the ARV assessment framework, a set of following KPIs are selected to assess the architectural quality intentions through the survey to the design team:

- The KPI for aesthetics and visual qualities is experimental and examines the following attributes: overall appearance, materiality/form, detailing, proportion/composition, visual connections, coherence (volumes, façade patterns, colours) and others.
- The flexibility and adaptability KPIs evaluate how easily building can be modified for a future change in use. Buildings that are versatile and adaptable have a longer lifespan and, consequently, a significant impact on life cycle costs and environmental performance.
- Sufficiency and adequacy of space is a descriptive KPI. In Europe, local codes set minimum area requirements depending on the building function.
- The solar and daylight access KPI is assessed to determine whether these factors are included in the design process beyond code compliance.
- The accessibility KPI highlights the significance of accessibility for individuals with varying abilities, including visual, motor, and mental, and variations in age and structure.
- To evaluate noise protection, the acoustic comfort KPI is employed. The purpose of a space determines what kind of sound absorption and noise protection are needed.
- For human comfort, access to sunlight or shade, depending on the climate, as well as shielding from wind and noise, are essential, and it is measured by the KPI for outdoor comfort.

The European Standard EN16798-1:2019 [6] establishes four IEQ categories, corresponding to the degree of expectations of building occupants from the highest to the lowest, IEQ_I to IEQ_{IV}, respectively. These categories are used to evaluate the following architectural quality KPIs related to IEQ:

- The percentage of time that the air quality falls into each category during occupied hours is shown by the Indoor Air Quality (IAQ) KPI. The four quality categories indicated in **Table 3** are utilized to evaluate IAQ using the Carbon Dioxide (CO_2) concentration range.

- The percentage of time the air temperature falls into a given range during occupied hours is shown by the thermal comfort KPI. The four quality categories indicated in **Table 3** are used to evaluate the thermal comfort of buildings.
- The overheating risk KPI is accessed via the Heat Index (HI). It is the result of combining air temperature and relative humidity to represent the human-perceived equivalent temperature in shaded areas. The percentage of time the HI falls into each category [7] during occupied hours is shown by this KPI.

Table 3. Comfort ranges for the different comfort indexes: CO_2 concentration, operative temperature, and Heat Index.

Cat.	Expectation	CO_2[1] [ppm]	T_{op} [°C]	HI Category	HI [°C]
IEQ_I	High	≤ 550	$T_{op} = 0.33 \cdot T_{o,rm} + 18.8 + 2$[2] $T_{op} = 0.33 \cdot T_{o,rm} + 18.8 - 3$	No risk	<26
IEQ_{II}	Medium	>550 and ≤ 800	$T_{op} = 0.33 \cdot T_{o,rm} + 18.8 + 3$ $T_{op} = 0.33 \cdot T_{o,rm} + 18.8 - 4$	Caution	26-32
IEQ_{III}	Moderate	>800 and ≤1350	$T_{op} = 0.33 \cdot T_{o,rm} + 18.8 + 4$ $T_{op} = 0.33 \cdot T_{o,rm} + 18.8 - 5$	Extreme	32-41
IEQ_{IV}	Low	>1350	-	Danger	41-54
IEQ_V	-	-	-	Extreme danger	>54

Two different methodologies have been used to calculate architectural quality KPIs. The design team survey to access how architectural quality concepts were considered in the design phase of the building. A monitoring campaign and a POE to determine the comfort conditions of the occupants.

3.2 The design team survey

The architectural team's design intentions were evaluated using a Microsoft Forms survey that was created to gather data for the following KPIs: Aesthetics and Visual Qualities, Flexibility and Adaptability, Sufficiency and Adequacy of Space, Solar and Daylight Access, Accessibility, Acoustic Comfort and Outdoor Comfort. The survey questions were selected from a questionnaire on social and architectural aspects developed for the ARV project design team. Three people formed the reference population of the survey: the current members of the team - the technical architect and the promotion technician - and the former development manager. The average time to answer a questionnaire with 33 questions was about 25 minutes.

1 Corresponding CO_2 concentration above outdoors (350–500 ppm).

2 $T_{o,rm}$ is the running mean outdoor temperature of the daily mean outdoor air temperature.

3.3 The IEQ monitoring campaign

The POE was used to assess occupant satisfaction and monitoring process to give a better understanding of the building's actual performance. From February to September 2023, 13 households who voluntarily agreed to participate in the IEQ studies underwent a 15-day IEQ monitoring campaign. To record the indoor air parameters, a temperature sensor (Elitech) was placed in the bedroom and a temperature, relative humidity, and CO_2 sensor (Comet U3430) was placed in the living room. Data is captured every two minutes. **Table 4** provides an overview of the sensors' technical specifications. A weather station in the neighbourhood provides the weather data, which is gathered every 30 seconds.

Table 4. Technical characteristics of the sensors.

	Characteristics	Measuring Range	Resolution	Accuracy
Comet U3430	Air temperature (°C)	−20 – 60	0.1	±0.4
	Relative Humidity (%)	0 – 100	0.1	±1.8
	CO_2 concentration (ppm)	0-5000	1	±50 + 3%
Elitech	Air temperature (°C)	−30 – 70	0.1	±0.5

Distributed concurrently, the POE surveys are intended to assess users' perception regarding air quality, thermal, visual, and acoustic comfort, as well as overall satisfaction with the IEQ of their households. Once the monitoring campaign and POE are completed, the last step was to provide feedback on the findings from the assessment of each household's indoor air quality, thermal comfort, and overheating/overcooling risk. The level of satisfaction section summarises the survey results, and the correlation between the actual measurements and the user's perception is provided at the end. In addition, volunteers were asked to attend a group presentation that included the compiled results of the monitoring campaign, along with some suggestions for making the optimal use of the mechanical and natural ventilation systems.

4 Results

4.1 Results of the design survey

Using the experimental KPIs listed in section 3.1, the primary goal of the design survey is to assess how architectural quality concepts were considered during the building's design phase. The survey includes open-ended, yes/no, and Likert scale questions to calculate these KPIs. As a result, the interpretation of each KPI's results varies based on the responses provided by the technical architect, the promotion technician, and the former development manager.

- Aesthetics and visual qualities: the project's architectural concept is reminiscent of the Balearic Islands Mediterranean architecture and is characterised by the harmony of materials and solutions. A clear rule of proportion is used in the arrangement of the architectural elements; the moving blinds produce a dynamic composition with repeating elements found in various plants. Three materials were sufficient to achieve all finishes, indicating a clear material concept for the building's structure. Three distinct colors are harmonious with the building's materials and surfaces. Overall, during the design process, every aesthetic and visual aspect was considered.

- Flexibility and adaptability: the opinion about building's flexibility and adaptability are not the same for all the respondents (**Fig. 2** left). This can be explained by the detailed technical questions, which not all the stakeholders involved in the design team need to be aware.

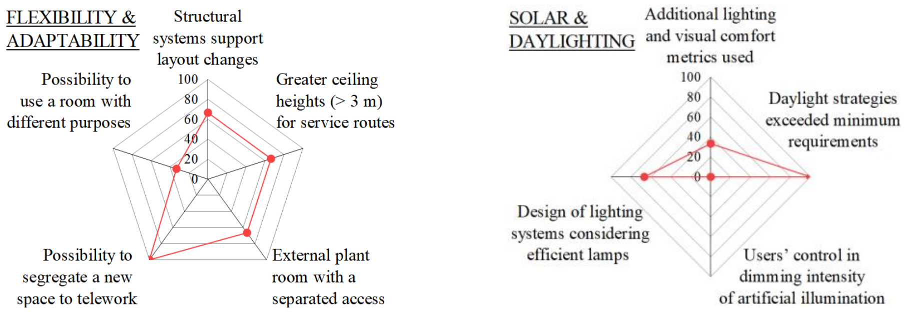

Fig. 2. Aspects of flexibility and adaptability (left) and aspects of solar and daylight access (right), where the axes show the percentage of affirmative answers to the survey questions.

- Sufficiency and adequacy of space: the surfaces of the single rooms are larger than is required by law, according to two out of three respondents. Every respondent expressed agreement that the residential apartments' spaces were intended to accommodate particular purposes.
- Solar and daylight access: questions for this KPI are quite specific, which is like flexibility and adaptability KPI can result in questions going unanswered or being misinterpreted (**Fig. 2** right).
- Accessibility: all respondents concurred that the building's design considers wheelchair or stroller accessibility in some of the apartments in accordance with Balearic Islands standards. Furthermore, the design complied with current regulations and considered individuals with disabilities other than vision impairments.
- Acoustic comfort: the design adheres to Palma's red noise map, and the acoustic insulation has been modified to mitigate airborne noise because of the building's proximity to the airport, in compliance with local regulations.
- Outdoor comfort: the following factors related to human comfort were considered when adapting a design concept for the outdoor areas: sun, shade, wind, and noise (one positive response for each of the parameters). Furthermore, one respondent emphasized how the building can provide shade from the sun and/or wind to the surrounding areas, particularly with its larger façade that has more solar radiation-absorbing lattices.

4.2 Results of the IEQ monitoring campaign

The monitored data and POE survey results are being used to assess the IEQ conditions of the households based on the monitoring campaign's outcomes. Based on the adaptive model categories listed in **Table 3**, **Fig. 3** (left) displays the operative temperature of each home along with the running mean outdoor temperature (grey dotes). Furthermore, the mean operative temperature for the monitored time frame is shown (green dots). It is evident that most of the time, households fall into at least medium category (IEQ_{II}). The percentage of time that the operative temperature falls within each comfort category (left y-axis) is shown in **Fig. 3** (right). The graph's bars, which are arranged in ascending order of mean outdoor temperature for each household, show the mean outdoor temperature (right y-axis) as indicated by the holed dots. Twelve of the thirteen households, according to the results, spend more than eighty percent of their time in categories IEQ_I and IEQ_{II}. Despite the HH2's relatively poor thermal conditions, the household's residents still rated it 9 out of 10 (**Fig. 5**). It may demonstrate that the household finds these conditions to be comfortable.

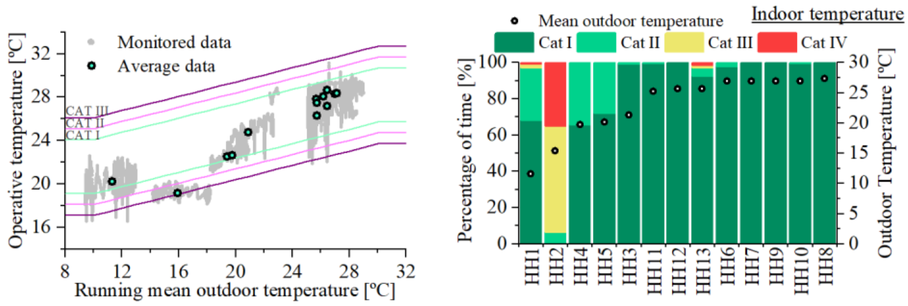

Fig. 3. Indoor operative temperature of monitored households as a function of running mean outdoor temperature (left) and percentage of time in each thermal comfort category (right).

The percentage of time that each monitored household spends in each HI category is used to determine the overheating risk, as shown in **Fig. 4** (left). Apart from HH9 and HH10, which have a moderate risk of overheating due to a high relative humidity, the majority of the households are not at risk of overheating. The air quality of the households is depicted in **Fig. 4** (right), and it is assessed using the CO_2 concentration and the percentage of time that each household spends in each air quality category. Twelve of the thirteen households, according to the results, spend more than eighty percent of their time in high (IEQ_I) and medium (IEQ_{II}) categories. HH8, which has a slightly lower percentage of time (78%), is the only exception.

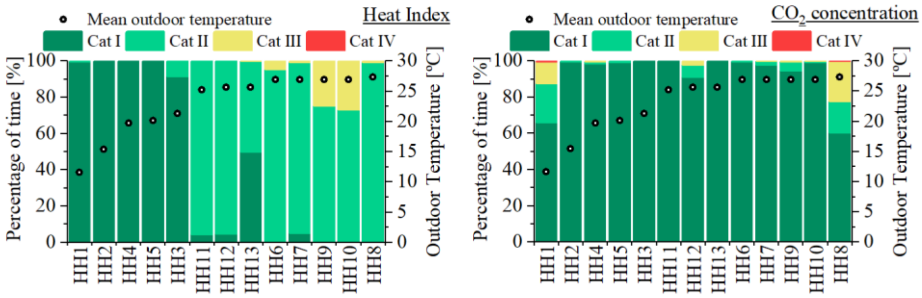

Fig. 4. Percentage of time in each HI category (left) and percentage of time in each air quality category based on CO_2 concentration (right).

Lastly, **Fig. 5** displays respondents' perceptions of their level of comfort in the indoor environment, with 10 denoting the highest level of comfort and 1 the lowest. The responses of each individual are shown as grey dots, and the average value across all respondents is shown as pink dots. With the majority of the dotes falling between 6 and 9 and an average of 7.5-8, users are generally satisfied with the IEQ conditions (air quality, thermal, visual, and acoustic comfort) of their households. With the exception of HH1, who scored poorly (2 out of 10) on both thermal comfort and air quality. However, the monitoring campaign's results showed that, in 98% and 88% of the time, respectively, HH1's thermal comfort and air quality fell into the high or medium category. As a result, the monitoring campaign's overall findings demonstrate a high degree of IEQ conditions that complies with EU standards.

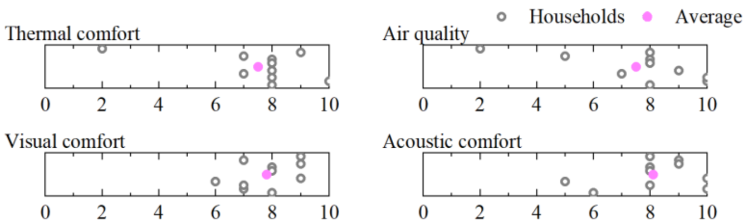

Fig. 5. Indoor environmental comfort perception of inhabitants.

5 Discussion

The viability of applying the set of experimental architectural quality KPIs specified in the ARV assessment framework to the actual case study will be covered in this section. The implementation of the design team survey has revealed two primary problems with the suggested methodology. The first issue is that the survey was completed nearly two years after the construction phase concluded, and it was challenging to get in touch with some of the original members of the design team who left the company during the project's duration. The survey should therefore be completed as soon as the construction process is complete. Another problem is the quite technical nature of some of the questions pertaining to some of the KPIs (like flexibility and adaptability or solar and daylight access). This could cause misinterpretation or leave questions unanswered by some members of the design team. Nevertheless, despite these difficulties and the KPIs' experimental nature it was feasible to get thorough responses and conduct a detailed analysis of the design team's goals while covering a wide range of elements that define the building's high level of design intentions. When it comes to applying KPIs related to IEQ conditions, the users' perception of comfort conditions didn't always align with the monitoring campaign's outcomes. It can be explained by the fact that user's satisfaction with thermal conditions is determined by subjective evaluation and the IEQ categories represent a probability to be in comfort conditions. Nevertheless, effective monitoring campaign, personalised reports, and group presentations have shown to be helpful resources for residents' involvement, which is a common problem in many energy and sustainability surveys.

6 Conclusions

The monitoring campaign's findings have demonstrated that, according to the European standard EN16798-1:2019, the majority of the demonstration project's IEQ indicators fall into the high and medium comfort categories. Moreover, a good correlation has been validated between the use of POE surveys conducted through the inclusion of key questions in post-sale satisfaction procedures in the real estate company and the detailed monitoring. The systematic use of POE surveys reveals to be a good and affordable way for the real estate sector to get feedback about the IEQ in their promoted buildings. Simultaneously, the building's high level of architectural quality and occupant comfort were attributed to the consideration of architectural quality indicators during the building's design phase. In summary, the suggested methodology has been effectively implemented in the actual case study and has proven to be a helpful framework for evaluating the building's design concepts and the IEQ of the occupants.

References

1. Li, P., Froese, T. M., Brager, G.: Post-occupancy evaluation: State-of-the-art analysis and state-of-the-practice review. In: *Build. Environ.*, vol. 133, pp. 187–202 (2018).
2. Clèries Tardío, E., Ortiz, J., Borghero, L., Salom, J.: What Is the Temperature Acceptance in Home-Office Households in the Winter? In: *Buildings*, vol. 13, no. 1, pp. 1-21 (2023).
3. Home · ARV, https://greendeal-arv.eu, last accessed 2024/03/15.
4. D2.1 Assessment framework for CPCC, https://greendeal-arv.eu/library/d2-1-assessment-framework-for-cpcc-2, last accessed 2024/04/10.
5. New European Bauhaus: beautiful, sustainable, together. - European Union, https://new-european-bauhaus.europa.eu/index_en, last accessed 2024/04/04.
6. EN 16798-1:2019 Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (2019).
7. Heat Forecast Tools, https://www.weather.gov/safety/heat-index, last accessed 2024/04/06.