Chapter 2
Indoor Microclimate

Kristian Fabbri

Abstract The study of indoor microclimate requires a specific set of tools to measure the physical variables and interpret the results. This chapter, in its first part, describes how to study Historic Indoor Microclimate. In particular, the main physical variables, the standard values, and the methods to measure them are described. Moreover the concept of thermal comfort is outlined, with its variables and comfort indexes, with particular attention to heritage buildings. The second part of the chapter gives an account of the interpretation of data on physical variables obtained from monitoring campaigns, as well as of the instruments to interpret the data, such as graphics and simulations.

2.1 How to Study and Measure Historic Indoor Microclimate

Indoor microclimate of buildings constitutes measurable physical elements, such as air, and energetic exchanges between air, objects, and people. To this must be added some intangible characteristics of the management and use of the building. Microclimate of a building can be studied in the same way as the structure or the constructive elements, and has its own history and identity.

The study of microclimate has two main focuses:

– Microclimate itself, as the sum of the physical variables that describe the volume of air within a space. This can be modeled, physically speaking, as an open system exchanging mass and energy with the surrounding architecture.
– The factors determining the variability range of indoor microclimate in relation to:

Thermal comfort, as the result of the system of relations between indoor environmental and people, including culture and habits.

K. Fabbri (✉)
Department of Architecture, University of Bologna, Bologna, Italy
e-mail: kristian.fabbri@unibo.it

M. Pretelli, K. Fabbri (eds.), *Historic Indoor Microclimate of the Heritage Buildings*, DOI 10.1007/978-3-319-60343-8_2

Factors related to the conservation of artifacts placed inside historical buildings, such as furniture, paintings, and frescoes. The physical variables of these spaces must be kept in the adequate ranges for the conservation of these objects.

In the specific case of heritage buildings, the study should focus on:

1. *Physical variables* objectively characterizing the microclimate:
   (a) Energy exchanges of the air volume within the building, subject to thermodynamic and psychometric laws.
   (b) The presence of indoor pollution due to internal sources, external ones, and ventilation rate, with the dilution of the pollutants
2. *Human and physiological variables* that allow to evaluate the thermal comfort perceived by visitors, which depends on metabolism, clothes, and culture of the use of the building.
3. Other aspects related to the architectonical characteristics, to those of the technical systems (HVAC, wiring, etc.) and artifacts conserved or exposed in the buildings. These are objects of museum environment studies, when heritage buildings host museums.

The subject of this book is not only the measurement of physical variables, but also the interpretation of indoor microclimate characteristics through time and changes in uses and intangible conservation of the microclimate.

In Chap. 3, the concept of Historic Indoor Microclimate (HIM) will be described along with its historical value for the study of buildings and of history of conservational architecture. In Chap. 4, on the contrary, the subject will be the tools for modeling and instrument relations between the variables.

Here follows a synthesis of the physical and physiological variables used to study Historic Indoor Microclimate (HIM):

– Physical variables allowing to describe present, past, and original indoor microclimate
– Physiological variables useful to understand how behavioral and cultural aspects (food, clothes, habits) interact with indoor microclimate conditions, which has an impact on how buildings are modified, including through HVAC (heating ventilation and air-conditioning systems)
– The conservation ranges of the main historical and artistic artifacts, as defined in Standards and Guidelines.

2.1.1 Scientific Literature on Indoor Microclimate

Microclimate in museums is widely discussed in literature, with the studies of Camuffo (1998) and Thomson (1986) as main documents in the area. Moreover, International Standards have been issued for the conservation of heritage exposed in museums, as a starting point to evaluate the parameter range to preserve them.

Microclimates in museums conserving delicate collections are regulated through specific conservation protocols, aiming at reducing damages and decay of artifacts due to microclimatic conditions. In Italy, in particular, this is a lively subject, and here follows a brief summary of some of the main documents.

ASHRAE (2011), ICOM (de Guichen 1995), and Pavlogeorgatos (2003) suggested specific rules for museums. A ministerial decree from the Italian Ministry for Culture (Atto di indirizzo sui criteri tecnico-scientifici e sugli standard di funzionamento e sviluppo dei musei, del 10 maggio 2001 from Ministero per i Beni e le Attività Culturali e de Turismo—MIBACT) includes a paragraph on microclimate alongside illumination, noises, etc. Microclimate disequilibria are perceived as a danger and to be avoided through correct management of HVAC (heating, ventilation, and air-conditioning) and other procedures to manage risks.

D'Agostino et al. (2015) debated on museum's microclimate, suggesting a protocol to evaluate it in five phases: I. observation, II. examination, III. survey planning, IV: Instrumental survey and result analysis, and V. focused specialized inspections. La Gennusa et al. (2005) focus on methods and protocols to manage museums in historical buildings, while Corgnati et al. (2009) focus on temporary exhibitions. Other papers are Camuffo et al. (2002, 2004, 2010), Ferdyn-Grygierek (2014), and Zivkovic and Dzikic (2015) about the management of collections in museums.

2.1.2 Scientific Literature on Heritage, Thermal Comfort, and Energy Efficiency

Heritage building, thermal comfort, and relation between heritage building and energy efficiency are the subjects of other researches. In particular, on the latter, there is a lively debate among the experts, discussing whether the conservation of historic buildings or their efficiency should be prioritized, to reduce impact and costs.

"Project 3ENCULT" is a research focused on the study of the relations between the conservation of historic buildings and their sustainability in terms of environmental impact. The results are exposed in Troi and Bastian (2014) ed in Vieites et al. (2015). This theme is debated as well within the EFFESUS project, historic urban district (EFFESUS).

Some studies have been aiming more at preserving heritage in museums (Penica et al. 2015; Silva and Henriques 2015), and others at reducing energetic expenditure (Kramer et al. 2015; Monetti et al. 2015). Some are specifically trying to give rules and praxes to enhance energetic efficiency of historical buildings, such as Mazzarella e de Santoli (Mazzarella 2015 e de Santoli 2015), or Boarin et al. (2014) in their "*GBC Historic Building protocol*."

Comfort is a relevant element for the fruition of museums (La Gennusa et al. 2008; Balocco and Calzolari 2008) and churches (Camuffo and della Valle 2007). Thermal comfort in heritage buildings is best reviewed in Martinez-Molina et al. (2016), covering the main studies on the relation between thermal comfort and energy efficiency in heritage buildings and presenting its subject as cross disciplinary and mixed. Lucchi (2016) and Litti et al. (2015) propose multi-criteria indexes to evaluate the problem.

2.1.3 Microclimate and Heritage Standard

A synthesis of the main standards specific for heritage buildings and museums follows.

Standard EN 15757 gives some useful definitions to regulate museums, galleries, libraries, and their archives and storage rooms.

– *Microclimate:* climate on a small spatial scale
– *Indoor environment:* area within a building where cultural heritage objects are preserved
– *Historical climate:* climatic conditions in a microenvironment where a cultural heritage object has always been kept, or has been kept for a long period of time (at least 1 year) and to which it has become acclimatized

These definitions give a description of the object to study: the space where heritage artifacts are conserved. Historical climate is not defined as a nonmaterial heritage, but as the conditions in which the artifact has been longer, to which it "got used." This rule is reported in other standards, as in the Italian one, stating that if an object has been preserved in specific conditions, these need to be kept constant even if not the ones prescribed for that object. In the same way, when moved, an object needs time to reacclimatize.

> 5.3 Priority of historical climate
>
> When the condition of objects made of organic hygroscopic materials that have been kept in a specific microclimate for a prolonged period (at least one year) has been found satisfactory by qualified specialists in indoor climate and conservation; the historical climate in the room, including average RH levels, the range of variability of the natural cycles (seasonal or daily) and the rates of change should be kept unchanged. The only acceptable changes are improvements that reduce fluctuations in the climatic conditions. (EN 15257 pg.9)

EN 15758 defines the procedure to measure air temperature and of surfaces in internal and external areas. Air temperature is easily measured with a thermometer, while effective temperature including radiant contribution (or mean radiant temperature) is measured with a black-globe thermometer. Standard EN ISO 7726 for the measuring. In some cases it might be necessary to measure the superficial temperature of artifacts or walls, with thermometers with contact sensor if it's possible to stick the probe to the object, or with infrared thermometer (remote temperature sensors) or quasi-contact thermometer, which uses the IR radiation emitted by the object. Instruments must be calibrated on EN ISO 7726, with range of resolution of ±0.1°C.

EN 15759-1 describes strategies to choose heating systems in churches, chapels, and other places, in order to prevent damage to cultural property. The standard defines as well the set point characteristics in heating systems, with a reference to the historic indoor climate characteristics in EN 15758 and prEN 16242.

The design of heating systems must guarantee thermal comfort to the users, with a "compromise between thermal comfort and conservation," with a "slightly cool" (PMV −0.5) comfort condition, guaranteeing a skin temperature of 30–33°C. In the last part there is a list of possible heating strategies.

Different standards define the criteria to measure specific variables such as humidity and moisture, for the buildings with EN 16242, for movable and immovable heritage and with prEN 16682, and the parameters to appropriate lighting with CEN/TS 16163. Moreover there are specific standards in Table 2.2 in Annex.

Standard ASHRAE "*ASHRAE, Museums, galleries, archives, and libraries, in: ASHRAE ApplicationsHandbook, American Society of Heating, Refrigerating and Air ConditioningEngineers, Atlanta, GA, 2011, Ch. 23*," among international normative and the Italian Standard UNI 10829 are other relevant standards.

UNI 10829 defines a method to measure thermo-hygrometric environmental values, and for the illumination, aiming at the conservation of historical and artistic heritage, as well as ways to synthesize and reconstruct data. In particular, the procedure to measure the physical variables of the indoor microclimate adequate to preserve artifacts is described. The values are measured to preserve the artifacts, and not to study indoor microclimate in itself, despite the fact that this is an useful concept for the correct monitoring. It defines the modalities to collect and reconstruct the data, the ranges for the conservation, and how to present the results.

Moreover, a "table to collect information on the climatic history of objects" is given, a useful tool focusing on the object itself. On it, the following are reported:

– The collocation of the object (in exposition, temporary or permanently, or stored)
– Noted on the conservation status of the object, with a description of the decay, if stable or in evolution, slow or fast, and the type of decay
– The values of the environmental measures in the day of the survey, both in the room and in the expository
– The values that can be modified and how
– (If present) the devices used to regulate the environmental parameters

2.2 Physical Variables

Indoor microclimate is related to the air volume enclosed in the building. This is an open system that:

- *Exchanges mass,* because of the air passage through doors and windows, and air leakage, which causes as well the movement of indoor pollutants, such as dust and CO_2
- *Exchange energy,* because of the difference in temperature between indoor and outdoor spaces, because of heating due to the sun or to the presence of people, or to the variation in latent heat due to absolute humidity, specific humidity and relative humidity

In this context it is not relevant to measure building energy performance (BEP) of buildings, but on the contrary its effects on microclimate. BEP concerns both the evaluation of the energetic behavior of the building, in dynamic conditions or steady state (following ISO 13790), intended as a shell, and the sizing of systems acting directly on microclimate, modifying and keeping it within the ranges required for the comfort and preservation of artifacts.

In this paragraph are described the variables influencing indoor microclimate, in particular for heritage buildings.

Physical variables:

- Air temperature, measured in °C (or °F)
- Mean radiant temperature (MRT) measured in °C (or °F)
- Absolute humidity, measure in g_v/m^3
- Specific Humidity measured in g_v/kg_a
- Relative humidity (RH), measured in percentage (%)
- Air velocity (v), measured in m/s

Indoor pollution variables, influenced by air pressure (Pa) and air velocity (m/s):

- Carbon dioxide (CO_2), mainly due to the presence of people, measured in parts per million (ppm)
- Carbon monoxide (CO), due to incomplete combustion and hence linked to the presence of hearths, stoves, or heating systems
- Particulate and dust, measured in ppm (or μg, or mg)
- Volatile organic compound (VOC) e.g. due to detergents, printer, etc. (formaldehyde, tetratrilene, benzene, etc.)

Pollutant related to light and not described further:

- Illuminance, measured in lux (lx)
- Ultraviolet radiation ($0.315 \leq \lambda \leq 0.400$ μm), measured in $\mu W\ l\ m^{-1}$

2.2.1 Air Temperature

Air temperature, measured in °C (or °F), described by t, or T, or θ, is the easiest physical variable to comprehend: it is the temperature of the air in the space, measured with a bulb thermometer. It is described as follows, for the conservation of artifacts:

Air temperature, T: Temperature read on a thermometer which is exposed to air in a position sheltered from direct solar radiation or other energy sources (EN 15758)

While for the evaluation of thermal comfort it is as follows:

The air temperature is the temperature of the air around the human body (ISO 7726)

In the case of heritage buildings and museums, it is useful to evaluate air temperature specifically around the artifacts, close to the walls, etc.

Air temperature depends on the one hand on the exchanges of energy between the building and the external environment or towards other spaces of the building at a different temperature, and on the other hand on the exchanges of mass, air, and between indoor and outdoor spaces. In other words, it depends on the building energy performance.

Air temperature is considered homogeneous within a space, i.e., equal in each point of it. This is in order to calculate the building energy performance and the sizing of heating systems.

In reality, and in particular for heritage buildings, the air temperature values tend to stratify, increasing in the upper part of the space. The actual temperature can differ by some decimals to 5 or more degrees. This difference, as well as the differences of values measured in different times of the day, or of the year, is called thermal excursion or thermal gradient ($\Delta\theta$) and can influence the conservation of artifacts.

Air temperature values depend on external climatic conditions, in particular external air temperature and solar radiation, on internal heat load (crowding, presence of people, devices or machines, etc.), on natural ventilation and on heating systems, if present.

The values of air temperature can influence heat exchanges between objects and air due to sensible heat (difference of temperature) or latent heat, linked to vaporization (humidification or dehumidification) of water vapor in the air volume. Changes in air temperature are strictly linked to those in relative humidity.

In the case of heritage building and in relation to the study of historic indoor microclimate, air temperature constitutes, alongside relative humidity, the most relevant parameter to define the characteristic microclimate. Air temperature is, indeed, strictly dependent on the architectonical and technological conformation of buildings, on the usage done, and on the technical systems present. All of these factors can change during the history of the building and influence air temperature.

Analyzing data from surveys or virtual simulations, it is interesting to evaluate:

- Daily trends of minimal/maximal thermal excursion (or thermal gradient), as isolated values or as points representative for each season
- Weekly or monthly trends, showing anomalies or variations in the width of minimal/maximal thermal excursion and the relation between internal and external air temperature
- Annual trend, from which it is possible to evaluate the seasonal cycle of temperatures, with minimum and maximum values for the whole year, in order to preserve objects and artifacts respecting the values defined in the Standards

Attention must be paid to:

– Peak, minimum, and maximum values, representing extreme conditions
– Abnormal values, punctual or lasting a certain amount of time, that might be due to heating systems, to the presence of visitors or to particular episodes of ventilation of the environments, both natural and artificial ones

Air temperature must be measured in a spot which can represent the whole space: in the center of the room, or close to artifacts that must be preserved. If more than one probe is available, it is useful to measure temperature at several points in space, close to the walls, to the floor or the ceiling, to evaluate possible stratification phenomena. It is advisable to place the probes following a grid.

Air temperature is monitored in order to establish a causal relation between atmospheric variables and the effect on cultural heritage artifacts. Energy exchanges cause variation in the dimensions of object, due to change in temperature, or variation in the resistance, becoming stiff and frail at lower temperatures, or can be damaged by condensation of freezing of the water vapor within the materials.

Air temperature influences the content in water vapor and hence low values are related to the formation of mold and other phenomena of decay of organic materials. At the same time, higher values can create an excessively dry environment, with low relative humidity and formation of dust.

The difference in temperature in a volume of air, because of asymmetry or stratification, can contribute to the generation of natural convective motions and consequently to the movement of dust.

In measuring air temperature, precautions must be adopted to reduce the effect of thermal radiation and inertia of the probe, due to sources of direct radiation, such as the sun, lamps, and heating devices.

Standard ISO 7726 specifies to take into account the reduction linked to the radiation effect, the thermal inertia of the sensor.

2.2.1.1 Other Temperature Measurements

Apart from air temperature, other values characterizing indoor microclimate can be measured, which are dependent on or influencing air temperature.

These values are:

– *Wet-bulb temperature* (°C), which, together with dry-bulb temperature (°C), allows to evaluate the content in water vapor and relative humidity.

Temperature, dry bulb (T_{ab}): The temperature of a gas or mixture of gases indicated by a thermometer shielded from radiation (Glossary of terms for thermal physiology (1987)

Temperature, wet bulb (T_{wb}): The thermodynamic wet bulb temperature of a sample of air is the lowest temperature to which it can be cooled by evaporating water adiabatically. This measurement is compared to that read by an ordinary thermometer, or dry bulb thermometer, to estimate the ambient humidity. (Glossary of terms for thermal physiology (1987)

– *Surface temperature* (°C), which is the contact temperature of surfaces, can be measured with different techniques, direct contact or infrared. It allows to measure the temperature of an object and it is hence useful for the planning of its conservation. In relation to thermal comfort, surface temperature of objects, skin, or clothes allows to evaluate the thermal ergonomics of spaces.

This value of temperature can be measured with a contact thermometer, where the sensor is in direct contact with the surface, or infrared sensor, where the radiant heat flux from the surface is measured and converted to a temperature. This may be influenced by the emissivity of surface (ISO 7726);

Surface Temperature; TS: temperature of a given surface of an object Note This can be measured with contact thermometers, quasi-contact total radiation thermometers or remote infrared thermometers. The surface temperature is generally different from the air temperature, and varies between different objects and different places on the same object. It is expressed in degrees Celsius (°C). In general, the measured surface temperature is not representative of the whole object (EN 15758)

– *Mean radiant temperature*, due to energy exchange linked to electromagnetic waves, between, for example, human bodies and environment and the walls themselves. The thermal exchange due to irradiation is useful for the evaluation of the thermal ergonomics of spaces and of the index of thermal feeling (predicted mean vote, PMV, that allows to determine the expected feeling of people). Mean radiant temperature doesn't have a direct influence in the preservation of artifacts, but it can influence the thermal comfort and the thermal stress of visitors, in particular in case of cold environments or surfaces. Low mean radiant temperatures (e.g. surface at 12°C) can have a bigger influence than air temperature on the feeling of comfort and hence the fruition of heritage buildings.

Temperature, globe (T_g): The temperature of a blackened hollow sphere of thin copper (usually 0.15 m diameter) as measured by a thermometer at its centre; Tg approximately equals temperature, operative. (Glossary of terms for thermal physiology (1987)

Temperature, mean radiant (tr): the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space; see Section 7.2 for information on measurement positions. (ASHRAE Standard 55)

Mean radiant temperature. The mean radiant temperature (MRT or T_{mrt}) is a parameter that combines all longwave and shortwave radiant fluxes to a single value. It is defined as the temperature of a surrounding black body that causes the same radiant heat fluxes as the complex radiant fluxes (Fanger 1972). In human bio-meteorology Tmrt is usually calculated for a standardised standing person. Since measurements are not available on many operational meteorological stations, different models exist, ranging from simple empirical models to full radiative-transfer models, which allow modelling of radiant fluxes based on standard meteorological measurements (Simon et al. 2014).

2.2.2 Relative Humidity

Relative humidity, RH as a percentage (%), might be the most relevant parameter of microclimate for the preservation of artifacts, of buildings, and for the thermal comfort of visitors and users. It is defined, in relation to conservation, as follows:

> Relative Humidity, RH: Ratio of the actual water vapour pressure to the saturation vapour Pressure (EN 15257)

While, in relation to thermal comfort, as:

> humidity, relative (RH): the ratio of the partial pressure (or density) of the water vapor in the air to the saturation pressure (or density) of water vapor at the same temperature and the same total pressure. (ASHRAE Standard 55)

Relative humidity is the ratio of the amount of water vapor in a volume of air over the maximum amount that can be contained. It is influenced by temperature, decreasing when it increases and the other way around.

The total amount of water vapor in a space, i.e., the absolute humidity, can have different origins: natural ventilation, external climatic conditions (rain, fog, sun, etc.), presence of people (breathing, sweating), other activities (cleaning, etc.), heating systems, presence of water as humidification systems, and hydraulic systems or toilets.

In the case of heritage buildings and museums, relative humidity is one of the most relevant causes of decay risk for objects and structures, because of materials' hygroscope. As far as thermal comfort of visitors and users is concerned, it contributes to the feeling of mugginess or dank cold, in particular in underground spaces or those exposed to little sun, where the content in water vapor is higher.

The cyclic changes in relative humidity in a space can cause physical damages to objects made in organic hygroscopic materials, such as wood, fabrics, paintings, books, graphical documents, coverings, doors, and floors. The vulnerability depends on the equilibrium moisture content (EMC) of materials when they absorb or release water vapor. Changes in the EMC of materials can cause physical damages and deformations in time.

The acclimatization process of monuments and artifacts consists in a slow adaptation towards the equilibrium in moisture content of the environment and the object. This includes energy and mass exchanges, with transfers of heat and of water vapor, between the environment and the object itself. The time required for this acclimatization process depends on the characteristics of decay of the objects and on those of the environment in which the object is placed, changing, for example, when it is lent to other institutions.

> The material is said to have "acclimatised" as it now responds differently to atmospheric conditions, though this acclimatisation should not be given a positive connotation because it is due to internal fracturing and results in a form of damage. The associated loss of historical value, aesthetic value and also monetary depends on the size and location of the crack. (EN 15257)

The decay of artifacts can be due to extreme conditions, punctual and related to peaks, to long-lasting presence of damaging conditions, or to frequent fluctuations of EMC that alter the mechanical and chemical characteristics of materials.

Decay and damage can concern the building as well, when water dew accumulates on or within walls. In heritage buildings, which shells have in most cases a single layer, interstitial condensation risk can be measured with calculations and thermo-hygrometric samplings, or after the damage is observed, as when plaster detaches, wood bends, etc.

Superficial condensation—due to relative humidity, air and superficial temperature, and conformation of the building, in particular to the presence of thermal bridges—favors the decay of materials, due to exsiccation, condensation, freezing, mold formation, or growth of other biocides. Condensation of water on glass or fixtures in windows can led to their decay and breakage, through deformation or oxidation of wooden and metallic fixtures, that can prevent the windows from insulating the indoor space.

The analysis of data from surveys or virtual simulations allows to evaluate:

– Daily trends of minimal/maximal variation in RH values, for the possible fluctuation of EMC
– Weekly or monthly trends, showing anomalies or variations in the width of changes in EMC values, and the permanence within the ranges of RH prescribed in the Standards, to avoid excessive dryness or humidity
– Annual trend, from which it is possible to evaluate the seasonal cycle, maximal, and minimal values in order to enhance the conservation of the objects, respecting the values defined in the Standards

Attention must be paid to:

– Peak, minimum, and maximum values, representing extreme conditions
– Abnormal values, punctual or lasting a certain amount of time, that might be due to heating systems, presence of visitors, or particular episodes of ventilation of the environments, both natural and artificial ones
– The relation between indoor relative humidity and external one and temperature trends

Two risks are associated with inappropriate relative humidity values:

– *Dew-point temperature* (DP), which is the temperature and water vapor pressure at which water changes state, from vapor to liquid, and hence condenses on surfaces, forming a liquid film.
– *Frost-point temperature* (FP), which is the temperature at which the water film freezes, causing higher risk when condensation and freezing happen not only on surfaces, but also within the material or the shell of the building. This is because freezing water increases in volume and can cause breakage and desegregation of materials.

The measuring of relative humidity, as much as that of air temperature, must be done in a point that is representative of the space, such as a central one, or close to the artifacts that must be preserved. If more than one probe is available, it is worth to measure RH in different points of the space, such as close to external walls, floor, or ceiling, to evaluate stratification, if present, and, if it is possible, probes should be placed following a grid. Relative humidity follows similar patterns to air temperature, with higher values in the lower parts of the air volume, unless specific sources of vapor are present.

Relative humidity is measured from absolute humidity following ISO 7726.

Absolute humidity of the air, expressed by partial vapour pressure (pa) in kilopascals; (ISO 7726)

The absolute humidity of the air characterizes any quantity related to the actual amount of water vapour contained in the air as opposed to quantities such as the relative humidity or the saturation level, which gives the amount of water vapour in the air in relation to the maximum amount that it can contain at a given temperature and pressure. With regard to exchanges by evaporation between a person and the environment, it is the absolute humidity of the air which shall be taken into account. This is often expressed in the form of partial pressure of water vapour. (ISO 7726)

Dew-point hygrometers, electrical conductivity variation hygrometer, absorption hygrometer (hair type), and psychrometer can be used to measure it. The latter is the most widespread, using wet-bulb thermometer, dry-bulb thermometer, and psychometric chart.

2.2.3 Air Speed

Air velocity, or air speed, measured in meters per second (m/s), is the sum of currents and airflows in a space. It can be due to several factors:

- Convective motions linked to difference in air temperature and pressure, to the vertical stratification of air in the upper levels of buildings, especially with domes, vaults, and other structures causing a stack effect.
- Convective motions close to surfaces with a temperature which differs from that of air, such as cold walls, windows, warm heaters, lamps, and roofs.
- Air leakage between internal and external spaces, caused by the difference in pressure between the air volumes and by the airtightness of the building. In the case of heritage buildings, air leakages are common, caused by openings in the old window fixtures and doors.
- Natural ventilation, when the windows are open, that in virtue of the difference in temperature and pressure, causes the movement of big air volumes.
- Mechanical ventilation, when the volumes of air are changed through technical systems such as fans, mechanically controlled ventilation, air-conditioning, or other mechanical devices.

The definition according to the Standards is:

air speed: The rate of air movement at a point, without regard to direction. (ASHRAE Standard 55)

Air speed is defined by the magnitude of the velocity vector of the flow at the measuring point and by its direction. In the case of confined spaces, the direction can be transversal, from one side to the other, or vertical. Its values are usually between 0 m/s (still air) and 1.5–2 m/s, when there are mechanical or natural ventilations in action.

Air speed in heritage buildings is usually linked to natural causes, such as convective motions, stratification, and transversal ventilation. Airflow has effects on the following:

– Movement, concentration (dilution), and distribution of dust, VOC, and other pollutants. In indoor areas with still air there is usually a higher concentration of dusts that, in the presence of high relative humidity or other conditions, can deposit on plasters, furniture, etc., which can lead to their decay through chemical reactions. In particular, convective phenomena close to heaters or lamps determine the deposition of particulate and dusts over objects and the wall, creating the characteristic smoke stains.
– Dilution of pollutant in the environment, in particular CO_2 due to the presence of people. Ventilation allows to move big volumes of air, reducing the concentration of pollutant dangerous to people and artifacts. From studies in heritage buildings a direct correlation between CO_2 concentration and ventilation resulted.
– The variation in air temperature and relative humidity, caused by the mass and energy exchange of air volumes, a phenomenon happening with air leakage or windows opening, and with an effect on building energy performance.
– Effects on thermal comfort of people: A weak air movement (0.15 m/s in winter and 0.25 m/s in summer) can contribute to increased convective exchanges between human bodies and the environment, with a consequent increased feeling of comfort during summer, or reduced one in winter.

In the analysis of data and trends from surveys and virtual simulations, it is useful to evaluate the following:

– The fluctuation in average speed in a space during a single day, a month, or an entire season, to comprehend the phenomena that happen continuously in relation only to the characteristics of the building.
– The specific fluctuations due to repeated events, such as the periodic opening of the windows, or exceptional ones, such as people crowding or moving of objects.
– Peak phenomena, when air speed exceeds 1.0 or 1.5 m/s, a rare event in indoor spaces and even rarer in heritage buildings or museums.
– The evaluation of air stratification, when it is possible to place several anemometers.
– The distribution in the internal space can be simulated with computer fluid-dynamics (CFD). These use real data of temperature, air pressure, etc. to reconstruct the air convection mores that are not measurable with surveys. This instrument is very useful, in particular, to understand which are the areas

with still air or with convective motions close to the walls. It is hence possible to simulate improving interventions in relation to the uses of the building.

Air speed is influenced by other physical variables:

- Average air temperature, through exchanges of mass due to ventilation, and distribution of air temperature in the space. Speed fluctuation reduces internal temperature and can increase or decrease stratification.
- Relative humidity, since water vapor dilution, due to the ventilation of spaces, can reduce its average value and change its distribution in the environment, with a positive effect.
- The concentration of CO_2, against which air speed and ventilation constitute the only solutions.
- The mean radiant temperature, i.e., the measure of the median radiant temperature, with a globe thermometer which is calibrated considering the convective motions around the probe.

Air speed is measured with an anemometer, of which several variants exist, as reported in ISO 7726: vane and cup anemometers (directional appliance), hot-wire anemometer (directional appliance), pulsed-wire anemometer (insensitive to flow direction), hot-sphere and thermistor anemometer (insensitive to flow direction), ultrasonic anemometer (insensitive to flow direction), and laser Doppler anemometer (insensitive to flow direction). The choice can depend on the appliance required: direction appliance, when the anemometer measures the speed of the air passing through it, or insensitive flow direction, when it consents to measure both intensity and direction of the airflow.

In indoor spaces, because of the low velocity of air, *hot-wire anemometers* are often used.

2.2.4 Indoor Air Pollution

Indoor air pollution constitutes a separate subject from other physical variables, as it is related to the effects of the chemical reactions of the pollutants.

Indoor air quality is the subject of specific researches, of several international standards, such as, of programs and guidelines from World Health Organization (WHO 2008) for indoor air quality: selected pollutants, (WHO 2010), Development of WHO Guidelines for Indoor Air Quality (WHO 2006).

Indoor pollutants have different origins (physical, chemical, or biological) and can pose serious risks to human health (causing diseases, chronic or acute pathologies, and eve death) and to the buildings themselves.

Indoor air quality. Refers to the constituents of the air inside a building or enclosed space, which affects the health of the users. This is of increasing concern as humans are spending greater amounts of time indoors where harmful gases and particles can be produced and then accumulate. Pollutants are released into the air from a variety of source activities (e.g. building materials, work/home tasks and activities, heating, painting, cleaning). Locations of highest concern are those involving prolonged, continued exposure, such as home, school, and workplace. Measuring and monitoring types of particles and gases of concern—such as moulds and allergens, radon, carbon monoxide, volatile organic compounds, asbestos fibres, NOx, carbon dioxide, and ozone—can determine indoor air quality. Computer modelling of ventilation and other airflow in buildings can predict air quality levels. Outdoor air may penetrate indoors via the ventilation systems of buildings, and thus must also be taken into consideration. In developing countries, carbon monoxide is a pollutant of high concern, affecting indoor air quality and occupant health in the home. This is due to the burning of any fuel such as gas, oil, kerosene, wood, or charcoal for cooking and heating. Proper ventilation, filtration, and source control are the most used methods for diluting and improving indoor air quality and comfort, with control of high temperature and humidity also important (Simon et al, 2014, p.288)

and

acceptable indoor air quality: air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction. (ASHRAE Standard 62)

Particular attention to pollutant must be reserved in heritage building, museums, and galleries. This is highlighted by Baer and Banks (1985), Tétreault (2003), Gysels et al. (2004), Grzywacz (2006), and Krupinska et al. (2013).

In these buildings, air pollutants are mainly due to the presence of visitors, their frequency, and crowding. Other sources are dampness or mold conditions, with the presence of microorganisms, and cleaning, bringing VOC and dusts and, rarely, external pollution. Formal distinction would divide them into the following:

- Biological pollutant, due to indoor microclimate conditions
- VOC and dusts, from cleaning, ventilation, and presence of people

Volatile organic compost (VOC) includes several substances such as alkanes, cycloalkanes, aromatic hydrocarbons, chlorinated, aldehydes (dichloromethane, toluene, etc.), and formaldehyde. Their presence is due to different reasons, if not due to the presence of machines or industry; they can come from the outside, but more commonly from the solvents and soaps used to clean.

The main risk comes from biological pollutant, when the concentration of microorganisms in the air is too high. This colonization from fungi and bacteria of materials and their damage happen when the microclimatic conditions are particularly favorable to the proliferation of microorganisms. In particular, with relative humidity over 60–65% and air temperature over 20°C (MIBACT 2001):

2.2.2 *Fungi*. Fungi are ubiquitous eukaryotic organisms, comprising an abundance of species. They may be transported into buildings on the surface of new materials or on clothing. They may also penetrate buildings through active or passive ventilation. Fungi are therefore found in the dust and surfaces of every house, including those with no problems with damp.

2.2.3 *Bacteria*. Bacteria are ubiquitous prokaryotic single-cell organisms, comprising an abundance of species. They can be found in the dust and on the surfaces of every house, including those with no damp problems. The main sources of bacteria in the indoor environment are outdoor air, people and indoor bacterial growth. Bacteria from outdoor air and those originating from people are considered to be fairly harmless; bacteria growing actively or accumulating in the indoor environment, however, may affect health, but this has not been studied extensively.

2.3 Dampness-related indoor pollutants

2.3.1 Allergens

2.3.3 Endotoxins

3. Moisture control and ventilation

3.2 *Sources of moisture*. Phenomena related to water intrusion, dampness and excess moisture are not only harmful to the health of a building's occupants, but they also seriously affect the condition of the building structure, which may diminish the indoor air quality of the building. (WHO guidelines for indoor air quality: dampness and mould)

2.2.4.1 Carbon Dioxide as an Indicator

Carbon dioxide (CO_2) concentration, measured in ppm o mg/m^3, is the main indoor pollutant due to the presence of people, with a positive correlation. The effects on health of a concentration over 1200–1500 ppm can be feeling of tiredness and head-spinning, if this situation lasts for long periods of time. It is true that in museums and heritage buildings it is rare for people to stay in a specific space for long time; hence CO_2 rarely causes problems in these buildings. Moreover, this substance is not damaging to artifacts and buildings. However, it is useful to measure CO_2 concentration to characterize indoor microclimate, contemporary and historical, because it allows to describe characteristics of spaces and can be used as a marker for other pollutants due to the presence of people, such as dust and water vapor coming from breathing.

Through the study of CO_2 trends, it is possible to evaluate frequency and crowding of visitors and the dilution of the air volume. CO_2 concentrations can indeed raise from a basal value of 300–500 ppm to 800–1500 ppm, in few minutes from the entrance of visitors, and keep high levels during the whole visit. When visitors leave, CO_2 concentration diminishes, even with no ventilation. The speed at which this value changes can give indications on the capacity of the space and of the mass exchanges happening, giving an account of air leakage, air movement, and pollutant dilution.

The fluctuation cases can be as follows:

– Low CO_2 concentration and short dilution time in spaces with low visitor frequency, big volumes compared to those occupied by tourists, high internal ventilation due to convective motions, air leakage, or natural ventilation; these spaces risk still air and an accumulation of dusts.

– High CO_2 concentration and short dilution time, in spaces with managed visits with high number of tourists for short span of time, ventilation, and/or big volumes; these areas risk an excessive movement of dust and peaks in water vapor concentrations if the ventilation is not guaranteed when there are no visits ongoing.
– Low CO_2 concentration and long dilution time, in spaces with low frequency of visits and small volumes and/or in an airtight building (which is rare in historical buildings); in these spaces pollutants stay for long periods of time and if they are not properly ventilated there is risk for condensation, molds, and dust deposition.
– High CO_2 concentration and long dilution time, in spaces with high frequentation of visitors, low air exchanges, and/or small air volumes; this is the case posing higher decay risks and it is necessary to organize a proper management and ventilation planning in the moments when visitors are not present.

The cycle and fluctuations in CO_2 depend mainly on the crowding of people, frequency of visits, and ventilation of the spaces. From the monitoring of CO_2 it is possible to check this correlation.

Trends of CO_2 dilution can be compared to those of the other two pollutants caused by the presence of people: water vapor and dust. Moreover, using the real data on CO_2 concentrations coming from surveys and those from computer models, with CFD Software, allows to validate and calibrate the modeling itself to define the pollution rate of visitors.

Hence, in the study of Historic Indoor Microclimate, CO_2 concentration can help calibrate the virtual environmental model (software simulation) and can be useful to deduce some information on the past use of the spaces. In rooms where stoves, braziers, or kitchens were present, CO_2 concentration can be used as a proxy for the fumes and products of combustion, such as carbon monoxide, that were produced by those devices. From the patterns of dilution of CO_2 it is possible to have insights into the intoxication risks or into the ventilation systems of the environment.

2.2.4.2 Dust and AirFlow

Dust, or atmospheric particulate matter or particulate matter (PM) or particulates, is, along with CO_2, a pollutant mainly linked to the presence of people. Atmospheric particulate matters are defined by the dimension of particles: PM10, if smaller than 10 micron, or PM2.5 smaller than 2.5 micron. They can be measured in ppm or mg/m3 and have different origins: dust, textiles, tobacco smoke, etc.

PM enters in heritage buildings and museums directly from the outdoor space, but their presence is more frequently due to the entrance of people. PM levels can hence be correlated to the frequency of visits, but as well as to natural ventilation and air leakage, following the same criteria described for CO2 concentration, since these particles are suspended in the atmosphere.

In the case of dusts and of PM_{10} e $PM_{2.5}$, measured as ppm o mg/m^3, it is necessary to take into account the frequency of cleaning of the spaces and other two phenomena linked to the physical characteristics of the building.

Dusts and particulate behave slightly differently from PMs; being of bigger dimensions, they tend to deposit on objects, floor, and walls. This can lead to other decay phenomena that happen when dust binds to plasters and paintings, penetrates into fabrics, and covers objects and surfaces. The decay and alterations vary in dependence with the materials, as described by Mecklenburg and Tumosa (1999).

The deposition of dust depends on the convective motions in the spaces, which can be simulated with CFD modeling. These motions can be natural convective motions in a laminar regime, such as upward and downward ones, linked to the presence of heat sources, irradiating ones (heaters, lamps), and convective ones (thermoconvectors, chimneys). As an alternative they can be due to quasi-still air motions, below 0.1 m/s, natural convection in a turbulent regime or forced one, with air leakage, air motions, transversal ventilation, etc., with speeds over 0.10 m/s. Higher risk is in the areas where air is still, which favors dust deposition, but as well as higher concentration of water vapor and risk of condensation.

2.3 Indoor Thermal Comfort

The physical variables described above allow to describe both present and past indoor microclimate, and are a useful tool to define decay risks for buildings and artifacts. In heritage buildings, the conservation of artistic artifacts is usually the priority, but it cannot be forgotten that the fruition of these resources is relevant and helps their preservation.

To speak of cultural heritage fruition, several aspects must be considered, concerning the conservation of the artifacts, tourism, economical sustainability of restorations, etc. Here the thermal comfort perceived by visitors and keepers is debated.

Thermal comfort is defined by the opinion of people who occupy a space, depending on the subjective feeling related to temperature. Its study, since Fanger (1970), is a self-standing discipline, which, after an initial developmental phase, has consolidated approval criteria, as in standard ISO 7730 e ASHRAE Standard 55. Generally speaking, in new buildings, thermal comfort must be guaranteed as a neutral condition, not too cold nor too hot. But heritage and historical buildings and museums are subject to a trade-off between thermal comfort and conservation of artifacts and the building itself. The decision on which to prioritize can be hard, but it is usually considered that, in order to visit the heritage, a visitor can endure some discomfort, while once the heritage itself is ruined its restoration might be very hard.

In the study of Historic Indoor Microclimate (HIM) the evaluation of thermal comfort concerns the following:

– Present thermal comfort, measured and evaluated through questionnaires and virtual modeling: It refers to the perception of visitors, and should be modified as possible to avoid situations of discomfort or thermal stress, such as heat strokes, that can negatively influence the visit of the tourists or, on the long period, the health of keepers and workers.
– Past thermal comfort, as who used the spaces in other historical times perceived and tolerated it: Differences in habits and conditions, in caloric income from the diet, or in clothing implied a different tolerance to variation in the temperature. Before the diffusion of heating or conditioning systems in buildings, indoor microclimate was hardly modifiable and a condition of thermal comfort was to be reached mainly through changes in habits.

Thermal comfort is, hence, a useful instrument to understand the habits of historic buildings in past times.

In this paragraph, the values and indexes useful to define thermal comfort are described.

Thermal comfort is the result of a complex system of energetic and mass exchanges between the human body and the environment, along with the feelings linked to these exchanges.

Its study considers several variables:

– *Physiological*, related to the human body, its metabolic activities, the clothing, and the work that the body does to thermoregulate, digest, and breathe in an environment.
– *Physical*, of the environment, indoor or outdoor, in which the human body is and with which it exchanges mass and energy. Frontczak and Wargocki (2011) report a literature survey on different factors influencing the comfort of indoor spaces. Air temperature, relative humidity, mean radiant temperature, and air speed are the considered values.
– *Psychological and cultural*, which are hard to measure, but have a direct influence on the perception of comfort, on the perceptive codification of the exchanges between body, physiological component, and environment, physical component.

Thermal comfort is defined by the exchanges of mass and energy between people and environment and by a knowledge code of each person in relation to this exchange.

> Thermal comfort: Subjective indifference to the thermal environment. Thermal comfort, zone of: The range of ambient temperatures, associated with specified mean radiant temperature, humidity, and air movement, within which a human in specified clothing expresses indifference to the thermal environment for an indefinite period. (Glossary of terms for thermal physiology (1987).

Thermal comfort is described with two indicators:

– Physiological equivalent temperature (PET), where the exchange between human body and environment is evaluated and, in relation to the different equilibrium situations, is defined as a perceived equivalent temperature by a

Table 2.1 The 7-point thermal sensation scale

PMV vote	+3	+2	+1	0	−1	−2	−3
Sensation	Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold

subject; these indexes, used mainly to define outdoor comfort, can vary from neutrality to thermal stress or shock, such as collapse because of excessive heat.
– Predicted mean vote (PMV) or percentage people dissatisfied (PPD) introduced by Fanger (1970), which is related to the felling and judgment of people.

Standards ISO 7730 and ASHARE 55 define the criteria to measure and calculate PMV and PPD indexes:

PMV. The PMV is an index that predicts the mean value of the votes of a large group of persons on the 7-point thermal sensation scale (see Table 2.1), based on the heat balance of the human body. Thermal balance is obtained when the internal heat production in the body is equal to the loss of heat to the environment. In a moderate environment, the human thermoregulatory system will automatically attempt to modify skin temperature and sweat secretion to maintain heat balance. (ISO 7730)

PPD. The PPD is an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people who feel too cool or too warm. For the purposes of this International Standard, thermally dissatisfied people are those who will vote hot, warm, cool or cold on the 7-point thermal sensation scale given in Table 2.1. (ISO 7730)

The study of thermal comfort, in the last decades, was carried on with researches that allowed to define different standards:

– Researches on standard study subjects, such as a standard man or child, looking for the criteria to determine thermal comfort of specific categories and in specific buildings, such as schools
– Researches on adaptive thermal comfort, which considers the adaptation that people acquire, in relation to clothing, culture, individual habits, season, and outdoor conditions:

Adaptation: A change which reduces the physiological strain produced by stressful components of the total environment. This change may occur within the lifetime of an organism (phenotypic) or be the result of genetic selection in a species or subspecies (genotypic). Acclimation as defined in this Glossary relates to phenotype adaptations to specified climatic components. In thermal physiology, the use of the term adaptation does not require specification of the climatic components of the total environment to which the organism adapts, but the most obvious component is often denoted (e.g., adaptation to heat). There are no distinct terms which relate genotype adaptations to the climate or particular components of climate. Note: In comparison to adaptation as defined in neurophysiology, the adaptive processes in thermal physiology usually occur with larger time constants. (European Journal of Physiology (1987) 410 p. 567-587)

– Other researchers focus on specific situations, such as ill people and stressed workers.
– Studies on heritage building and historic thermal comfort (such as this book) or in the cultural heritage sector.

Martinez-Molina et al. (2016) describe the relation between thermal comfort and energy efficiency in historical buildings.

As it has been said, thermal comfort depends on the environmental and physical conditions and on the characteristics of individual people. These physiological variables are:

- Metabolic activity, which summarizes, in a single value, basal metabolism and activities, such as sleeping or working
- Clothing and thermal resistance that insulates the individuals from the environment

Metabolic activity, *met* from metabolic rate, is a measure of metabolism describing the power (W) per square meter (m^2) of the skin of individuals. Hence this value is a measure of energy, per unit of time per unit of surface (1 met = 58 W/m^2).

> met: An assigned unit of measurement to designate "sitting-resting" metabolic rate of man. 1 met = 58.15 W 9 m -2 : 50 kcal - h -1 9 m -2 It is an empirical unit of measurement to express the metabolic rate of a man whose clothing has an isolative value of 1 CLO when he is sitting at rest in comfortable indoor surroundings (Glossary of terms for thermal physiology (1987).

Values of metabolic rate met are present in the Standards themselves, as in the following tables, or can be calculated as prescribed in ISO 8996.

Clothing constitutes a resistance to thermal exchange between human body and the environment, which can be increased if required by colder environments. Clothing is, henceforth, one of the main strategies of humans to adapt to the different climates, together with buildings. To this primary function of clothes, others were added, linked to their ergonomics, ease of work, utility, as well as esthetics, fashion, culture, religious, sexual, and symbolic significance, in a way that nowadays it is impossible to consider thermal protection as the only function of clothes. Concerning thermal comfort, as it is perceived in an indoor space, it is relevant to know the thermal resistance (m^2K/W) of clothes, i.e., its resistance to the passage of heat. The unit to measure it is *clo*, from clothes (1 clo = 0.155 m^2K/W), which expresses:

> clo: a unit used to express the thermal insulation provided by garments and clothing ensembles, where 1 clo = 0.155 m2 °C/W (ASHRAE Standard 55)
>
> The clo is a unit developed to express thermal insulation in practical terms and represents the insulation provided by the normal indoor clothing of a sedentary worker in comfortable indoor surroundings. The term is used in heating and ventilation engineering in the determination of environmental conditions for human comfort. (Glossary of terms for thermal physiology 1987)

Values are defined in Annex of ISO 9920.

In the study of Historic Indoor Microclimate, the values of met and clo can be analyzed historically. Clothing and eating habits can be linked to the indoor microclimate conditions of buildings.

2.3.1 PMV and PPD Comfort Indexes

Comfort indexes summarize the complexity of the reactions occurring between human bodies, activities, habits, clothing, etc., and the variation of physical dimensions of the environment, such as air temperature, mean radiant temperature, air velocity, relative humidity, absolute humidity, and plane radiant temperature.

The index is a predictive instrument, as it allows to hypothesize the feeling of thermal comfort in as it is determined by design choices, or an evaluation tool, to confirm the choices already done.

Predicted mean vote (PMV) is the most used sensation index in international standards. It allows to evaluate the judgment of a healthy adult individual in moderate environment and it is expressed in a 7-point scale from cold (−3) to hot (+3). The value results from an equation which considers indoor microclimatic variables and metabolism and clothing of the individual, with a basis on the balance equation of heat exchange between human body and environment. PMV of 0 (zero = neutral) is the optimal situation of thermal comfort, the one in which discomfort is absent.

Predicted percentage of dissatisfied (PPD) is a statistical index correlated to PMV, or to other indicators such as CO_2, illumination level, or local situations of discomfort. It is the expected percentage of visitors complaining, expressing a discomfort, and it increases, obviously, as the comfort decreases.

Physiological equivalent temperature (PET) is a temperature index, defined

> as the physiological equivalent temperature at any given place (outdoors or indoors) and is equivalent to the air temperature at which, in a typical indoor setting, the heat balance of the human body (work metabolism 80 W of light activity, added to basic metabolism; heat resistance of clothing 0.9 clo) is maintained with core and skin temperatures equal to those under the conditions being assessed (Höppe 1999, p.73)

Apart from these indexes there are local discomfort indicators due to radiant vertical/horizontal asymmetry, cold or warm floor, and air currents.

In the field of studies on heritage buildings and on Historic Indoor Microclimate, the thermal comfort indexes PMV and PPD can be measured and monitored and simulated with virtual environment modeling software. This can be determined:

– PMV or PPD trends for a subject of which metabolic activity (met) and clothing (clo) are known, in relation to the physical variables of air temperature, relative humidity, air velocity, and mean radiant temperature.
– PMV and PPD can be evaluated for a single day, for the length of a month, season, and year, to evaluate specific discomfort situations or long-lasting ones, relevant to preserve the health of keepers, exposed to nonconditioned environments for long periods of time.
– With equal microclimatic conditions, PMV and PPD can be monitored or modeled in relation to the variation of metabolic activity (met) and clothing (clo) of the subject. This allows as well to consider historic clothing.
– The priority to give to thermal comfort, simulating the conditions allowing the entrance of visitors.

2.4 Interpret Physical Variables

The study of indoor microclimate and in particular of Historic Indoor Microclimate in heritage building requires the evaluation and interpretation of physical, chemical, and human-related variables that have been described above. This evaluation considers the values of the variables in the building or considered spaced. This can be done with:

- Punctual *measuring* (spot or one-shot) of the physical variables relevant to describe the environment. This activity usually gives information for a single point in time and can be useful to calibrate simulations or evaluate specific decay situations.
- *Monitoring*, i.e., the measuring of one or more variables along a period of time, ranging from one day to one or more years.
- *Simulation* (*software modeling*), with virtual environmental software, evaluating building energy performance, CFD, etc.

In these cases it is possible to know and evaluate the values, fluctuations, and behaviors of the different variables. The measuring, monitoring, and simulations should include an interpretation of data, with the help of graphics and similar tools.

Here follows a summary of measuring and monitoring activities and a list of instrument to study indoor microclimate.

2.4.1 Measure and Monitor

The difference between measuring and monitoring lies in the duration of the action. Measure is the single acquisition of the information, with a specific mode and technical instrumentation, while to monitor implies to repeat measures along a length of time. Measuring is done with technical tools, probes, sensors, dataloggers, microclimatic stations, etc., and can be punctual in space or distributed in more than one space. Monitoring consists in repeated measuring in a long span of time, related to several variables and instruments in one or more spatial points in the studied space. To plan a monitoring campaign, several things must be considered:

- Period and length.
- Number of points in space to measure.
- The measuring instrument and its accuracy with respect to the measured variable.
- The cost and management of the devices, acquisition of data, including the modalities and continuity of access to the online resources: A trade-off is usually required between accuracy and number of the probes, i.e., on the cost of the system. If a high amount of data is collected, coming from a long-term monitoring or from many probes in space, the accuracy of the single probe can be

reduced, while a high accuracy is usually used in the case a single space is monitored for a short period of time.
- The security of the placement, considering damage, theft, and manumissions.
- The control and acquisition of data, in situ or from remote (online platform).

The monitoring must be done with instrumentation adequate to measure thermo-hygrometric characteristics. It usually includes data-logger or micro-data-logger, which can be wireless, placed in relevant positions.

The results of the monitoring activity can be the following:

- Data in a table, with daily, weekly, monthly, and yearly values:

  Mean value
  Median value
  Maximum and minimum values
  Peak values (upper and lower)
  Minimal and maximal thermal excursion
  Gap, i.e., the percentage of time in which the physical variable is not within the acceptable range (data from the cumulative frequency of the hourly values graphic)
  Gap on the variation of temperatures over a day, week, or month

- Graphics:

  Trend of the physical variable
  Comparison of trends of several correlated variables, such as air temperature and relative humidity
  Percentage of cumulative frequency of hourly values
  Percentage of cumulative frequency

- Maps and layouts:

  Indoor microclimate map (IMM)
  Spatial 2D or 3D distribution of the variables from simulated results

2.4.2 Historic Climatic form for Objects

In the case of museums and spaces containing objects or furniture, as in historical buildings, with the goal of assuring the best conservation conditions, a specific form can be filled for every artifact.

This *"Form for the collection of information on the climatic history of objects"* is a useful tool to record the information on a specific object. It states:

- The placement of the object (permanently or temporarily exposed, stored)
- Notes on the conservation status and decay (stable, in slow or fast evolution, the type of decay)

– Detected values on specific dates for physical variables in the expositor or in the room
– The variables that can be modified and modalities of intervention
– (If present) devices used to regulate indoor microclimate

2.4.3 Probes and Measuring Instruments

The measure of variables in situ is done with specific probes and measure instrument. They are defined by:

– Probes for specific physical variables:

  Measurable range (minimum and maximum values)
  Accuracy of measure
  Modes of use
  Electricity supply type
  Answering time
  Working temperature
  Degrees of electronic protection

– Data-logger:

  The number of probes that can be connected
  Memory, external connection to remote systems (connection bridge, cables, Wi-Fi)
  Software characteristics to download and elaborate data

– Wireless systems for remote online monitoring, control over frequency of measure, and data transfer

ISO 7726, in annex, states the "*Principle for measuring*" for all the variables, living calculation criteria, and precaution in the use of probes and sensor types. The same norm gives the characteristics of measuring instruments:

> The measuring ranges, measuring accuracy and 90 % response times of the sensors for each of the basic quantities are summarized in table 2. These characteristics shall be considered to be minimum requirements. According to needs and technical manufacturing possibilities, it is always possible to specify more exact characteristics. (ISO 7726)

and

> An environment may be considered to be "homogeneous" from the bio-climatic point of view if, at a given moment, air temperature, radiation, air velocity and humidity can be considered to be practically uniform around the subject, i.e. when the deviations between each of these quantities and their mean spatial value calculated as a mean of the locations does not exceed the values obtained by multiplying the required measuring accuracy
>
> (. . .)

> When the environment is too heterogeneous, the physical quantities shall be measured at several locations at or around the subject and account taken of the partial results obtained in order to determine the mean value of the quantities to be considered in assessing the comfort or the thermal stress. (ISO 7726)

In the measure of *air temperature* (t_a), particular attention must be given to the effect of radiation on the probe, as direct radiation can alter the measure of air temperature. Moreover, the sensor should have periods of elapsed equal to at least 1.5 times the response time (90%) of probe. The temperature sensors can be:

- Expansion thermometers: (a) liquid expansion thermometer (mercury), (b) solid expansion thermometer
- Electrical thermometer: (a) variable resistance thermometer (platinum resistor or thermistor), (b) thermometer based on the generation of an electromotive force (thermocouple)
- Thermo-manometers, with variation in the pressure of a liquid as a function of temperature

Mean radiant temperature (tr) can be measured with several instruments, and the most common is the black-globe thermometer. The black-globe thermometer consists of a black globe (from 0.05 to 0.15 m of diameter) in the center of which is placed a temperature sensor such as the bulb of a mercury thermometer, a thermocouple (more common), or a resistance probe.

To use a black-globe thermometer the facts that the response time is about 20–30 min, that people are not actually identical to a globe thermometer, and that the measure is highly influenced by direct solar radiation (for example the sun) and by the color of the globe, which must be black with no dust or other alterations, must be taken into account.

Other measuring instruments are as follows:

- *Two-sphere radiometer*, constituted by two spheres at the same temperature but with different emissivity, since one is black and the other polished. The emissivity of the black sphere is higher than that of the polished; the measurement of the radiant temperature comes from the difference in heat supply between the spheres.
- *Constant air temperature sensor*: In this method a sensor is controlled at the same temperature as the surrounding air temperature, there being no convection heat loss and the necessary heat supply (cooling supply) to the sensor being equal to the radiant heat loss.

The measure of the *mean radiant temperature* can be obtained:

- From the plane radiant temperature (t_{pr}).
- From the temperature of the surrounding surface: in this case, mean radiant temperature is obtained from the function of the shape and of the emissivity of the walls.

To measure the *plane radiant temperature* (t_{pr}) the following can be used:

- A *heated sensor* consisting of a reflective disc (gold platter) and an absorbing disc (matt black painted): The two discs have an emissivity and the difference of heat supply needed to keep them at different temperatures allows to measure the radiant temperature.
- With *net-radiometer* (more common), consisting of a small black flat element with heat flow meter (thermopile) between the two sides of the element. The net heat flow between the two sides is equal to the difference between the radiant heat transfer at the level of the sides of the element.

Absolute humidity of the air can be measured with a *psychrometer* (more common), or a lithium chloride hygrometer, or using a psychometric chart from a dry-bulb temperature thermometer and wet-bulb temperature thermometer.

Air velocity is measured with an anemometer, which can be directional (only one direction) or with sensors in the three directions. Several models of anemometers exist: vane and cup anemometers; *hot-wire anemometers* (more common); pulsed-wire anemometer; hot-sphere and thermistor anemometer (more accuracy); ultrasonic anemometer; or laser Doppler anemometer.

In the evaluation of comfort in moderate environments, given the reduced air speed (<1.5 m/s), hot-wire anemometers are used. They consist of a couple of thermal resistances placed very close to one another, which, thanks to the measure of differences in current intensity, allows to determine air speed.

At last, to measure surface temperature, the following instruments can be used:

- (a) *Contact thermometers* (resistance, or thermocouples), consisting of sensors in direct contact with the surface of the wall; temperature is obtained from the measuring of heat exchange between surface and environment and then the measured surface temperature.
- (b) *Infrared sensor* (or remote temperature sensor) does not allow for a contact with the wall and the measuring is realized with infrared radiometers; a radiometer only measures the energy level of the radiation incident on the detector, and its incident radiation includes radiation emitted by the object and radiation reflected from the surface of the object.

2.5 Graphic Outputs

The results of the monitoring campaign can be elaborated with different tools. Here are presented the most common graphic outputs describing indoor microclimate of historical buildings and Historic Indoor Microclimate.

2.5.1 Trend of a Single Physical Variable (x-time, y-value)

A graphic showing the trend of a variable has time on the *x*-axis, such as hours, days, and months, and the value of the variable on the *y*-axis, such as air-temperature in °C. A graphic like this allows to visualize the trend of the physical variable along time, its variation, distribution, and fluctuations and oscillation of values.

In the case of air temperature or mean radiant temperature, the trends tend to follow external climatic conditions. An increase in the external parameters determines an increase in the internal ones, and the fluctuation follows the thermal daily excursion. It is relevant, as well, to consider the width of the thermal excursion in different times. During winter times, for example, this excursion is higher than in summer. The same data can give information on the aerial thermal capacity of the air volume and of the build case. The graphic can highlight anomalies, peak values, and extreme minimum and maximum values with several causes (problems of technical systems, peculiar outdoor climatic conditions, anomalies in the management of the spaces such as crowds). Relative humidity allows to evaluate situations in which the values exceed the optimal range for the conservation of artifacts and the frequency of these situations. Carbon dioxide concentration and that of other gases follows, in its trend, the cyclic processes of the pollutant source, which is, in the case of CO_2, the abundance of visits.

In this graphic it is possible to overlap more than one trend for the same variable measured in different places. This was the trend of air temperature, oscillations in different rooms or spaces are shown, and the effects of solar radiation, orientation, and visits can be evaluated (Figs. 2.1, 2.2, 2.3).

In the graphics it is possible to compare different physical variables, with a similar orientation of the graphic to that of a single variable: time on the *x*-axis and the physical variables on the *y*-axis. In this case, though, there are two variables and thus two scales on the *y*-axis, one for each variable. This graphic allows to observe how the two variables change accordingly in time.

An example is the graphic showing air temperature and relative humidity, which is useful to observe how RH varies with changes in air temperature. There usually is a negative correlation, and RH decreases with increases in air temperature, and exceptions to this pattern might be relevant to study. Other interesting comparisons are air speed and CO_2 concentration, illumination or radiation, and air temperature, surface temperature, or median radiant temperature (Fig. 2.4).

2.5.2 X/Y Graphic

In the *x*/*y* graphic two variables are placed on the two axes. If air temperature and *y*-axis = relative humidity, each point of the graphic matches a specific value of both variables.

A *x*/*y* graphic of air temperature/relative humidity (T/RH) defines the characteristic microclimate of a space, giving the point cloud of different indoor

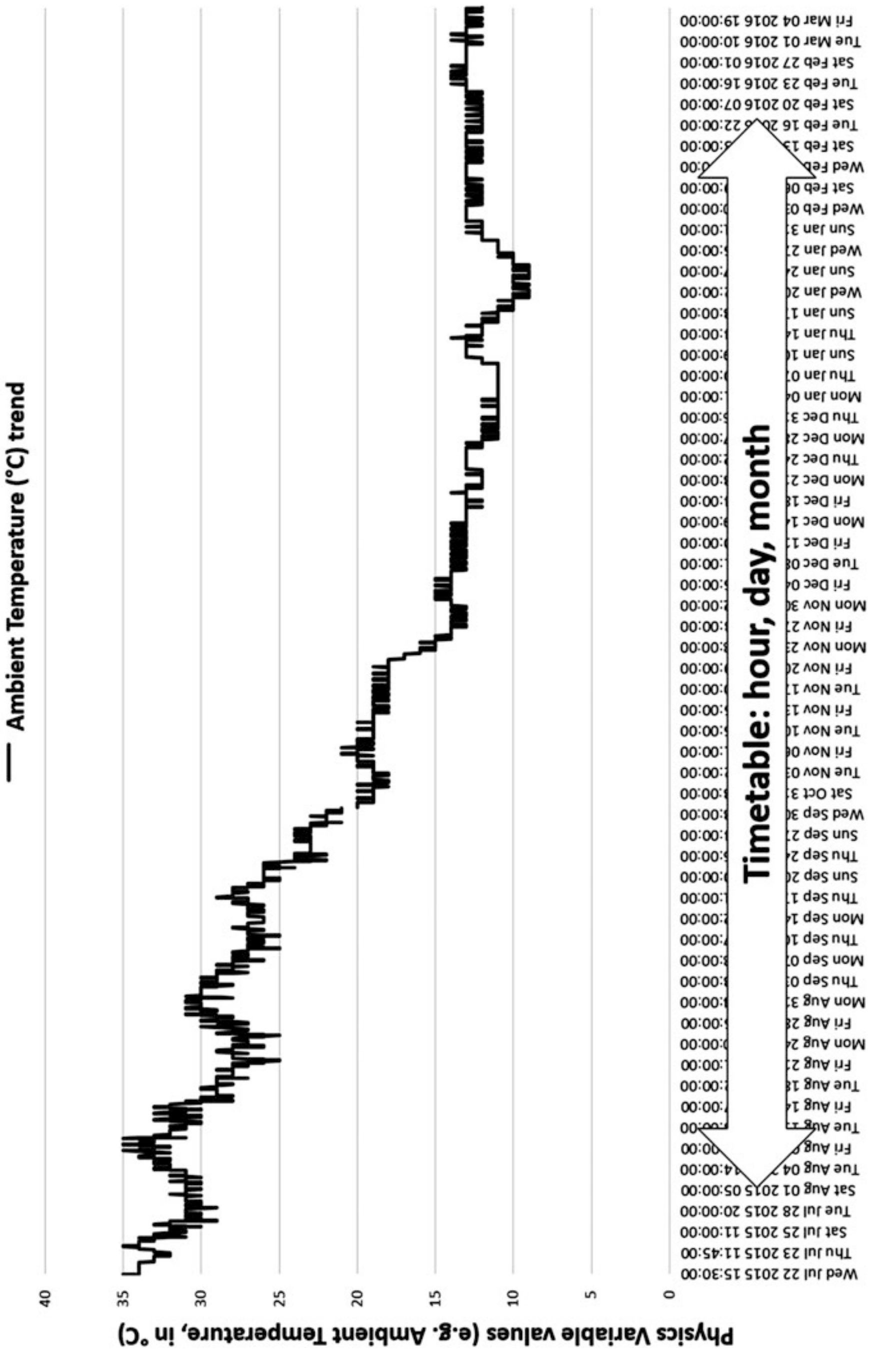

Fig. 2.1 Example of air temperature trend

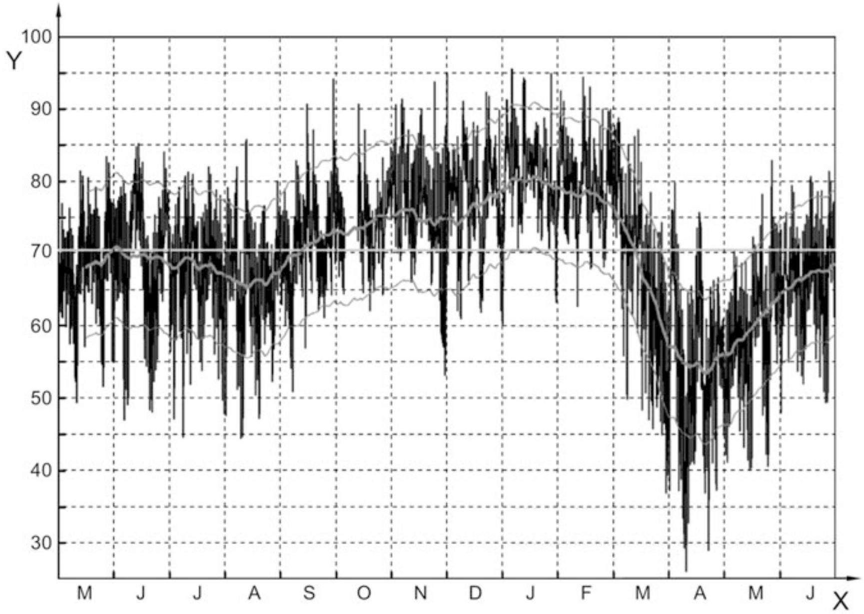

Fig. 2.2 Example of relative humidity trend. Target RH values for this sample set of RH readings (EN 15757 pg.17)

microclimate values. The area occupied by the cloud, where the points are denser and where the range of minimum and maximum variables falls are the most relevant parameters. A compact and dense point cloud represents a stable microclimate, less subject to fluctuations than one represented by a dispersed point cloud. Moreover it is possible to have an idea of the correlation between variables, i.e., how they vary one with respect to the other, and to observe anomalies shown by points deviating from the main body of the cloud. In some cases two or more nodes concentrate a higher density of points, which reflect seasonal trends (Figs. 2.5 and 2.6).

2.5.3 Graphics with Cumulative Curves and Frequencies

Other graphic instruments give more elaborated information, resulting from a calculation. Cumulative curves express the sum of the number of times or percentage of times that a determined value appears.

Frequency is calculated as:

$$F_i(\%) = \Sigma_i f_i(\%)$$

where f_i comes from:

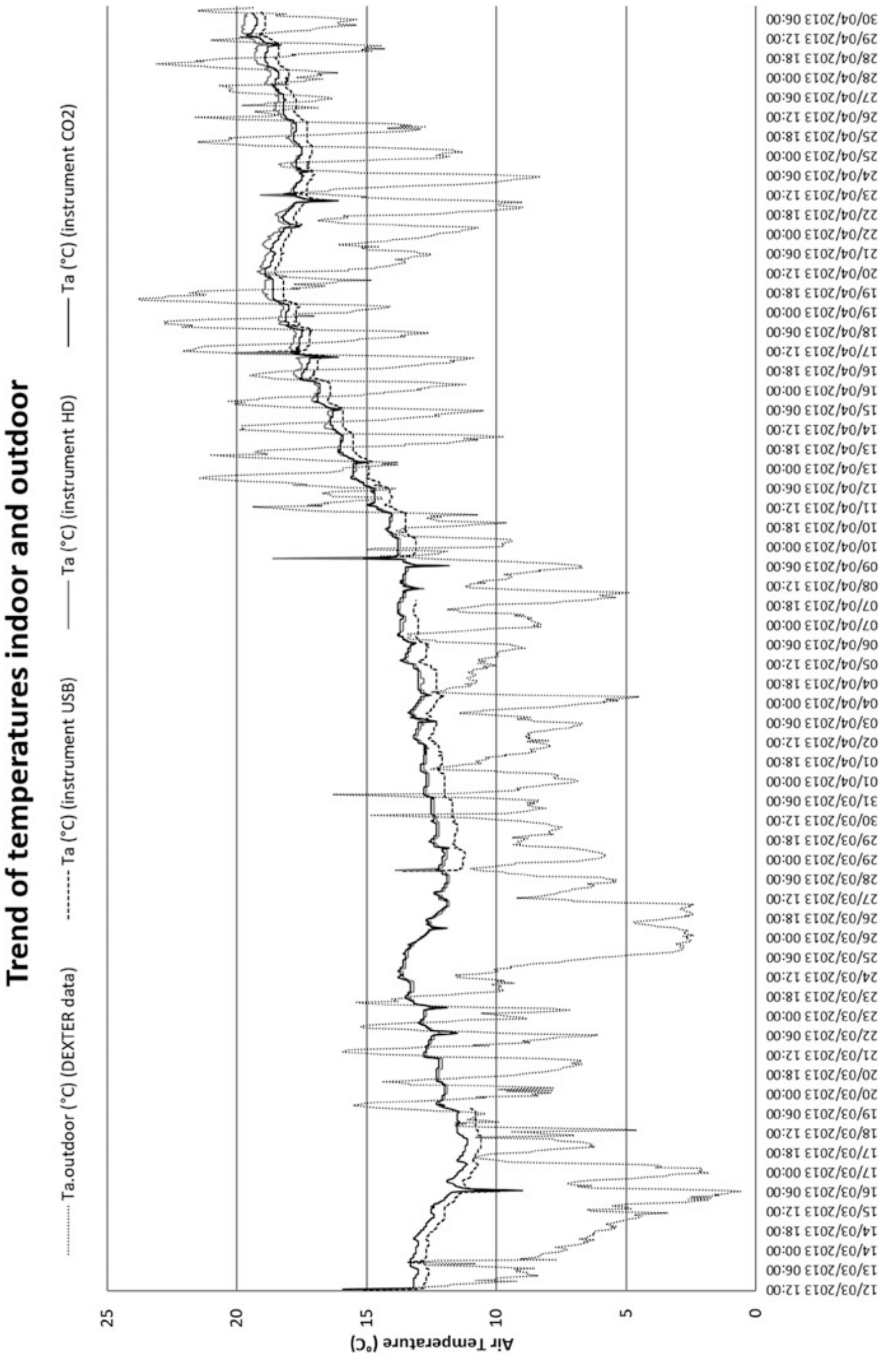

Fig. 2.3 Example of relative humidity trend with multiple probes

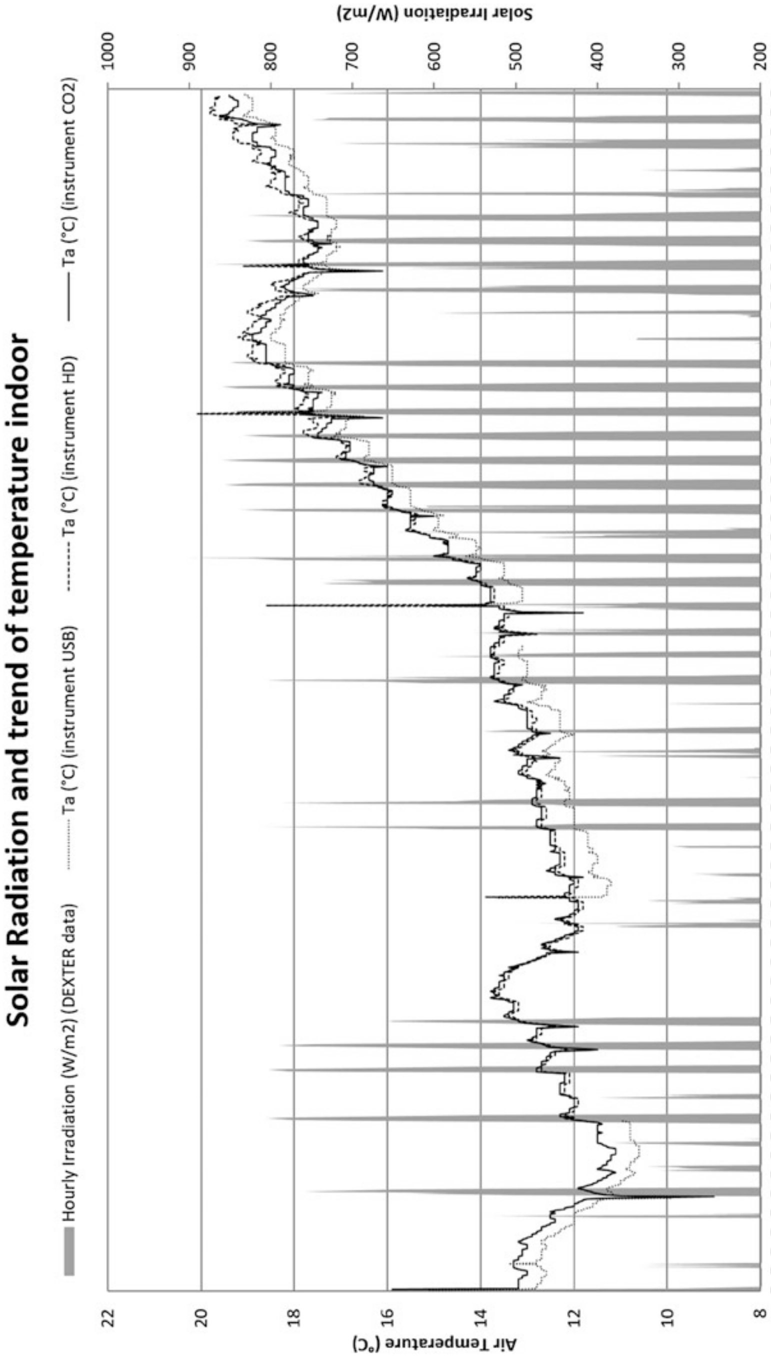

Fig. 2.4 Trends of two variables: air temperature and relative humidity

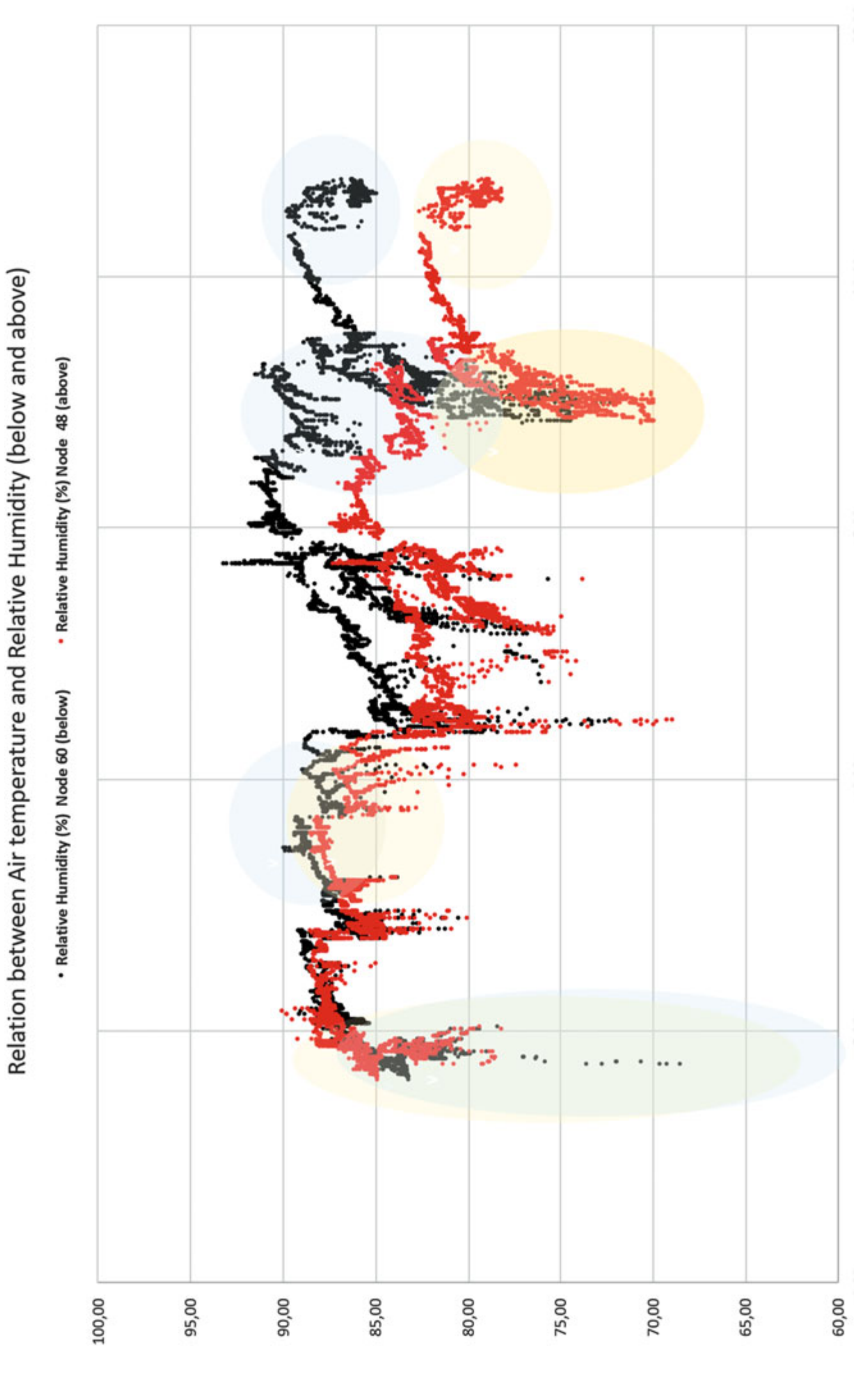

Fig. 2.5 Example of *x/y* graphic, with air temperature and relative humidity

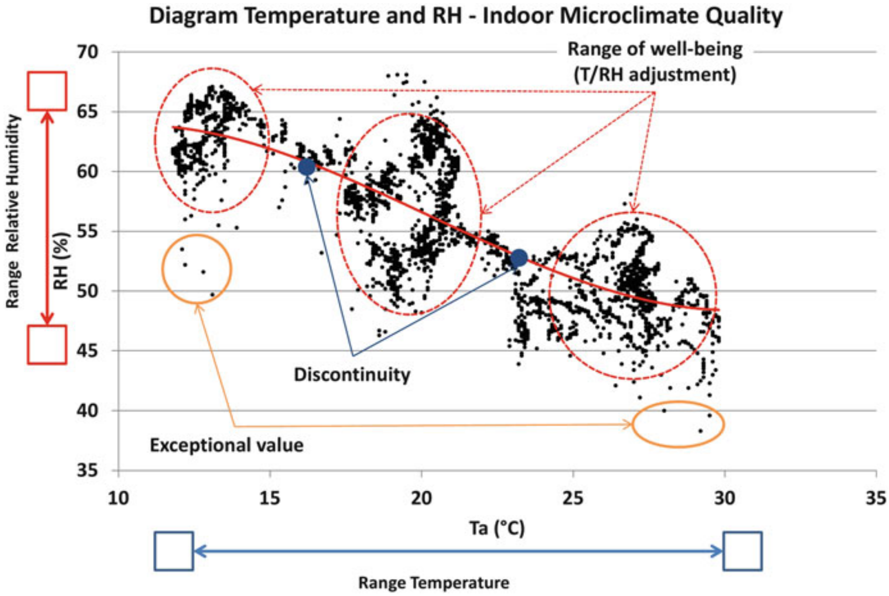

Fig. 2.6 Example of *x*/*y* graphic with air temperature and relative humidity or relative humidity matrix

$$f_i(\%) = (f_i \times 100)/N$$

where N is the total number of recorded values (Figs. 2.7 and 2.8).

The cumulative curve is usually characterized by an S shape, more or less elongated, with the recorded values on the *x*-axis and, on the *y*-axis, the percentage or count of times in which the measured values are below the value on the *x*-axis.

The frequency of a specific value is represented by the height of the proper column in a histogram, where on the *x*-axis are the values of the variable and on the *y*-axis the number or percentage of events in which the value has been recorded. This way are shown the distribution of the values and if there are anomalies in the ranges.

2.5.4 Psychrometric Diagrams (Psychrometric Charts)

Measured values of air temperature and relative humidity can help draw psychrometric diagrams (ASHRAE or Carrier Diagram).

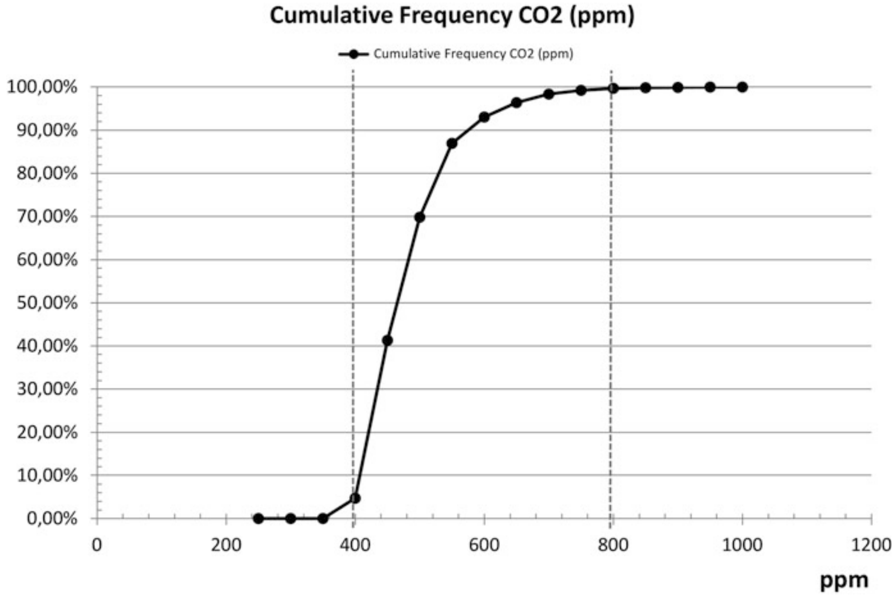

Fig. 2.7 Examples of single cumulative curves and relatives of the same variable measured in multiple spaces

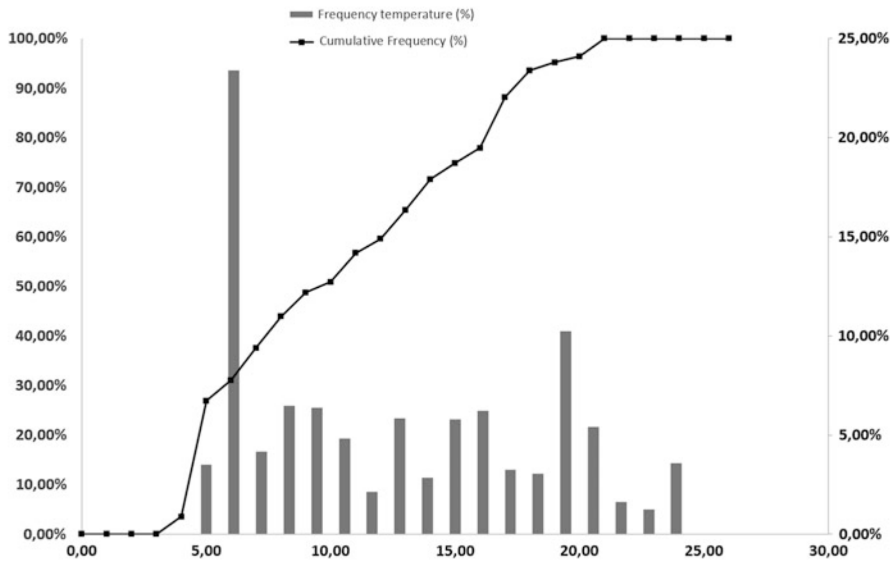

Fig. 2.8 Example of histogram of frequencies and cumulative curve

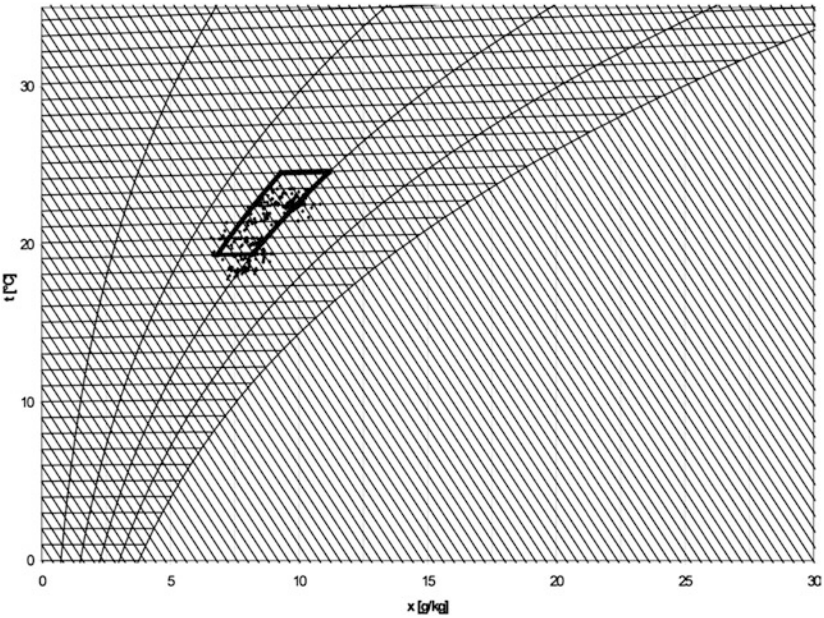

Fig. 2.9 Psychometric diagram. From La Gennusa et al. (2005)

Psychrometry is the discipline studying the thermodynamic behavior (physical dimensions, energy, and mass exchanges) of air at atmospheric pressure in temperature ranging between −10°C and 40°C, with particular attention to applications for comfort in indoor spaces and to the functioning of HVAC systems.

A psychrometric diagram or chart shows on the *x*-axis the value of air temperature reported by a dry bulb, while on the *y*-axis is the water vapor content of a kilogram of dry air, as absolute humidity. Moreover are reported the values of relative humidity and enthalpy.

This representation of values can be useful to evaluate if the comfort zone is guaranteed in a space, concerning the functioning condition of technical systems and/or possible designing actions, in order to improve the comfort in the building. In other words it is some sort of *x*/*y* graphic, corrected in accordance to psychrometry (Figs. 2.9, 2.10, 2.11).

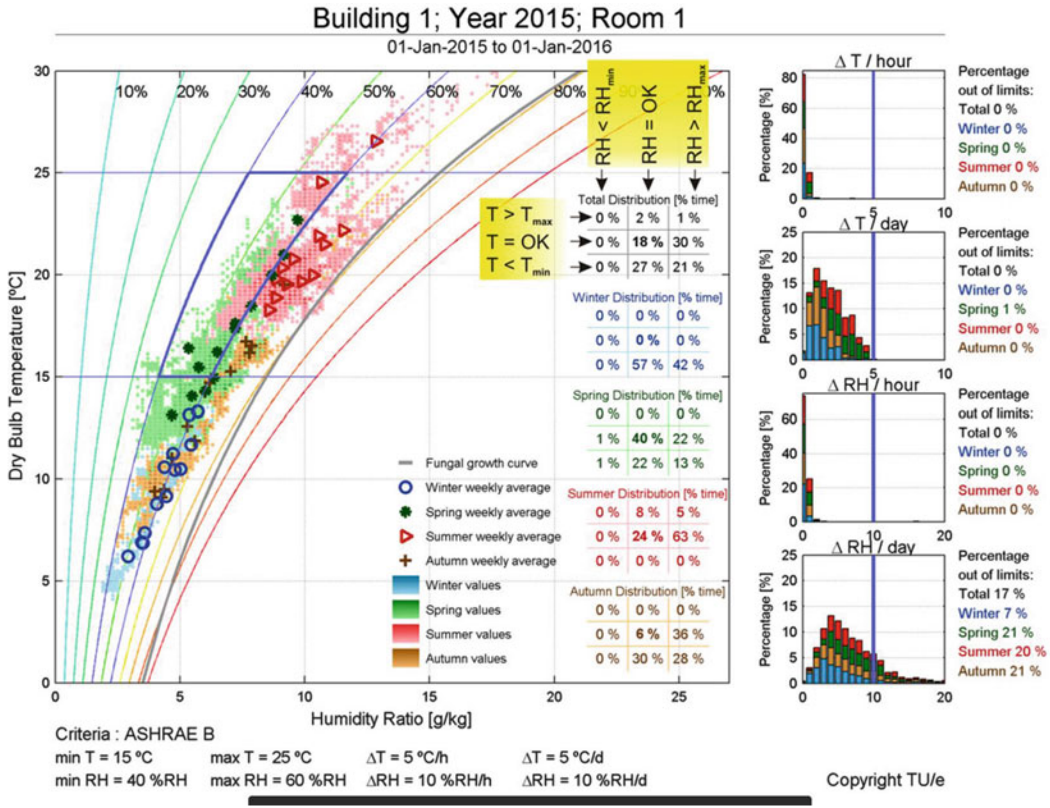

Fig. 2.10 Psychometric diagram. From Huijbregts et al. (2012)

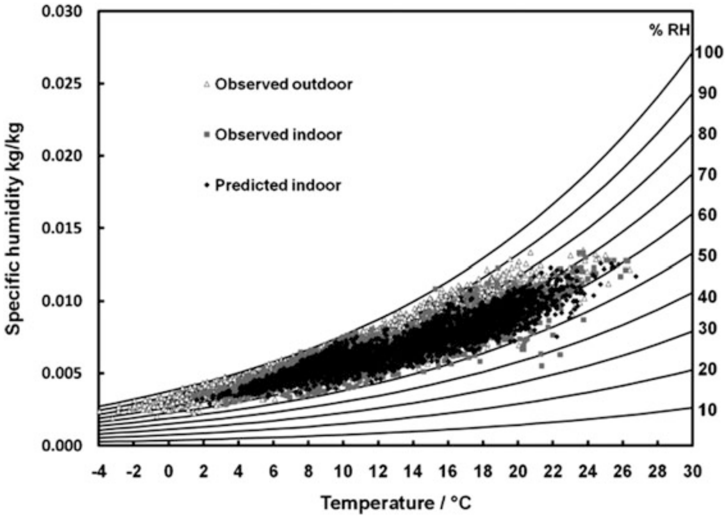

Fig. 2.11 Psychometric diagram. From Lankester and Brimblecombe (2012)

2.5.5 Indoor Microclimate Map

Values of physical variables, measured or simulated, can be represented in their distribution within a space. If the values are measures with instrumentations, either several probes that must be placed following a grid are required or the same probe can be moved to different points of the grid in a short span of time (even if this method is less accurate). The goal is to have several measure points distributed in space, so that it is possible to deduce the spatial trend of climatic variables.

Indoor microclimate maps showing the spatial distribution of physical variables allow to observe particular situations: where air is still, where relative humidity is high, where air temperature is layered horizontally or vertically, or where decay can occur. Moreover they can help to evaluate the effects of a specific microclimatic condition and the decay associated to it, as in weather forecast (Figs. 2.12, 2.13, 2.14).

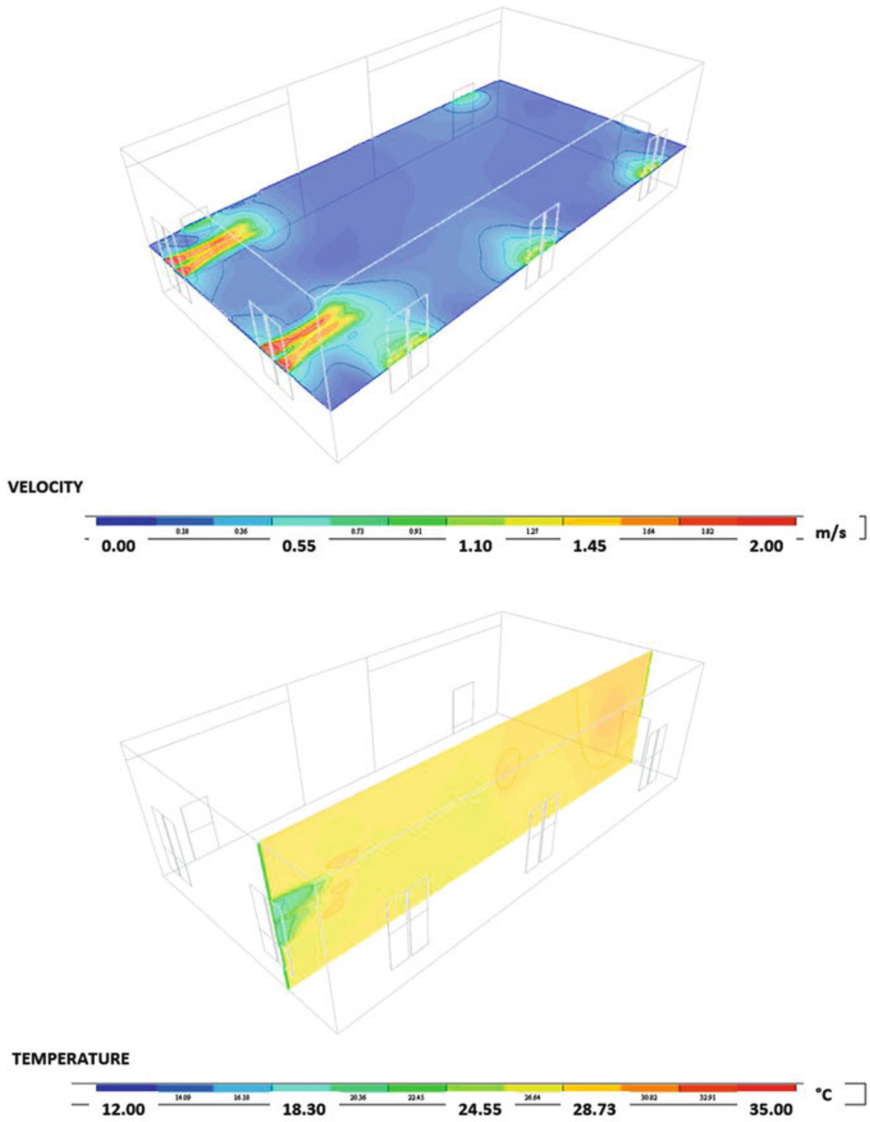

Fig. 2.12 Indoor microclimate map in 3D simulation

Fig. 2.13 Indoor microclimate map, Cattedrale di Otranto, from Cataldo et al. (2005)

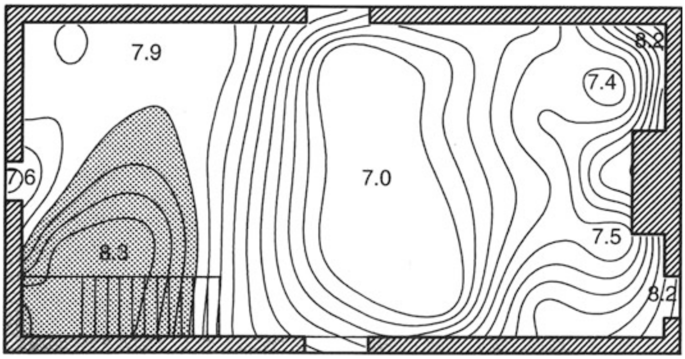

Fig. 2.14 Indoor microclimate map, S. Rocco Oratory, Padova (Camuffo 1998)

Annex

See (Tables 2.2, 2.3, 2.4, 2.5, 2.6 and 2.7).

Table 2.2 Main standards concerning heritage buildings, artifacts, and microclimate

CEN/TS 16163	Conservation of Cultural Heritage - Guidelines and procedures for choosing appropriate lighting for indoor exhibitions
EN 15757	Conservation of Cultural Property - Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials
EN 15758	Conservation of Cultural Property - Procedures and instruments for measuring temperatures of the air and the surfaces of objects
EN 15759-1	Conservation of cultural property - Indoor climate - Part 1: Guidelines for heating churches, chapels and other places of worship
EN 15801	Conservation of cultural property - Test methods - Determination of water absorption by capillarity
EN 15802	Conservation of cultural property - Test methods - Determination of static contact angle
EN 15803	Conservation of cultural property - Test methods - Determination of water vapour permeability (δp)
EN 15886	Conservation of cultural property - Test methods - Colour measurement of surfaces
EN 15898	Conservation of cultural property - Main general terms and definitions
EN 15946	Conservation of cultural property - Packing principles for transport
EN 15999-1	Conservation of cultural heritage - Guidelines for design of showcases for exhibition and preservation of objects - Part 1: General requirements
EN 16085	Conservation of Cultural property - Methodology for sampling from materials of cultural property - General rules
EN 16095	Conservation of cultural property - Condition recording for movable cultural heritage
EN 16095	Conservation of cultural property - Condition recording for movable cultural heritage
EN 16096	Conservation of cultural property - Condition survey and report of built cultural heritage
EN 16096	Conservation of cultural property - Condition survey and report of built cultural heritage
EN 16141	Conservation of cultural heritage - Guidelines for management of environmental conditions - Open storage facilities: definitions and characteristics of collection centres dedicated to the preservation and management of cultural heritage
EN 16242	Conservation of cultural heritage - Procedures and instruments for measuring humidity in the air and moisture exchanges between air and cultural property
EN 16302	Conservation of cultural heritage - Test methods - Measurement of water absorption by pipe method
EN 16322	Conservation of Cultural Heritage - Test methods - Determination of drying properties
EN 16455	Conservation of cultural heritage - Extraction and determination of soluble salts in natural stone and related materials used in and from cultural heritage
EN 16515	Conservation of Cultural Heritage - Guidelines to characterize natural stone used in cultural heritage
EN 16572	Conservation of cultural heritage - Glossary of technical terms concerning mortars for masonry, renders and plasters used in cultural heritage
EN 16581	Conservation of Cultural Heritage - Surface protection for porous inorganic materials - Laboratory test methods for the evaluation of the performance of water repellent products
EN 16648	Conservation of cultural heritage - Transport methods

Table 2.3 Thermo-hygrometric values suggested to assure the optimal physical-chemical preservation conditions for artifacts of different materials

	Relative humidity (%)	Air temperature (°C)
Iron armors, weapons	<40	
Ivory, bones	45–65	19–24
Bronze	<55	
Paper, papier-mâché	50–60	19–24
Anatomical collections	40–60	19–24
Mineralogical collections, marbles, stones	45–60	<30
Leather, hides, parchment	50–60	
Discs, magnetic tapes	40–60	10–21
Herbaria and botanical collections	40–60	−5 + 15
Film	30–50	2–20
Pictures (b/n)	20–30	19–24
Insects and entomological collections	40–60	19–24
Oriental lacquers	50–60	19–24
Wood	40–65	19–24
Painted wood, polychrome sculptures	45–65	19–24
Manuscripts	50–60	19–24
Ethnographic material	40–60	19–24
Generic organic material	50–65	19–24
Plastic materials	30–50	
Metals and polished alloys, brass, silver, pewter, lead, copper	<45	
Inlaid and lacquered furniture	50–60	19–24
Mosaics, frescoes, and wall paintings	45–65	Min 6° (winter) max 25°C (summer)
Gold	<45	
Papyri	35–50	19–24
Pastel, watercolor paintings, drawings, prints	50–60	19–24
Fur, feathers	45–60	15–21
Paintings on canvas	35–50	19–24
Porcelain, pottery, terracotta	20–60	
Silk	50–60	
Fabrics, carpets, tapestry	40–60	
Glass and stable glass windows	25–60	

From Ministerial Decree (Ministero per i Beni e le Attività Culturali e de Turismo – MIBACT. Atto di indirizzo sui criteri tecnico-scientifici e sugli standard di funzionamento e sviluppo dei musei, 10th May 2001)

Table 2.4 Microclimatic conditions to prevent microbiological attacks to organic materials

Organic artifacts		Relative humidity (%)	Max daily variation	Air temperature (°C)	Max daily variation
Paintings	On canvas	40–55	6	19–24	1.5
	On panel	50–60	2	19–24	1.5
Wood		50–60	2	19–24	1.5
	Archaeological	50–60	2	19–24	1.5
	Wet	–		<4	
Paper		40–55	6	18–22	1.5
	Pastel, water-color paintings	<65		<10	
	Books and manuscripts	45–55	5	<21	3
	Graphic material	45–55	5	<21	3
Leather, hide, parchment		40–55	5	4–10	1.5
	Cellulosic	30–50	6	19–24	1.5
	Protein based	>50–55		19–24	1.5
Ethnographic collections		20–35	5	15–23	2
Stable materials		35–65		–30	

From Ministerial Decree (Ministero per i Beni e le Attività Culturali e de Turismo - MIBACT), Atto di indirizzo sui criteri tecnico-scientifici e sugli standard di funzionamento e sviluppo dei musei, 10th May 2001)

Table 2.5 Reference values in stable climate conditions, if other specific information are lacking (UNI 1890)

Historic and artistic heritage	Air temperature (°C)	Max excursion air temperature (Δ°C)	Relative humidity (%)	Max excursion relative humidity (Δ%)
Organic materials and objects				
Artistic artifacts in paper, tissue paper, papier-mâché, tapestry	18–22	1.5	40–55	6
Fabrics, curtains, carpets, fabric tapestry, silk, costumes, clothes, religious vestments, objects in natural fibers, sisal, jute	19–24	1.5	30–50	6
Wax, anatomic waxes	<18	Not relevant	Not relevant	Not relevant
Herbaria and collections	21–23	1.5	45–55	2
Entomological collections	19–24	1.5	40–60	6
Animals and anatomical organs in formalin	15–25	–	Not relevant	Not relevant

(continued)

Table 2.5 (continued)

Historic and artistic heritage	Air temperature (°C)	Max excursion air temperature (Δ°C)	Relative humidity (%)	Max excursion relative humidity (Δ%)
Dried animals and anatomical organs, mummies	21–23	1.5	20–35	–
Fur, feathers, stuffed animals	4–10	1.5	40–50	5
Drawings, watercolor paintings, and others on paper support	19–24	1.5	45–60	6
Ethnographic collections, masks, leather, leather clothes	19–24	1.5	45–60	6
Paintings on canvas, oil on canvas, gouache	19–24	1.5	45–55	6
Documents from archives on paper or parchment, papyri, manuscripts, printed volumes, philatelic collections	13–18	–	50–60	5
Book ligatures in leather or parchment	19–24	1.5	45–55	6
Lacquers, inlaid, lacquered, and decorated furniture	19–24	1.5	50–60	4
Wooden polychrome sculptures, painted wood, paintings on wood, icons, wooden musical instruments, wooden pendulum clocks	19–24	1.5	50–60	4
Wooden non-painted sculptures, wicker objects, wooden or bark panels	19–24	1.5	45–60	4
Inorganic materials and objects				
Porcelain, pottery, terracotta, shingle not from excavations or deprived of minerals from excavations	Not relevant	–	Not relevant	10
Porous stones, rocks, minerals, and meteorites	19–24	–	40–60	6
Stone mosaics, nonporous stones, rocks, minerals and meteorites, fossils, stone collections	15–25	–	20–60	10
Metals, polished metals, metallic alloys, silvers, armors, bronzes, coins, copper, iron, steel, lead, pewter and tin objects	Not relevant	–	<50	–
Metals with active corrosion sites	Not relevant	–	< 40	–
Gold	Not relevant	–	Not relevant	–
Chalk	21–23	1.5	45–55	2
Instable, iridescent, sensitive glasses or glass mosaics	20–24	1.5	40–45	–

(continued)

Table 2.5 (continued)

Historic and artistic heritage	Air temperature (°C)	Max excursion air temperature (Δ°C)	Relative humidity (%)	Max excursion relative humidity (Δ%)
Mixed objects				
Wall paintings, frescoes, sinopias (detached)	10–24	–	55–65	–
Wall dry paintings (detached)	10–24	–	50–45	–
Ivories, horns, malacological collections, eggs, nests, corals	19–24	1.5	40–60	6
Phonographic disks	10–21	–	40–55	2
Synthetic fibers	19–24	–	40–60	–
Film, colored pictures	0–15	–	30–45	–
Film, b/w pictures	0–15	–	30–45	–
Magnetic tapes (excluded tapes for computer and videotape)	5–15	–	40–60	–
Organic objects coming from wet excavation sites (before treatments)	<4	–	Saturated air	–
Plastic materials	19–24	–	30–50	–

Table 2.6 Characteristic of measuring instruments (ISO 7726)

Physics variable	Measuring range (comfort)	Measuring range (thermal stress)	Accuracy	Response time (90%)
Air temperature (t_a)	10–40°C	−40 C +120°C	Required: ±0.5°C Desiderable: ±0.2°C	The shortest possible. Value to be specified as characteristic of the measuring instrument
Mena radiant temperature (t_r)	10–40°C	−40 C +120°C	Required: ±2°C Desiderable: ±0.2°C	The shortest possible
Air velocity (v)	0.05–1 m/s	0.2–20 m/s	Required: ±0.05 m/s Desiderable: ±0.2 m/s	Required: 0.5 s Desirable: 0.2 s
Absolute humidity (expressed as partial pressure of water report Pa)	0.5–3.0 kPa	0.5–6.0 kPa	Required: ±0.15 kPa	The shortest possible
Surface temperature (t_s)	0–50°C	−40 C +120°C	Required: ±1°C Desiderable: ±0.5°C	The shortest possible

Table 2.7 Characteristic of measuring instrument temperature (ISO 15758)

Instrument	Symbol	Measuring range	Uncertainty	Repeatability	Resolution	Response time	Stability
Thermometer for air temperature	T	Outdoors: −40°C to 60°C Indoor: −40°C to 60°C	Required: 0.5°C Desiderable: 0.2°C	0.1°C	0.1°C	The shortest possible not longer than 60 s	± 0.2°C/year
Black-globe thermometer	Trg	Outdoors: −40°C to 100°C Indoor: −20°C to 100°C	Required: 1.0°C Desiderable: 0.5°C	0.5°C	0.1°C	The shortest possible not longer than 20 min	± 0.2°C/year
Black-strip thermometer	Trs	Outdoors: −40°C to 100°C Indoor: −20°C to 100°C	Required: 1.0°C Desiderable: 0.5°C	0.5°C	0.1°C	The shortest possible not longer than 200 s	± 0.2°C/year
Surface temperature (contact or proximity sensors)	Ts	Outdoors: −40°C to 100°C Indoor: −20°C to 80°C	Required: 1°C Desiderable: 0.5°C	0.2°C	0.1°C	The shortest possible not longer than 200 s	± 0.2°C/year
Surface temperature (remote sensors)	Ts	Outdoors: −40°C to 100°C Indoor: −20°C to 80°C	Required: 1°C Desiderable: 0.5°C	0.5°C	0.1°C	The shortest possible not longer than 60 s	± 0.2°C/year

References

ASHRAE (2011) Museums, galleries, archives, and libraries. In: ASHRAE applications handbook. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta

ASHRAE Standard 55-2014, Thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta

ASHRAE Standard 62.1 (2016) Ventilation for Acceptable Indoor Air Quality

Baer NS, Banks PN (1985) Indoor air pollution: effects on cultural and historical materials. Int J Mus Manage Curatorship 4:9–20

Balocco C, Calzolari R (2008) Natural light design for an ancient buildings: a case study. J Cult Heritage 9:172–178

Boarin P, Guglielmino D, Zuppiroli M (2014) Certified sustainability for heritage buildings: development of the new rating system GBC Historic Building. In: REHAB 2014 – Proceedings of the international conference on preservation, maintenance and rehabilitation of historic buildings and structures, 2014, pp 1109–1120

Camuffo D (1998) Microclimate for cultural heritage. Elsevier, Amsterdam

Camuffo D, Bernardi A, Sturaro G, Valentino A (2002) The microclimate inside the Pollaiolo and Botticelli rooms in the Uffizi gallery, Florence. J Cult Heritage 3(2):155–156

Camuffo D, della Valle A (2007) Church heating: a balance between conservation and thermal comfort, Contribution to Experts Roundtable on Sustainable Climate Mangament Strategies, April 2007, Tenerif, Spain. The Getty Conservation Institute

Camuffo D, Pagan E, Bernardi A, Becherini F (2004) The impact of heating, lighting and people in re-using historical buildings: a case study. J Cult Heritage 5(4):409–416

Camuffo D, Pagan E, Rissanen S, Bratasz L, Kozłowski R, Camuffo M, della Valle A (2010) An advanced church heating system favourable to artworks: a contribution to European standardisation. J Cult Heritage 11(2):205–219

Cataldo R, De Donno A, De Nunzio G, Leucci G, Nuzzo L, Siviero S (2005) Integrated methods for analysis of deterioration of cultural heritage: the Crypt of “Cattedrale di Otranto”. J Cult Heritage 6:29–38

CEN/TS 16163 (2014) Conservation of cultural heritage—guidelines and proce-duresfor choosing appropriate lighting for indoor exhibitions. European Committee for Standardization, Brussels

Corgnati SP, Fabi V, Filippi M (2009) A methodology for microclimatic quality evaluation in museums: application to a temporary exhibit. Build Environ 44:1253–1260

D’Agostino V, d’Ambrosio Alfano FR, Palella BI, Riccio G (2015) The museum environment: a protocol for evaluationof microclimatic conditions. Energy Build 95:124–129

de Guichen G (1995) La conservation préventive: un changement profond de men-talité. In: Cahier d’étude ICOM. International Council of Museums, Paris, pp 4–6

de Santoli L (2015) Guidelines on energy efficiency of cultural heritage. Energy Build 86:534–540

EFFESUS http://www.effesus.eu/

EN 15757 (2010) Conservation of cultural property—specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials. European Committee for Standardization, Brussels

EN 15758 (2010) Conservation of cultural property—procedures and instruments for measuring temperatures of the air and the surfaces of objects. European Committee for Standardization, Brussels

EN 15759-1 (2011) Conservation of cultural property - Indoor climate - Part 1: Guidelines for heating churches, chapels and other places of worship

EN 16242 (2012) Conservation of cultural heritage—procedures and instruments for measuring humidity in the air and moisture exchanges between air and cultural property. European Committee for Standardization, Brussels

Fanger PO (1970) Thermal comfort-analysis and applications in environmental engineering. Danish Technical Press, Copenhagen

Ferdyn-Grygierek J (2014) Indoor environmental quality in the museum buildings and its effect on heating and cooling demand. Energy Build 85:32–44

Frontczak W, Wargocki P (2011) Literature survey on how different factors influence human comfort in indoor environments. Build Environ 46:922–937

Glossary of terms for thermal physiology (1987) Pflugers. Archiv 410:567–587

Grzywacz CM (2006) Monitoring for gaseous pollutants in museum environments. In: Maggio E (ed) Tools in conservation. Getty Conservation Institute, Los Angeles

Gysels K, Delalieux F, Deutsch F, Van Grieken R, Camuffo D, Bernardi A, Sturaro G, Busse H, Wieser M (2004) Indoor environment and conservation in the Royal Museum of Fine Arts, Antwerp, Belgium. J Cult Heritage 5(2):221–230

Höppe P (1999) The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. Int J Biometeorol 43:71–75

Huijbregts Z, Kramer RP, Martens MHJ, van Schijndel AWM, Schelen HL (2012) A proposed method to assess the damage risk of future climate change to museum objects in historic buildings. Build Environ 55:43–56

ISO 13790 Energy performance of buildings – Calculation of energy use for space heating and cooling

ISO 7726 Ergonomics of the thermal environment – Instruments for measuring physical quantities

ISO 7730 Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria

ISO 8996 Ergonomics of the thermal environment. Determination of metabolic rate

ISO 9920 Ergonomics of the thermal environment — Estimation of thermal insulation and water vapour resistance of a clothing ensemble

Kramer RP, Maas MPE, Martens MHJ, van Schijndel AWM, Schellen HL (2015) Energy conservation in museum using different setpoint strategies: a case study for a state-of-art museum using building simulation. Appl Energy 158:446–458

Krupinska B, Van Grieken R, De Wael K (2013) Air quality monitoring in a museum for preventive conservation: results of a three-year study in the Plantin-Moretus Museum in Antwerp. Belgium Microchem J 110:350–360

La Gennusa M, Lascari G, Rizzo G, Scaccianoce G (2008) Conflict need of the thermal indoor environment of museums: in search of a practical compromise. J Cult Heritage 9:125–134

La Gennusa M, Rizzo G, Scaccianoce G, Nicoletti F (2005) Control of in-door environments in heritage buildings: experimental measurements in an old Italian museum and proposal of a methodology. J Cult Heritage 6(2):147–155

Lankester P, Brimblecombe P (2012) Future thermo hygrometric climate within historic houses. J Cult Heritage 13:1–6

Litti G, Audenaert A, Braet J, Fabbri K, Weeren A (2015) Synthetic scan and simultaneous index aimed at the indoor environmental quality evaluation and certification for people and artworks in heritage buildings. In: 6th International Building Physics Conference, IBPC 2015, Energy Procedia 78:1365–1370

Lucchi E (2016) Multidisciplinary risk-based analysis for supporting the decision making process on conservation, energy efficiency, and human comfort in museum buildings, Journal of Cultural Heritage. Journal of Cultural Heritage - Available online 24 June 2016, In Press, Corrected Proof — Note to users

Martinez-Molina A, Tort-Ausina I, Cho S, Vivancos JL (2016) Energy efficiency and thermal comfort in historic buildings: a review. Renewable and Sustainable Energy Rev 62:70–85

Mazzarella L (2015) Energy retrofit of historic and existing buildings: the legislative and regulatory point of view. Energy Build 95:23–31

Mecklenburg MF, Tumosa CS (1999) Temperature and relative humidity effects on the mechanical and chemical stability of collections. ASHRAE J 41(4):77–82

MIBACT (2001) Decreto Ministeriale 10 maggio 2001, Atto di indirizzo sui criteri tecnico-scientifici e sugli standard di funzionamento e sviluppo dei musei, (Ministero per i Beni e le Attività Culturali e de Turismo-MIBACT)
Monetti V, Davin E, Fabrizio E, Andrè P, Filippi M (2015) Calibration of building energy simulation models based on optimization: a case study. Energy Proc 78:2971–2976
Pavlogeorgatos G (2003) Environmental parameters in museums. Build Environ 38 (12):1457–1462
Penica M, Svetlana G, Murugl V (2015) Revitalization of historic buildings and an approach to preserve cultural and historical heritage. Proc Eng 117:883–890
prEN 16682 (2013) Conservation of cultural heritage—guide to the measurements of moisture content in materials constituting movable and immovable cultural heritage. European Committee for Standardization, Brussels
project 3ENCULT http://www.3encult.eu/en/project/welcome/default.html
Silva HE, Henriques FMA (2015) Preventive conservation of historic buildings in temperate climates. The importance of a risk-based analysis on the decision-making process. Energy Build 107:26–36
Tétreault J (2003) Airborne pollutants in museums, galleries and archives: risk assessment. Control strategies and preservation management. Canadian Conservation Institute, Ottawa
Thomson G (1986) The museum environment. Elsevier, Amsterdam
Troi A, Bastian Z (2014) Energy efficiency solutions for historic building. A handbook. Birkhauser, ISBN 9783038216469
UNI 10829 (1999) Works of art of historical importance. Ambient condition for the conservation. Measurement and analysis. UNI Ente Nazionale Italiano di Unificazione, Milano
Vieites E, Vassileva I, Arias JE (2015) European initiative towards improving energy efficiency in existing and historic buildings. Energy Proc 75:1679–1685
WHO (2006) World Health Organisation, WHO Guidelines for Indoor Air Quality
WHO (2008) Guidelines for indoor air quality: dampness and mould. World Health Organization
WHO (2010) World Health Organisation, WHO Guidelines for Indoor Air Quality: Selected Pollutants, 2010 [20th August 2011]; Available from: http://www.euro.who.int/en/what-we-publish/abstracts/who-guidelines-for-indoor-air-qualityselected-pollutants
Zivkovic V, Dzikic V (2015) Return to basics - Environmental management for museum collections and historic houses. Energy Build 95:116–123