Indoor Environment Enegineering (IEE) in cultural heritage – a REHVA guidebook

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1 Introduction

REHVA, the European Federation of HVAC National Association, is involved to prepare a document concerning how to minimize the rate of deterioration of cultural property and to create safe and correct environment in preservation areas, by defining technical and scientific specifications for HVAC design, installation, O&M operations serving macro or micro environment for conservation. Starting from IAQ, temperature and HR preservation requirements for new and existing museums and taking into account the classification of artefacts by deterioration properties, the aim of the document (a guidebook) is to achieve a classification of control strategies and systems based on environmental requirements of the areas served by HVAC systems.

Technical means of achieving and maintaining IAQ, climate and illumination control in exhibition, storage, and preservation spaces must also be considered. The authors of the Guide are Livio de Santoli and Marco Filippi from AiCARR (Italy) who coordinate a task force (Matteo Mariotti, AiCARR, Morten Rhyl Svenson, ISIAQ, Luis Malheiro, ODE, Derek Braham, CIBSE) coming from different HVAC National Associations.

In the following sections are reported the chapters as proposed in the Guidebook.

2 General principles for indoor conservation of Cultural Heritage

Thie Guide provides a general microclimate selection and control for indoor conservation of cultural heritage, such as in museums, galleries, archives, libraries, churches and historic buildings.

The object of the Guide is related to *cultural heritage materials* that are both artefacts and natural finds, referred to hereinafter simply as "*objects*".

The variety and complexity of the objects that make up cultural heritage is such that research carried out on deterioration processes caused by environmental driving forces have not yet to establish conclusive results. So far it is impossible to determine precise threshold values or optimal ranges of environmental parameters for the conservation of every object. It is, however, possible to establish general principles which must necessarily be followed by those responsible for conservation.

Deterioration is a cumulative process, involving both number and intensity of individual driving force events. It happens gradually as the object ages and its chemical and physical properties change, and any environment disturbance contributes to the deterioration process, though sometimes it is imperceptible to the human eye.

Different causes may produce different effects depending on the type of object and its history, often being the combination of more causes able to produce synergistic effects.

The most important factors for the preservation of an object are its previous history, the microclimate that led to a stabilization of the material in response to external environmental driving forces and its own physical and chemical characteristics. The situation becomes increasingly critical as materials age and tolerance is reduced.

The microclimate, also in synergy with other factors, plays a key role in the processes of deterioration and the various materials or individual parts of the object respond differently to environmental variables and changes in both time and space. Rapid temporal variations and strong spatial gradients in temperature and/or relative humidity, or exchanges of heat and mass, cause internal stress in many materials with cumulative and irreversible effects that accelerate the process of deterioration.

To determine the environmental parameters for conservation purposes we should refer to specific studies defining the most appropriate microclimate for each object. Please note that, even with results known in literature, these give useful guidelines but are not always entirely applicable to other cases, however similar, especially if the objects are particularly delicate or consist of composite materials.

The choice of microclimate for conservation must take into account the direct impact on the materials of which the objects are made. Particular attention is needed to the presence of air pollutants and their potential chemical reactions with objects. Different materials have a different response to thermohygrometric environmental conditions and their variations. For example, wax and certain photographic emulsions need to be stored at low temperatures. Oil paintings and tempera undergo a transition phase from an elastic rubbery state to glass fragility as a result of the cumulative effect of thermal cycles. In some cases higher levels of heat causes accelerated deterioration processes, especially of a chemical and biological nature. All materials expand or contract more or less markedly as a result of thermal variations and some also due to humidity. Particularly critical situations can arise if the object presents differential deformations. Transitions around freezing point can cause structural damage to materials that contain water in the liquid state.

Some materials are not sensitive to relative humidity (for example, metals as gold), while others need to be kept in a dry atmosphere (for example, ceramics impregnated in salt or metals with active corrosion); others require precise relative humidity ranges (for example: collections of hydrated minerals). Finally, there are hygroscopic materials which are highly sensitive to changes in relative humidity over the entire environmental variability range (for example, wood, ivory, animal glue, parchment, paper). These materials are the most critical and difficult to preserve. Other materials which initially do not suffer damage from thermohygrometric changes may undergo alterations and develop microcracks over time which make them highly vulnerable, as often happens with archaeological finds.

In some cases it is possible to establish an optimal compromise solution for conservation conditions beforehand. For example, high relative humidity, in the presence of acids and/or oxidizing agents, leads to deterioration in cellulose, as well as biological deterioration and irreversible physical changes. Therefore, paper should be preserved in a moderately dry environment.

In the case of objects consisting of one or more materials with more complex characteristics or conditioned by previous history (like wood), particular procedures should be followed.

In the case of objects which are to be placed in a conservation environment, the microclimate must be studied on the basis of the object's chemical and physical properties.

If an object is already in a favourable microclimate and no deterioration processes are in place and there is no risk, the object should be maintained in the environmental conditions to which it has adapted and by which it has been conditioned. Care has to be put in improving in this case the original microclimate by reducing one or more disturbances (diurnal cycles, fluctuations, abrupt transitions, gradients, etc).

If it is really necessary to change the original conditions of an object that has long remained in a given microclimate, this should be done on the basis of specific compatibility studies on the object's conservation history (including climate), its chemical and physical characteristics and its new environmental conditions.

If it is necessary to alter the microclimate in which an object is preserved, the transition to the final microclimate must take place over a very long period of time (to be determined in relation to the size of the object and the materials of which it is made), by adapting the object gradually to the new conditions, and continuously verifying that it is able to withstand the transition without suffering deterioration.

Should the object need to be moved for temporary exhibitions, restorations or otherwise, the greatest care must be taken to ensure compliance with the initial microclimatic conditions. This care must be maintained during transport and storage.

In the case of objects with photosensitive surfaces, it should be noted that deterioration due to light radiation is cumulative, so the items must be displayed under the lowest possible level of illumination, filtering the ultraviolet and infrared components, and only for a time that is compatible with real needs.

It is preferable to follow the policy of preserving the integrity of each individual object in the original microclimatic context, as long as there is no obvious deterioration due to the microclimate. The application of an abstract standardized microclimate, to be applied without difference in different climate condition is generally a process to be avoided or carefully evaluated.

The choice of environmental parameters depends primarily on the needs of the objects preserved, the human welfare being as less priority.

For items most sensitive to changes in environmental parameters, the locations chosen should naturally have the most stable microclimatic conditions. Objects that require specific microclimatic conditions must be placed in protected areas.

To avoid unwanted temporal or spatial variations in environmental parameters, mainly passive control strategies should be applied. Passive actions include, for example, thermal insulation, use of materials and structures with high thermal and hygrometric inertia, limiting uncontrolled exchanges of heat and water vapour, filtering solar radiation, replacing light sources.

In general, the objects must always be protected from active elements that can alter the microclimatic balance, such as sources of heat, cold, and water vapour, light sources and intense air currents.

Active systems are to be used only when strictly necessary, to eliminate daily cycles and mitigate seasonal variations. The application of these installation systems must be carefully controlled in order to minimise fluctuations due to sensitive and latent thermal loads created by the presence of visitors, lighting installations and external driving forces. It should also be pointed out that movements of air within an environment can accelerate the process of depositing gas and aerosols present in the environment or coming in from the outside.

3 Environmental parameters for Conservation

The complexity and variety of the objects that make up cultural heritage makes it particularly difficult to identify and define in absolute terms the optimal environmental parameters that are critical for the preservation of works of art. Therefore, the correct choice of the parameters should always and necessarily be accompanied by a specific interpretation methodology based on what the document “Atti di indirizzo sui criteri tecnico-scientifici e sugli standard di funzionamento e sviluppo dei musei” reports in the section “Environmental parameters”. This methodology will include:

- the evaluation of the item’s state of conservation;
- the analysis of the variations in the microclimatic, lighting and air quality parameters of the environment in which the item is located;

- the analysis of the variations in the microclimatic, lighting and air quality parameters of the environment in which the artefact will be located;
- the overall assessment of the "conservation/environment state";
- knowledge of how the item interacts with the environment.

The procedures for planning and guaranteeing conservation quality objectives are based on: threshold values and benchmarks for microclimate, lighting conditions and air quality;

Objects	**Relative Humidity (%)**	**Temperature (° C)**
iron armour, weapons	<40	
ivory, bone	45-65	19-24
Bronze	<55	
paper, paper mache	50-60	19-24
anatomical collections	40-60	19-24
mineralogical collections, marble and stone	45-60	<30
leather, skins, parchment	50-60	
records, tapes	40-60	10-21
herbs and botanical collections	40-60	
Film	30-50	-5 - +15 *
photographs (b / w)	20-30	2-20 **
insects and entomological boxes	40-60	19-24
oriental lacquer	50-60	19-24
Wood	40-65	19-24
wood painting, polychrome sculpture	45-65	19-24
books, manuscripts	50-60	19-24
ethnographic material	40-60	19-24
organic material in general	50-65	19-24
Plastics	30-50	
polished metals and alloys, brass, silver, tin, lead, copper	<45	
furniture with inlays and lacquers	50-60	19-24
mosaics and murals	45-60	min 6 ° C (winter) max 25 ° C (summer) with max daily gradient 1.5°C/H
Gold	<45	
Papyrus	35-50	19-24
pastels, watercolours, drawings, prints	50-60	19-24
Furs, feathers	45-60	15-21
paintings on canvas	35-50	19-24
porcelain, ceramics ***, stoneware, earthenware	20-60	
Silk	50-60	
fabrics, carpets, tapestries, cloth wall coverings	40-60	
glass and stable windows	25-60	

* Depends on film sensitivity.

** Valid for photographs on paper, plastic, glass. On nitrate based material and glass with colloidal emulsion lower temperatures are recommended.

*** For certain pottery made at a low temperatures the RH value must be <45%.

Finally, they must outline the environmental standards for proper conservation at various levels and provide management guidelines and measures.

Proper conservation conditions must also take account of the maximum recommended values for airborne chemical pollutants, as shown in the table below.

Maximum concentration value for airborne pollutants

Pollutant	**Archives (NISO-TR01/95)**	**Museum (Brimblecombe)**	**UNI 10586/97**
Sulphur dioxide	5-10 ppb (vol)	<0.4 ppb (vol)	<10 µ g/m3
Nitrogen dioxide	5-10 ppb (vol)	<2.5 ppb (vol)	<2 µ g/m3 (NOX)
Ozone	5-10 ppb (vol)	1 ppb (vol)	<2 µ g/m3
Particulate (fine)	> 95% removed	> 95% (2µ m) removed	<50 µ g/m3

4 Measurements and analisys

A set of environmental parameters for the conservation in climate conditions that are stable over time, can be taken into account in the design of new air conditioning systems for environments containing works of historical or artistic interest. The values provided as in tables of the Guide should be seen as "recommended values" to be adopted in the absence of specific rules or standards.

The measurements refer to the following parameters (which should not be considered the only ones that are important for conservation):

- Air temperature T_o;
- Relative humidity RH_o;
- Maximum daily temperature range ΔT_{max};
- Maximum daily relative humidity range ΔRH_{max};
- Maximum illuminance E_{max};
- Maximum quantity of ultraviolet radiation UV_{max};
- Maximum annual light dose LO_{max}.

For proper conservation, values for the environmental magnitudes to which the object has been subjected over time should be collected and compared to the sequence of events that cause deterioration in the object.

In order to identify deviation indicators in the environment under consideration, the cumulative frequencies referred to environmental parameters (air temperature and humidity and surface temperature) should be calculated and put into diagram form.

A report of the measurements and calculations in this document includes:

- enough information to identify the area in which the measurements were carried out, the techniques and equipment used, periods in which the readings were taken, operators, and processing procedures adopted;
- benchmarks adopted for calculating the deviation indicators and the criteria used to define these benchmarks, in relation to objects or categories of objects in the area examined;
- deviation indicators values and if some are missing why they have been omitted (for example, unimportant or no available values, etc.);
- average, maximum and minimum T and RH and the maximum range in a day, month, or other period of time considered significant (specify the reasons for doing so).

5 General aspects of climate control

It is clear from the foregoing considerations that indoor thermo-hygrometric conditions need to be kept constant throughout the day and annual variations should be restricted as much as possible. This can be done with air-conditioning systems but a preliminary analysis should be made to identify possible ‘non-system’ or ‘passive’ measures to limit the above variations, since this would mean less complex systems, and lower installation and management costs.

The first thing to be considered is the effect that the building envelope has on the way the outside environment interacts with the internal environment.

The control of a building’s indoor microclimate starts not with the air-conditioning system but with the design of the building itself. "Passive" interventions should therefore be considered, that is those which are inherent to the building itself.

In addition, the thermal inertia of the building or, rather, a high time constant (thermal capacity and thermal insulation) could help to mitigate or eliminate the negative effects of shutting down the air-conditioning system at night, if it has been necessary to install this method of climate control.

Given the complexity of the phenomena, the effect of passive interventions must be carefully analysed in the design phase, for example using numerical models.

The air exchange of the rooms, which is necessary for air quality control (elimination of pollutants, containment of $C0_2$), has a fundamental effect on humidity. Ambient air can be renewed by means of an HVAC system equipped with all the components necessary for thermo-hygrometric control (hot and cold coils, humidifiers, etc), as described below, or more simply, by letting in or extracting outdoor air or from infiltrations (i.e. air passing through cracks or openings due to temperature gradients or the dynamic effects of wind); this second case of untreated air intake is very common in historic buildings (halls of residence, churches, etc.), a situation which can be difficult to rectify due to the alterations that the installation of a air-conditioning system would involve.

It is worth highlighting the consequences of untreated exchange of indoor and outdoor air on the room's hygrometric balance.

In some cases the air-conditioning systems must also take into account routes followed by guided tours and the time spent in rooms. This might always be the same or change from time to time, depending on the duration of the exhibitions and the type of exhibits on display. Some rooms may remain unused and the system must be able to meet the need for functional flexibility and provide a quick response to compensate for possible rapid changes in thermal loads.

A crowded room directly influences the production of moisture, sometimes to a large extent. The need to maintain a relative humidity value that is constant, at the same indoor temperature, involves an equally invariant value of specific humidity inside the room.

6 Typologies of climate control systems

Climate control is an argument that has been and continues to be treated by several authors, confirming the complexity of the topic. Below are some general considerations; please refer to specialist literature for more details.

If it is decided to install an air-conditioning system, various factors will have to be taken into account:

- The system should be compatible with construction technologies used in the building, taking care not to overload floors or make overlarge holes in the walls;
- The heat distribution system should be chosen with care, with a view to facilitating management and maintenance; possible leakage of fluids should not pose any threat to exhibits;
- The system should be compatible with the intended use and preservation of the material kept in the building.

The following aspects should be analysed when deciding on air-conditioning systems:

- Choice of system (just heating, with or without ventilation, summer air-conditioning);

- Choice of heat distribution fluid;
- Choice of mechanical rooms;
- Identification of vertical and horizontal passages for pipes and distribution ducts;
- Appropriate positioning of climate control equipment in the rooms;
- Accessibility of components that require maintenance.

We shall now consider some climate control solutions on the basis of different environmental control needs. Sometimes systems that are apparently, and in theory, too "simple" are more than enough and perhaps even necessary.

Many museums have never had and still lack any form of climate control system, and sometimes even a small "artificial" thermo-hygrometric intervention can stabilise or slightly improve environmental conditions, which are already per se sufficiently suitable for conservation. Then, the complexity of a system should be considered and evaluated in terms of the structural disruption that it would cause. As will be seen, in fact, sophisticated and highly articulated systems provide better environmental control but require considerable space for the components

The first thing to decide is what functions are required of the system: only winter heating or all-year-round conditioning? The first solution primarily involves temperature control but in its simplest form it does not provide humidity control if not through humidifiers placed in rooms to correct low humidity values; but excess humidity cannot be reduced.

The second solution, if properly implemented, provides the best simultaneous control of temperature and humidity. It should be noted that the removal of heat from an environment (e.g. through refrigerated water fan coils) produces a "symmetrical" situation, as opposed to simple heating in which temperature but not humidity can be controlled.

Year-round control of the thermo-hygrometric conditions and air quality can be achieved only through an "air-conditioning" plant, i.e. a system that is equipped with all the components needed to achieve the necessary psychrometric transformations.

7 HVAC choices for building typologies

We shall now take a look, from the point of view of possible air-conditioning solutions, at the three types of museums most commonly found.

Newly built museums undoubtedly give the greatest freedom in all aspects of building design, management and control, i.e. security and safety systems, air-conditioning and all other necessary services. In terms of thermo-hygrometric control, all systems can potentially be installed since the most important constraint on choice (interaction with the building) does not exist in this case. Building structure and installations are in fact conceived and designed simultaneously and, in the case of buildings for conservation, must be assessed in equal measure in terms of importance and usefulness.

Choice depends first of all on the needs of the works preserved in the building and an assessment of their safety.

Among the heat conductors usually used, i.e. water or air, the all-air solution is preferred since it provides a greater control of ventilation flow to ensure the quality of indoor air (IAQ) by removing pollutants. The number of hourly exchanges of indoor air volume is usually linked to a set value of ambient carbon dioxide concentration; this is a direct function of the number of people present, so variable airflow systems are often advised.

Systems with radiant panels placed on the floor have the advantage of being hidden from view, but their functions are mostly limited to heating only, although there are noteworthy cases of summer air-conditioning with primary air radiant floor panels.

Museums in historic buildings and historic buildings as museums may be characterized by an inadequate indoor microclimate. In this case air-conditioning systems should be installed to achieve the appropriate indoor conditions for the preservation of the materials. .

Although range of possible interventions in the design phase is wide, in practice is significantly reduced due to constraints regarding the material that is preserved in the building, the value of the collection, duration of exhibitions and other factors affecting the organization of visitor flows to rooms. Another consideration is the particular but not rare situation of having to operate in pre-existing buildings often of historical and artistic value.

Recent architectural restoration theory and practice stresses the characteristics of conservation in the restoration or regeneration of historic buildings. It follows that the design of a system that is integral to and indispensable for the role of the museum requires a profound historical knowledge of the building, the stratifications, the materials and use in different eras.

It is therefore a case of working out a compromise in consideration of the parameters to be used by the air-conditioning system, the degree of architectural and structural interference, and installation and running costs. The system must be installed in a way that is non-traumatic, avoiding highly visible alterations to the architectural lines and respecting the basic structures as much as possible: in the past walls were all too often hollowed out to make channels for pipes of considerable size.

On the other hand, however, safeguarding objects contained in historic building does not always have to involve damaging or otherwise disrupting the building. As said, sometimes the artwork is an integral part of the architecture: the deterioration of a wall painting, for example, is closely linked to that of the architectural structures of the building, from the mechanical, thermal and hygrometric points of view.

In principle, if we exclude buildings with large rooms intended for exhibitions or museums, we can say that a water system is almost always the most appropriate because it involves less disruption to existing structures.

It is difficult to use predetermined solutions that are valid in any situation. However, the choices concerning systems design should be made according to the same principles that are used for building renovation. Then there is the complex debate between those who consider the strict conservation of architectural heritage to be pre-eminent and those whose priority is the use of the building and who justify any intervention that can guarantee the health and safety of the occupants.

In the case of historic buildings there are, therefore, further constraints on installations:

1. installation must be compatible with the construction technologies used in the building;
2. it must be possible to carry out maintenance and repair work without having to resort to destructive operations;
3. installation must be compatible with building use and the preservation of its artistic heritage.

Special care must be taken to avoid damaging horizontal and vertical structures by boring holes or cutting deep channels, overloading floors with heavy equipment (such as cooling units, water tanks, heat generators, etc) and weakening them with flues or mechanical rooms.

8 The importance of energy management

The importance of efficient energy management for sustainable development is a priority, as is demonstrated by both Community and national policies; it is also being looked at with increasing attention by economic and industrial operators, as is attested by the growing number of requested and issued EMAS and ISO 14000 certifications (environmental certifications). All energy management activities require specific professional skills, which fit the job description of energy manager, even if these skills can be used and applied for different purposes and in different areas, ways and specificities. So, depending on the circumstances, the energy manager will be responsible for design, diagnosis, systems management, inspection and evaluation, and verification. Industrial and services sectors or public administrations using significant amounts of energy, which have free access to the electricity and gas market and are characterized by a consumption of primary energy that is the equivalent of over 1,000 tonnes of oil per year, are required by law to appoint an energy manager. However, it should be highlighted that, even without legal obligations, due attention should be given to the containment of energy consumption and costs, which should be below the limits set by law. The duties of an energy manager in this case, especially as regards the public administration, are:

- detailed analytical energy auditing, involving end-users and associated costs;
- optimization of energy purchases, identifying the most appropriate sources and contractual

arrangements;

- the identification and implementation of operations to improve efficiency;
- definition of appropriate contractual arrangements with a view to entrusting the implementation of interventions and/or management of the plant to an outside energy services company.

9 Energy-environmental sustainability

To obtain the desired parameters inside a building may require a considerable amount of energy. Generally speaking, the construction sector, and therefore cultural heritage, produces a great impact not only on social and economic human activities but also on natural and manmade environment. Enhancing the environmental efficiency of a building means reducing the impact that the building has on the environment; this can be done through the introduction of effective environmental policy instruments aimed at achieving three main objectives:

- Reduction of $C0_2$ emissions;
- Optimization of waste, by eliminating or reducing waste generation at the source, and reusing, recycling and recovering materials;
- Prevention of indoor pollution.

Apart from reducing the demand for primary energy and improving supply capacity, energy conservation, a particularly delicate issue also reduces emissions into the atmosphere and thus environmental pollution.

That the welfare of a country cannot be defined only by its GDP is now largely accepted, and many authors propose the introduction of environmental auditing and precise environmental indicators to identify the qualitative and quantitative depreciation of natural heritage. It is not only about protecting the environment but making proper use and implementing proper management of natural resources.

10 References

Atti di indirizzo sui criteri tecnico-scientifici e sugli standard di funzionamento e sviluppo dei musei
ASHRAE Handbook, Applications
Conservation Environment Guidelines for Libraries and Archives (Canadian Council of Archives)
Recommendations on Artifact Preservation (State Russian Museum)
Delta Plan for Cultural Preservation (Netherlands Government Building Agency)