Marco Pretelli
Kristian Fabbri *Editors*

Historic Indoor Microclimate of the Heritage Buildings

A Guideline for Professionals who care for Heritage Buildings

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Preface

Life exists on earth only within a limited range of temperatures. It is basically impossible over 45°C and below −20°C, if we exclude some unicellular or simple multicellular organisms. Human life is naturally restricted to an even smaller range and, within this range, the conditions of comfort fall only between 15°C and 30°C. During its evolution, mankind developed different strategies and technical solutions to deal with conditions falling regularly (seasonally or continuously) out of this range: clothing, food, and architecture, here intended as the whole sum of possible shelters, as Lodoli referred to it. It is not random, indeed, that these are the main elements defining cultures of the different populations on the planet.

Adopting an exclusively functional criterion, the whole history of architecture could be condensed in various solutions to guarantee livable spaces to people in different places and historic times. Temperature, for exemplum, is definitely a relevant element to define a space livable and, given the variability in external conditions, the solutions to guarantee livability can used to differ of a large span.

This study starts from the consideration above: in recent times the logic consequence chain of an environment defining architecture has been somehow reverted. Architectures are cloned and placed in considerably different conditions. This research aims at demonstrating how indoor microclimate was, in the past, not a random consequence of architectonic choices led by other needs, but one of the main goals that an architect or designer aimed at, adopting architectonic solutions, building techniques and proto-HVAC systems to determine the microclimatic conditions inside each of their architectures.

Why Starting from Afar?

Historic Indoor Microclimate constitutes now a new area of research on historic architecture, but it is the result of a longer path of research started with the analyses of indoor microclimate in the Malatestiana Library in Cesena (built on a project from Matteo Nuti in the first half of the fifteenth century, study case described in Chap. 8).

Out of scientific curiosity, in 2013 we asked and obtained permission to place probes monitoring indoor microclimate in the Historic Room in the Library. From the analysis of data, we started to observe the role of the architectonic configuration of the building: its three layer structure where the ground and second floor held no apparent function, the number and distribution of the windows and the regular pattern of their opening, etc. As the research proceeded, it appeared clear that this configuration, as well as the materials used in the construction, was not the result of random planning or of careless use of formal rules of early Renaissance. On the contrary, all those choices led to the definition of a specific indoor microclimate in the room where the books are hosted.

The result is that the Malatestiana Library produces (a carefully chosen term, as the process does not imply any external mechanical intervention or system) its own microclimate, an absolutely nonrandom product of strategies used to achieve a specific result: guarantee the best conditions possible to the books representing the heritage preserved in the Library, a corpus of precious medieval manuscripts collected by Novello Malatesta, Lord of Cesena. It is not accidental that, as the Malatestiana Library, many historic libraries built in the same period share similar planimetric and altimetric schemes, as well as structure and materials.

Starting from this single observation that the structure of a building heavily influences its microclimate, we tried to individuate specific study cases to confirm this relation, some of which are described in this volume. This led to the definition of Historic Indoor Microclimate and of the research area its study is related to. Indoor microclimate acquired a significant status as immaterial and irreplaceable part of its building, so that its characteristics, its role, and consequences of changes are important and worth studying.

The present volume is divided in two distinct parts. The first one describes the contest and the instrument of research on Historic Indoor Microclimate, as well as the interpretation of results. In the second one are analyzed four study cases: the Malatestiana Library in Cesena, the Santuario del Valinotto in Carignano, Villa Medici La Petraia in Florence, and Vleeshuis Museum: Antwerp (Belgium).

Chapter 1 deals with the relation between architecture and indoor microclimate, while in Chap. 3 is defined the field of research of Historic Indoor Microclimate and its component, Original, Subsequent and Actual Indoor Microclimates. Chapters 2, 4, and 5 give methodological instruments to study HIM: they describe the thermophysical variances, probes, software modeling, archival research, and in situ surveys. Chapter 6 suggests criteria for indexes to characterize indoor microclimate and Chap. 7 describes the complex theme of HIM conservation, highlighting the need to study indoor microclimate in order to preserve and restore heritage buildings. Finally, the last four chapters are dedicated to the study cases.

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Marco Pretelli
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A last, sincere, thanks goes to Ilaria Pretelli for her work in the translation as well as for her critical activity, the comments and observations which, as we hope, led this volume to reach its goal: to focus the attention of technicians and researchers dealing with Historic Buildings on the preservation of their specific and delicate Historic Indoor Microclimate.

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Chapter 1
Architecture and Indoor Microclimate

Marco Pretelli and Kristian Fabbri

Abstract In this chapter, the meaning of Historic Indoor Microclimate is debated, alongside with its relations with architecture, in particular historical one. This constitutes the main subject of the book, which holds high relevance in order to increase architectural knowledge, in the study of artistic and cultural heritage and in many other researches in a wide range of fields.

1.1 Architecture and Indoor Microclimate

What first comes to mind in response to the word "architecture" are magnificent buildings, with mighty walls, genial orientation systems, vaulted ones even if fake, sculpted and decorated elements, and frescoes. It is easy to remember how the spaces are articulated, usually quite differently from modern architectures, with complicated and sometimes spectacular geometries. The boldness of a pinnacle or of a gothic flying buttress and the bulk of full domes strike us, as in the walls of these magnificent rooms the signs of passing time interlace with those left by man that can be read as a story.

On the contrary, it is rare to think to the microclimatic conditions that those enclosed spaces were guaranteeing. These were very different from modern ones, so much that they might represent the factor of major novelty of the post-Industrial Revolution conditions.

The same concept of comfort, intended as adequacy of the microclimatic characteristics of a room to the human well-being, is a recent product of industrial revolution, as Melograni and Ricossa (1988) highlight. In their book "*Le rivoluzioni del benessere*" ("The revolutions of comfort"), they explain how some habits we consider guaranteed nowadays, such as demographic increase, enlargement of cities, and introduction of health practices and of personal hygiene—with the introduction of a bathroom in houses in the nineteenth century, have been possible thanks to Industrial Revolution.

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Visiting Versailles Palace, it is possible to observe how the highest noblemen of one of the richest countries in Europe were living in sumptuous residences, but in conditions that most of us would find incredibly hard to endure, mainly during winter times. Indeed, despite the incredibly high number of hearths, it was recurrently happening that water or even wine to serve in banquets would freeze during the day. This is to exemplify the temperatures faced by counts, earls, barons, and king, as well as valets, waiters, cooks, and so on.

It has to be admitted that the years when the palace was terminated have been particularly cold, so that it has been called the Little Ice Age: the winter of 1709, 6 years before the death of King Luis XIV, is considered the coldest in Europe in the last 500 years.

Acot (2003) says:

> Starting in 1691, in France, climate worsened: long periods of frost during winter delayed the growth of cereals, while, in summer, rains and ice destroyed the harvests. In 1793 a cold spring with delayed monsoons caused wheat not to germinate up to August, and a rainy September caused it to rot. The price of bread increased so much that Louis XIV decreed bread to be sold at cheap prices in many places in the city, to reduce the effects of famine. The winter between 1693 and 1694 was particularly cold and rainy. (...) It has been calculated that the crisis determined a number of victims in two years comparable to those in the four years of First World War. In 1708 the weather gets worse again: snow covered France and the birds fell while flying. This detail is frequently reported in chronicles of other situations and places. It is hard to establish how much this is exaggerated, but it has to be considered ... the situation remained hard until 1709. (Acot 2003, pp. 128–129)

In general, the role of climate on history of people is more relevant than usually thought. It was a great determinant of battles, as during the Napoleonic campaign in Russia, in the form of the so-called General Winter, but other effects can be seen in other human activities: food, clothing, and architecture.

In past times, compared to modern ones, indoor microclimate of buildings was much more dependent on external climate. Modern heating, ventilation, and air control (HVAC) system has a significant role in maintaining indoor microclimate within a range of values that does not change significantly from summer to winter.

Before the invention of HVAC systems, indoor microclimate, i.e., air of spaces within buildings (indoor microclimate and Historic Indoor Microclimate are described in Chap. 3), was modified only with rudimental systems such as braziers or hearths in the early Middle Ages, and with stoves in later times. Only with Industrial Revolution, it became to regulate climate within buildings independently from clothing and rudimental systems.

Before that, buildings had the only role of helping to mitigate the most extreme peaks of external temperatures and humidity, and indoor microclimate was varying very much depending on seasonal changes of outdoor temperatures. This is why in the wide rooms of Versailles, in the cold winters between the end of seventeenth and beginning of eighteenth centuries, the temperatures were easily dropping below 0 °C.

From these considerations, several questions rise as follows:

- Which are the conditions that define a confined space (delimited by a boundary of system) adequate to living? This depends on medicine, physiology, cultural habits, sociality, food, clothing, etc.
- Which were the competencies of builders of old times on what we define microclimatic design of buildings? Such a question involves architectural disciplines, engineering and constructive system ones, economic and material resources, culture of building and external climatic conditions, history of fuels, system of energy management, etc.

The answer to the first question varied significantly in time and, as in the Versailles example, the limit to the acceptable microclimatic ranges reached limits that are nowadays hard to imagine. The concept of comfort, indeed, is quite recent, its first definition being probably not older than the 1970's (Fanger 1972). As for the second question, the ability to design an architecture with the goal of obtaining specific indoor microclimate conditions, to inhabit or to conserve, has been developed early in the history of mankind. It often happened that the aspects linked to the use of the building, its energetic functioning, had a higher relevance than the aesthetic ones in defining the architectonic and technical conformation of buildings (using words from Vitruvio, *Utilitas* first).

Despite the higher tolerance for harsher indoor microclimatic conditions of past times, these conditions, at least, had to be kept and without the help of any heating system. The structure of the building, its ceiling and walls, was hence the only instrument to guarantee adequate microclimatic conditions.

In other words, in buildings built before the introduction of heating systems, the comfort of people, i.e., their perception of well-being, depended only on what the building could guarantee, and changes in behaviors or clothing (physiological and cultural adaptation).

These architectures were able to guarantee an indoor microclimate which was completely different from the one present in buildings dating from the second half of the twentieth century. Thanks to the presence of HVAC systems, indoor microclimate variations are almost completely independent from external climatic conditions. As a consequence, indoor temperature in summer and winter can vary of only 1 or 2 degrees, and similarly small are the variations in relative humidity. To reach this result, mainly fossil energy has been used up to the current time.

Starting from the considerations above, two main research subjects can be defined:

- ***Comfort***, as the result of the complex system of relations between people, including culture and habits, and indoor environment
- ***Microclimate (indoor microclimate)***, as the whole of physical variables describing the characteristics of the air within a space, an open system exchanging energy and mass with the external one, which is the architecture.

It is hence possible to affirm that historic architectures have, alongside with the characteristics that make them so impressive, a specific indoor microclimate different from what is typical of modern buildings, modified by HVAC systems. Each of those buildings had an original Historic Indoor Microclimate, which is nowadays lost and about which new interest is rising only lately.

> The term ‘cultural heritage’ has changed content considerably in recent decades, partially owing to the instruments developed by UNESCO. Cultural heritage does not end at monuments and collections of objects. It also includes traditions or living expressions inherited from our ancestors and passed on to our descendants, such as oral traditions, performing arts, social practices, rituals, festive events, knowledge and practices concerning nature and the universe or the knowledge and skills to produce traditional crafts. (http://www.unesco.org/culture/ich/en/what-is-intangible-heritage-00003, last visit 26-12-2015)

We believe that the UNESCO definition for Intangible Cultural Heritage (ICH) must have a place in this book, given its first sentence—“*Cultural heritage does not end at monuments and collections of objects*”—which is a perfect frame for the subject of Historic Indoor Microclimate (HIM). Through studies on Italian and foreign historical buildings and detailed descriptions, it will be demonstrated the relevance of this subject to the comprehension of historical architecture and to many problems concerning the preservation of the material part of the historical building as well as its content.

This book aims at giving a wide description of the research field of HIM: from the methodologies of surveys and modeling to its relevance in restoration and other disciplines, as well as some exempla of implementation. In order to do so, some specific terms must be introduced. The study of Historic Indoor Microclimate includes the study of different indoor microclimates in the history of a building that can be divided into the following:

- OIM—Original Indoor Microclimate: which is the historic microclimate in the building when it was just built. It can be simulated and evacuated starting from historical data on climate and on the building, including the building phases of the architecture.
- SIM—Subsequent Indoor Microclimate: historic microclimate in the building, following changes in the architectonic structure (such as added volumes), in its technologies (modification of parts), or in its usage (monastery, barracks, museum). It can be simulated, as the original one, with the support of data on climate and on the history of the building, with particular attention to heating or other systems.
- AIM—Actual Indoor Microclimate: the current microclimate in the building as it is today. It can be measured in situ with a monitoring campaign and the data can be used to calibrate a digital model.

Historic Indoor Microclimate (HIM) studies include Original Indoor Microclimate, as the study of historical architectures before HVAC systems, which has been incorporated in almost the totality of the buildings survived to modern times. This indoor microclimate is characteristic for each architecture and it was very variable in summer and winter. It depended on the techniques used, on the management of the windows, on the exposure to the sun, and on some specific expedients, such as the presence of nonused areas with microclimatic purposes specifically.

Chapter 3 gives details of the single definitions and relative modalities of study, monitoring and modeling. As any other subject of study, indoor microclimate is described by some specific physical characteristics, which define the different HIM: these are described in Chap. 2 (air temperature, relative humidity, etc.) as well as the instruments to show the results. In Chap. 4 are explained how to realize a monitoring campaign and the criteria of building simulation for the study of HIM, with respect to the interventions described in Chap. 7. Chapters 5 and 6 focus on the application of archival research and in situ survey, as well as the elaboration of characteristic indexes.

The approach used to study this aspect of historic architecture includes the new methodologies developed for the study of microclimate in architectures, alongside to the traditional methods of research on historic buildings:

- On the one hand, the collection of current microclimatic data with system of probes remotely managed
- On the other hand, the elaboration of these data with digital software able to simulate microclimates based on different configurations than the current one, in consideration of geometry and construction of historical architectures

Starting from this kind of researches, the relevance of microclimate and its correlation with comfort and with the building itself has been cleared.

1.1.1 Which Are the Reasons Behind This Interest for Historic Indoor Microclimate?

Historic reasons focus on the relevance of OIM as an information on historical building. Alongside the construction date, the name of the author, or the reasons behind the construction, it helps to understand the function and role of each architecture.

There are then other reasons, linked to the need to valorize historic heritage, of understanding it better, to make it available for the public, to preserve it. To reach this goal, any added information can give valuable support.

Any knowledge on the past history of a building, in particular on the changes in its structure and material component, cannot ignore the HIM of that building. Without this information, indeed, the understanding of phenomena of decay is inadequate or incomplete.

To people working to valorize historic heritage, the physical act of restoring is one of the instruments of action, but this should be considered only an extreme one, to use only if the decay is so advanced that any other option is impossible. On the contrary, the attention for the phenomena happening in a building should be increased, in order to plan preventive actions and avoid invasive restorations.

Brandi (1977) and Urbani (2000) were the first to describe preventive restoration. Brandi, in particular (Brandi 1977, pp. 53–61), includes in this definition any activity that, acting on the context, would reduce the extent of the damage on artworks. Stepping from these considerations, keeping the same attention for the material aspect of the pieces, Giovanni Urbani defines planned conservation as the systematic control of the context in which the monument is placed,

> in order to slow as much as possible the process of decay, intervening at the contemporarily, if necessary, with appropriate maintenance treatments on each material ("per rallentare quanto più possibile la velocità dei processi di deterioramento, intervenendo in pari tempo e se necessario con trattamenti manutentivi appropriati ai vari tipi di materiali", Urbani 2000, p. 104).

Planned conservation has the goal of preventing emergencies, acting in advance through the study of the interactions of the monument with environmental and microenvironmental factors. Both if the level of decay made an intervention necessary or if a preventive restoration is ongoing, adequate attention should be paid to HIM and to its "restoration," as part of the whole conservation strategy. To speak of HIM restoration is a mere provocation, if not intended in the meaning given by Brandi, but a significant attention to this aspect should allow to avoid invasive interventions changing the original microclimatic conditions, which would increase the speed and extent of decay phenomena.

1.2 Energy and Architecture

In the last two centuries, two main novelties involved historical buildings, thanks to the contribution of technical innovations brought by industrial revolution.

On the one hand, along the nineteenth century, restoration acquires its modern role as the field of study dedicated to the permanence of architectures as document and memory (Torsello 1984). This is when the design of interventions on old architectures became a different thing compared to the design of new architectures, object of the architectonic avant-gardes first and of the Modern Movement in the twentieth century.

On the other hand, new technologies and material appear in architecture, first only in new buildings, and then in existing and historical ones. In particular, technical systems that allow to control indoor microclimatic conditions are introduced, with heating, cooling, and ventilation systems.

Two more considerations are required in relation to this second point:

1. The introduction of new systems caused immediate damages in the existing structures, linked to the pipes, vents, root canal systems, etc.; further effects followed in the long term, due to the radical changes with the introduction of modern systems in the unique dynamics of the characteristic indoor microclimate of a building.

2. Architectonic culture rarely cared for technical systems, independently of their value as historic heritage, and considered them an “extemporary accident” with only practical uses. To most designers, old technical systems must absolutely be substituted with modern ones, independently from their historical value.

Since the night of time, with the discovery of fire, the management of energy to cook, heat, and illuminate has been one of the most relevant activities for humans, alongside those aiming at the production of food and protection. To improve indoor microclimatic conditions and guarantee minimal comfort conditions many instruments have been developed; braziers, heaters, stoves, and heating systems followed each other in many centuries.

If the first inventions were quite distant in time, in more modern times the evolution of these systems has become incredibly fast, until, nowadays, indoor conditions can be controlled independently from outdoor ones. This changed the relations between men and the spaces they live: in past times each individual was adapting to the environment, which conditions are now considered non tolerable; on the contrary, nowadays, indoor microclimate is changed to adequate to ideal comfort, based on the maintenance of stable conditions of relative humidity and temperature, utterly rare in nature.

The introduction of HVAC systems in buildings represents a change of paradigm which is rarely the object of debate (on the meaning of the term, see paradigm Kuhn 1970; Ginzburg 1979). This involved a plurality of phenomena that are the object of many different disciplines: from the studies on history of climate to those on architecture, building technologies, heating protosystems, and electrical ones and to completely unrelated fields, such as the history of food and clothing, culture, and taste.

All of these factors have a relation with the changes of indoor microclimate of architectures, in different historical times, such that we are led to believe that Historic Indoor Microclimate can constitute a specific field of research.

With respect to the present text, the main contributions to the studies on the relation between man, climate, and architecture are the researches of Huntington (1915) and Huntington and Cushing (1920), who were the first to relate climate and the evolution of civilization, and then Cavalli-Sforza and Cavalli-Sforza (1995) and Cavalli-Sforza and Pievani (2016). On a different perspective are the researches of Markham (1944), which relate climate and use of energetic resources in nations, a problem that became evident in the 1970s, with the publishing of “The Limits of Growth” (Meadows et al. 1972) and with the energetic crisis of 1973 in relation to climate, resources, and architecture.

The control of energetic resources of equipment of buildings was known to the technicians and building service designer, and in 1951, on one of the first technical manuals for architects and engineers, Environmental Technologies in Architecture, Kinzrey and Sharp (1951) state:

> Architecture has evolved from a concept of simple shelter is not a complex environmental control system. Science and engineering have developed equipment and techniques which make possible light, heat, sanitation, and noise management, close to the norm required for

> the balanced functioning of the human being. Far-sighted provision for the control and distribution of electrical power is essential, not only for the immediate operation of necessities but for the inevitable expansion in future techniques and concept. The building itself, while only one part of the environmental control, must provide accommodation for the multitudinous mechanical and electrical facilities required. (Kinzrey and Sharp 1951, Preface).

On the other side of architectonic design, Victor Olgyay was the first to publish a study with a strong scientific background on the relation between architecture, comfort, energetic resources, and climate. In his Design with Climate (Olgyay 1963), a milestone of scientific architectonic literature, Olgyay highlights since the premises the role of climate in architectonic shapes:

> The problem of controlling his environment and creating conditions favourable to his aims and activities is as old as man himself. Through the ages men have sought, in the building of shelter, to fulfil two basic human needs – protection from the elements and provision of an atmosphere favourable to spiritual endeavour. House design has reflected, throughout its history, the different solutions advanced by each period to the continuing problem of securing a small a controlled environment within a large scale natural setting – too often biased by adverse forces of cold, heat, wind, water, and sun. (Olgyay 1963, p. V)

Many other studies follow, such as those of Givoni, who, in 1969, publishes “Man, Climate and Architecture” (Givoni 1969), giving in it a description of the effect of microclimate and architecture on the comfort perceived by the inhabitant of a building. Indoor thermal comfort acquires autonomy as a field of study in the 1970s, in Thermal Comfort by Fanger (1972). From the first chapters, the importance of the study of indoor microclimate and comfort and of the effect of industrial revolution on “*Artificial Climate*”:

> The present study will deal with the conditions necessary for optimal thermal environments for human beings, the methods of evaluating a given thermal environment, and the principles for the establishment of a detailed thermal analysis of any environment. The growing mechanization and industrialization of society has resulted in most people spending by far the greater part of their lives (often more than 95%) in an **artificial climate**. This fact has caused an increased interest in the environmental conditions which should be set, i.e. which climates should be aimed at. With the techniques at our disposal today we have the possibility of creating almost any indoor climate. (Fanger 1972, p. 13)

Again in the Anglo-Saxon area, a historian of architecture such as Banham Reyner understands that the theme of climate and comfort cannot be ignored in the studies of history of architecture (Banham 1960, 1969).

Architecture and energy are the object of many other publications in the 1970s, such as Knowles RL, Energy and Form (Knowles 1974); Steadman P, Energy, Environment and Building (Steadman 1975); Stein RG, Architecture and Energy (Stein 1977); and Skurka and Naar Design for a Limited Planet (Skurka and Naar 1976).

Among the books published in this time, Heschong L, Thermal Delight in Architecture (Heschong 1979), wrote one which includes an interesting perspective on the role of architecture to guarantee a comfortable environment:

> This work began with the hypothesis that the thermal function of a building could be used as an effective element of design. Thermal qualities – warm, cool, humid, airy, radiant, cozy – are an important there but also how we feel about the space. (Heschong 1979, p. vii)

To understand what microclimate of an architecture means, the definition of thermodynamic "*System*" represents an excellent starting point: "*a system is a portion of space, delimited by a real or apparent surface, open or closed, hard or deformable in its whole or just in parts, which constitutes the border of the system itself. Anything outside the border constitutes the boundary of the system.*"

The building itself is a portion of space, has a non-deformable border (constituted by walls, windows, ceilings, etc.), through which flows an exchange of mass (air volumes, people, objects, etc.) and energy. As a confirmation that this interpretative model works for buildings, the protocol to calculate the building energy performance is nothing else but the application of the first principle of thermodynamic which includes the boundary condition, i.e., external climatic conditions, as variables in continuity.

There hence is an "outside" and an "inside" of the system, where the "inside" is the indoor air volume for which it is necessary to guarantee conditions of temperature, relative humidity, etc. adequate to permit human activities. These conditions depend on the energetic exchanges between human body and indoor environment, which determine the perception of indoor comfort. The outdoor of the system is represented by anything which ac on it, i.e., the outdoor climatic conditions, temperature, and solar radiation.

To guarantee acceptable indoor microclimate conditions it is necessary to generate energy within the system with any kind of heating systems, such as fire, braziers, hearths, stoves, and HVAC systems. The quantity of energy needed depends on the external conditions and on the shape and energetic characteristics of the boundary. For a long time, due to the efficiency of heat generators, the shape and building technologies of an architecture have been the main system to regulate energy exchange between indoor and outdoor of the building. In this model, it is evident that when both the boundary and the indoor energy generation system were inadequate to maintain minimal comfort conditions (again, even if different from those we nowadays consider at least acceptable), other strategies were needed to reduce energetic exchanges between human bodies and indoor microclimate. Among these we list some, such as clothing, metabolic activity, food, and the ability to stand an excessive feeling of heat and cold.

Solutions and adaptation of people, choices of clothes, shape of the building and building techniques, as well as energetic resources used in the different climates, all of the above demonstrate *the process of modification of the planet that mankind brought on to guarantee its own survival.*

History of architecture can be read from a thermodynamic point of view, where the architectonic shape corresponds to a specific climatic context, as it has been highlighted in different researches and studies on the orientation of buildings, from Vitruvius, Leon Battista Alberti, and the Milizia to the eliothermic axis in the Modern Movement, and in more scientific terms in the researches on architectonical regionalism of Olgyay.

From the literature presented above, it looks like that climate is the only determinant of shape of architectures, so that in similar climatic context the architectures should be similar, in a mechanistic approach to the phenomena of the existence. But, in truth, only some traditional shapes and technologies remain constant, and in general the evolution of architectonic shapes in time results from many cultural and material factors, as well as social, political, and infrastructural ones, that cannot be summarized in a list of equations. The architectonic system is very complex and is linked to the same elements that globally determined the different levels of social, cultural, and technological development, analyzed by Jared Diamond in his book from 1997 (Diamond 1997).

Following these considerations, it is now important to consider what happened in the nineteenth century, which is the turning point in both the fields of study underlying this book: restoration and thermodynamics. Industrial Revolution led to an acceleration in the evolution of the techniques to manage energy and energetic resources, as well as in the transformation of land. With equal incoming energy, steam machines produce more work than a single man, and they do not have connections with social or ethic phenomena. Power and speed of this transformation imply consequences in architecture: buildings are demolished, transformed, and rebuilt at a faster pace; railways constrict landscapes; and a modernist frenzy appears, where New is better than Old and Future more important than Past. Following these appeared the need to study and preserve architectures from the past, which was summarized in restoration researches. This has a tight link with history and memory; past buildings become witnesses of a world changing fast, completely detached from what preceded it. And after buildings have been used, in the past, as quarries to collect building materials and destroyed at an incredible speed, the field of restoration comes to life.

On the side of the researches on microclimate, the problems on the use of energy and efficiency have been studied by many scientists and technicians (Watt, Joule, Carnot, e poi Kelvin e Celsius) who try to comprehend what is energy, how it transforms, how it is conserved, and how it degrades. In 1851, then, thermodynamic appears in the field of physics with a paper from Kelvin (1851). This is the discipline that studies energy and energy efficiency.

The introduction of technical systems in buildings increased devices' efficiency, in particular in the heating of rooms. It becomes then possible to use a sufficient amount of energy to buffer the climatic contest in indoor spaces. Architecture has an efficient instrument to guarantee incredible comfort levels to its users, a much better one than the boundary, the architectural construction.

This is when architecture, both as construction industry and as culture, history and landscape, starts to detach from its context and from its traditions. With increases in the devices to influence microclimate, the context becomes irrelevant in the determination of the comfort of a building. This is why theories of architecture of the beginning of the twentieth century do not speak of climate as a factor to keep into account to plan new buildings.

This process depends on a new application of the techniques and leads to a cultural redefinition of comfort. Since there is no need any more to stand cold temperatures, heating systems must be added to all the buildings to guarantee adequate microclimatic conditions. This material modernization produces an immaterial change linked to comfort.

This process was based on the energy factor being independent and infinite, and it was interrupted in the 1970s when the energetic crisis due to Yom Kippur War of 1973 showed the limits of energetic resources. This consequentially led to the need to redefine building techniques.

What appears evident is that indoor microclimate is not the mere combination of temperature and humidity in a room, but it is a witness of how history of architecture changed, slowly before the nineteenth century and fast from twentieth century, from building techniques to systems and comfort, intended as the mixture of different cultural elements.

Here, and in relation to restoration goals, stems the need of a study of this immaterial information history and evolution of mankind.

1.3 Indoor Microclimate, from Fire to Heating Systems: The Long-Time Assessment

The definition of "*artificial climate*" introduced by Fanger (see previous paragraph and Fanger 1972) allows to introduce the history indoor microclimate, intended as the history of how the microclimate of human-inhabited environments has been controlled and modified through technical and cultural solutions. These solutions can involve the adaptation of the single individual through food intake or clothing, or an adaptation of the surroundings that the individual inhabits, i.e., the confined environment represented by an architecture.

It is worth to remember that *comfort* and *indoor microclimate* are not the same thing, the first referring to the feelings of a specific individual, while the latter represented by the physical conditions of the indoor space, which can or cannot guarantee comfort. Technical solutions to control microclimate are the shape of a building, building techniques, and systems to manage energy.

History of indoor microclimate has its origin when first hominids looked for natural shelters, and continued with the discovery of fire, which has been the first mean to heat an indoor space, such as a cave.

These first shelters changed forms, and became more efficient: sheds, palafittes, wood, and brick buildings. The changes aim, among other things, at reducing the energetic exchanges between intern and extern in winter, and at controlling the solar radiation in summer. This process lasted for millennia, leading to a great number of architectonic shapes and technical solutions, in relation to the local climate, developmental stage of civilities, and presence of building materials. Lewis Mumford, in his "The City in History" (Mumford 1961), describes this development in different historical times.

With respect to the heating systems in buildings, up to the Middle Ages the only mean was the management of fire and of its product, with braziers for example. During Middle Ages, then, hearths were introduced and, from the fourteenth and fifteenth centuries, metal and brick stoves. These constitute the technological step forward in the control of indoor microclimate, the first that does not depend on the quality of the building itself. Even if today they are not considered very efficient; they represent a significant improvement because they allow to modify extensively indoor microclimate.

This remained constant until the nineteenth century, when thanks to Industrial Revolution (see *Revolution* in Kuhn 1970, p. 92 and following) and to the invention of steam machines the boiler found an application in architecture and appeared in the first heating systems. The concept of indoor microclimate changes completely; energy produced centrally with the combustion of fossil resources or wood can be distributed with a vector fluid, such as water, in the different areas of a building. This is in itself a revolution in the modes to control indoor microclimate in architecture.

Microclimate becomes then completely artificial and people inhabiting a building can regulate the quantity of energy needed to guarantee comfort conditions. These people are not passively standing indoor microclimatic conditions, with only primitive mechanisms to help (light a fire or vary the quantity of combustible), but have refined devices to artificially modify the environment. The consequences are big: clothing inside buildings change, but change the building itself, since its role in the determination of microclimate is reduced. Consequently there is a change in the capability to stand situations of discomfort, the tolerance towards adverse microclimatic conditions. The user of a building becomes less prone to adapt to a less than ideal comfort acting on food or clothing, as well as more prone to take care of personal hygiene thanks to hot current water in buildings.

Twentieth century brings another acceleration in the ability to control “artificial climate,” thanks to the devices to cool and condition air and to the development of systems to control and thermoregulate. It is nowadays possible to determine a preferred indoor microclimate with thermostats, which depends on objective measuring of values that are considered the best for thermal comfort. It is interesting to observe differences in the mean indoor temperatures preferred in different geographic areas: summer indoor temperature tolerated in the United States is usually of 18–20 °C, which is perceived as discomfort by European people, who are used to 25–26 °C in summer and who can be led by these temperatures to wear a sweater.

Indoor microclimate is not an accidental phenomenon, but the consequence of choices connected to cultural and technical determinants, gradually modified along history. This change in perspective and in the perceived comfort had an effect on new constructions, but as well as on existent ones and on heritage buildings. In all of them a minimum level of thermal comfort is required, and this led the majority of historic buildings to lose the original indoor microclimate OIM, sometimes with irreversible effects, since the damages due to altered microclimates can hardly be recovered.

1.4 Heritage Building and Microclimate

The disciplines orbiting around heritage buildings share the common goal of preserving as much as possible the built heritage. To get to this goal they study the decay phenomena and their causes, trying to individuate the best strategies and solutions useful to slow down these phenomena or to prevent them. Some specific decay risk factors, internal and external to the building, are related to phenomena connected to the site geology, its interaction with the building itself, or the action of water or the loss of structural efficiency of the materials, or seismic movements. Virtually all of the remaining decay factors are due to microclimatic conditions and usage of indoor environment.

The problems related to the conservation of historic buildings and heritage are many and involve many fields of research. They are linked to the multitude of phenomena described above and spread from the more specifically structural aspect of a building to the management of visitors and to the studies on decay of heritage to its valorization in cultural and touristic terms.

A list of the physical-chemical causes of decay phenomena would hardly be complete. They are due to mechanical, chemical, biological, or physical causes, often mixed in their action, concurring to determine the decay of objects and buildings (Rocchi 1990). The most effective approach is to analyze analytically the different components, individuate the single elements affecting the artifact, and understand the different interactions.

Among the physical causes, energy exchange, in particular as heat, i.e., temperature, and water vapor content variations, i.e., relative humidity, are the most relevant to the phenomena of decay. These exchanges determine different dynamics of alteration of materials and the speed of this alteration.

The level of relative humidity, in relation to the variation of temperatures, determines the dew point, at which water condenses on plaster, which in turn is linked to specific chemical or biological phenomena, as the formation of salts, or the solubilization of pollutant and the growth of molds (biodeteriogens). The same phenomenon can cause even more serious problems in organic materials, as wood, up to reducing the mechanical and structural performances. Temperature and water vapor content of air are hence highly relevant in determining the indoor microclimate of architectures, and depend on the presence of people, HVAC systems, etc. which are studied by the disciplines linked to indoor microclimate.

These phenomena are obviously influenced by macroclimatic variations at global, regional, and local level. Global warming, increase of greenhouse gases, etc. represent a risk factor in the preservation of historical buildings, as reported in many studies, such as Fabbri et al. (2012), Lankester and Brimblecombe (2012a, b), and Sandrolini et al. (2011).

The evaluation of microclimatic conditions in highly valuable historical buildings must have the main goal of individuating the best conditions to conserve the artifacts, and only in second place of improving the comfort of visitors and users.

In this kind of buildings, indeed, the approach must place as most important the object than the people, at least as referred to the comfort conditions (it is obviously different from the case of seismic risk, in which the preference must be place on ensuring safety). This is why the range of conditions imposed in the building must be calibrated to preserve the artifacts. In the control of indoor microclimate, priority must be given to the comfort of objects and not of people, which should guarantee the best conservation conditions.

In real cases, on the contrary, the approach varies widely, depending on the characteristics and functions of the buildings, often giving higher importance to improving the experience of visiting the building, without much attention to collateral effects on buildings.

HVAC systems (heating, ventilation, and air condition) can modify indoor microclimatic conditions up to the level that they produce microclimatic stress on the building and in the objects it contain, a stress that was absent in OIM conditions. On the role of plants on historical buildings ad on the need to intervene on them, see Fabbri (2013) and Pretelli et al. (2013).

Historical buildings can be used in many different ways, from musealization, which might aim mainly at conserving, as in outdoor archaeological sites, where it will be enough to assure that the visits do not interfere with preservation, to reuses of the buildings for specific activities, as libraries and to old residencies and sacred buildings. The characteristics and variability of indoor microclimate constitute a specific study subject in each of these cases, since the variation of temperature and humidity has an effect on the conservation of the architectonical building and the materials that constitute it.

In this context, the scientific literatures are constituted of many different contributions, from the conservation of specific artifacts—*frescoes, paintings,* and *manuscripts*—to the vast list of studies on the conservation of buildings.

The main researches about microclimate are reported in Camuffo (1998) and other museum studies by Camuffo et al. (1999, 2010) and Ballocco and Boddi (2010). In the same way the "*historic climate*"—related to object—is defined in Italian Standards UNI and EN 15757 described in Del Curto (2010). The standard EN 15757 defines historic climate as:

> 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 one year) and to which it has become acclimatized (EN 15757)

Historic climate is intended as the range of physical parameters to which the conserved object is used, while Historic Indoor Microclimate, the subject of this book, is referred to the whole building.

With the goal of guaranteeing the fruition of a building, solutions can be adopted to monitor and control microclimate, using the heating or other systems present and restricting the access of visitors. One of the most well-known cases is that of the technological complex to control microclimate in the Scrovegni Chapel, in Padua, described in Basile (2003).

Other articles report other significant case studies: Krupińska et al. (2013) report on a 3-year study in chemical pollutant in museums; Baggio et al. (2003) report on the Last Supper di Leonardo da Vinci; the case in Padua is also described in Camuffo and Bernardi (1991).

The effects of outdoor climate on indoor one are object of studies from Lankester and Brimblecombe (2012a, b), in Huijbregts et al. (2012) and van Schijndel et al. (2015). As for the energetic risks related to climate change in museums, see D'Agostino et al. (2015), where a protocol to evaluate climatic conditions in museums is proposed. Lucchi (2016) defines multidisciplinary criteria to evaluate conservation, efficiency, and comfort.

Microclimate of heritage buildings used as museums and archives is studied in Corgnati et al. (2009), where useful instruments to elaborate data and normative references are applied; vernacular architecture is studied in Cardinale et al. (2010, 2013) and Cardinale et al. (2014); La Gennusa et al. (2008) describe microclimatic minimum requirements of museums for different objects in the collections; in the study of Camuffo et al. (1999), concerning the Correr museum in Venice, micromapping and other analysis instrument are suggested, while Camuffo et al. (2013) describe a methodology to reconstruct the historic climate and predict the future climate of the cabinet.

Other researches focus on indoor environmental quality relative to energetic demand for heating and cooling, as in Ferdyn-Grygierek (2014), Ferdyn-Grygierek and Andrzej Baranowski (2015), and Ferdyn-Grygierek (2016), which relates the results of instrumental monitoring with energetic consumes, as well as in Ascione et al. (2009).

The relation between heritage buildings and energy efficiency is another well-developed study field, despite being marginal to the subject of this book. The debate is lively on the effective need to adequate or improve energy efficiency of buildings following the criteria of efficiency or preservation of heritage, as described in Fabbri (2013).

Among the most important researches recently published are the project 3ENCULT Efficient Energy for EU Cultural Heritage 2010–2014 (3ENCULT) and the project EFFESUS Energy Efficiency for EU Historic Districts Sustainability (EFFESUS). Vieites et al. (2015) report the list of European initiatives concerning energy efficiency and historic building.

Energy Efficiency Solution for Historic Building (Troi and Bastian 2014) describes a list of technical solutions to improve energy performances of historical buildings. The theme is described by de Santoli (2015) with the suggestion of several guidelines, while Mazzarella (2015) summarize the legislative point of view.

The study from Martínez-Molina et al. (2016) is a good review of the main researches on the subject.

1.5 Thermal Comfort and History of Clothes and Food

Historic microclimate is a subject concerning several disciplines, among which there is the history of climate and of climatic change. This, in turn, influences society and the perception of comfort, history of food, and clothing. History of climate is itself a research field studying long time spans and whole geologic eras from before human history.

> The climate of Earth has its own history. To reconstruct it, to look for causes and to perspect fiture developments is the goal of the scientific discipline of climatology, the science of climates (. . .). Climatology is a young discipline, since the idea that climatic conditions have been different in the past is somehow new: in absence of archives, himan memory can go back of a couple of generations, a short time to infer the presence of regular variations on a long time span. (. . .) Climatology is a fundamental discipline, linked to the development or even survival of mankind, since history of living beings depend on climate: climatic variations had a relevant role in the evolution and diversification of life, which, in turn, contributed to modify atmosphere and climate. (Acot 2003, pp. XI–XII)

From the macro scale to the micro one, observing how climate influenced life during the short span of human presence on Earth could give interesting insights into the history of architecture and more in general of creation of livable confined spaces (from caves to religious places, etc.).

Acot (2003) goes through the history of climate, from the origins of our planet to modern times, focusing on climatic changes that influenced the history of mankind, such as during Viking colonization of Greenland, Napoleonic conquer of Russia, and the role of General Winter or, finally, in Operation Barbarossa during World War II. Acot approaches history with the eyes of the climatologist and looks at how changes in climate influenced human events (such as how the famines that hit Europe during the eighteenth century influenced French Revolution) without exceeding into any form of climatic determinism:

> In truth, the epistemologic background of climatic determinists lays in their refusal to consider the human specific capacity to influence their environment and to use changing resources. (Acot 2003, p. 113)

Climate is not the only factor that can explain historic or architectonical events, as much as Historic Indoor Microclimate is not the only reason behind the structure of buildings, but the role of these factors should be considered and sometimes is very relevant.

The study of the story of climate can count on several sources: archives, descriptions, diaries, dates of agricultural events such as grape harvest, up to chemical and physical data collected from ice cores. Briefly, it requires two different approaches, from pure and human sciences both. We can divide as follows:

- *Earth archives*, constituted by glaciers and sediments, from which cores are extracted and studied with several methods, such as oxygen isotopes, radiocarbon, thermoluminescence, and dendroclimatology
- *Society archives*, such as public and private collections, libraries, paintings, tales, systematic collection of data of harvests and rainfall

These are as Behringer (2010) reports in "*Kulturgeschichte des Klimas*" adding instrumental collection of data after the invention of the thermometer in the seventeenth century. The cultural approach of Behringer to climate is interesting as it evidences that, even in the short temporal scale of human history, climate changes still had a relevant influence on the phenomena connected to the different human civilizations. For example during the Little Ice Age (from about 1550 to 1800):

> There were also architectural implications, as large buildings had many more rooms in need of heating than in the Middle Ages. The greater space in castles was a sign of growing wealth, but it also meant that a single set of heated apartments was no longer enough. Heating become necessary to survival, and this made the man in charge of it more important in castle life. In Hradschin, the Prague castle (now the Czech Hradčany), only the director of heating had the keys to all rooms; he was the first to enter then each morning to make them habitable.
>
> Changes in the cityscape as the ‘Gothic’ houses gave way to ‘Baroque’ at the end of the sixteenth century may also have been related to the climate. Admittedly these were long term trends, but stone did increasingly replace timber in house construction around the turn of the century. This permitted a more rational use of fuel and contained the danger of fire despite the longer heating periods. (Behringer 2010, A Cultural History of Climate, p. 135)

And, during the same time, as far as clothes are concerned:

> At more or less the same time, undergarments in both the narrow and broader sense began their triumphal march: those worn directly on the body, beneath layers of shirts and doublets, such as Weisberg had made for himself in September 1585 and had to wear again in 1586 until late May because of the great cold; but also articles of underclothing (bodices, dress frames, wire supports) that gave the visible clothing its desired shape. (Behringer 2010, A Cultural History of Climate, p. 135)

The architectonic consequences of the need for fireplaces, to store logs to burn and allow the exit of smokes, are clear, if studying the Historic Indoor Microclimate of related buildings. To guarantee a minimum level of comforts in castles and buildings an extra layer of clothes was not enough anymore, given the changed external conditions, and it was necessary to introduce another source of heat, i.e., fireplaces.

The collection of data with specific instruments to understand historic external climate is a precise source of information and can be used as input data in the simulations of virtual environment to reconstruct the historic microclimate in different time periods. The scientific literature on climatic data from periods before the twentieth century constitutes an additional source of information, when speaking of historic microclimate.

The thermal comfort depends on physical variations of indoor microclimate, such as air temperature, relative humidity, air speed, and mean radiant temperature, which are always dependent on external climate, characteristics of the building, and physiological characteristics of individuals. The human physiological variables to be considered are age, sex, etc., but as well as metabolic activity, measured as the power exchanged between the body and the environment, expressed in Watt and defined as *met*. Moreover the thermal resistance of clothes must be considered, a variable described as *clo*.

Metabolic activity depends on health, usual physical activity carried on, and food habits and varied during historic times in relation to climate, influencing food abundance and agricultural and alimentary traditions and habits.

History of food is a useful basis to understand the total amount of caloric intake that was usual in different historic times. The amount of energy needed to counteract unfavorable indoor and outdoor climatic conditions can be considered to grow linearly: the coldest is the environment, the higher amount of food is necessary to resist to it. The relation between indoor microclimate, as thermal comfort, and caloric requirements is not enough studied and HIM can give interesting insights into this subject.

Obtaining a comfortable indoor microclimate has been a difficult goal to achieve for a long time in the past, with a consequent resignation to inadequate condition for most of the population, which had effects on length and quality of life.

In Europe, since the Renascence, the diet of the population underwent consistent changes thanks to new food sources from the New World, so that the needs and possibilities for indoor spaces changed as well: changes in the caloric intake are expected to have influences on HIM.

From 1750 onwards, i.e., with Industrial Revolution, agricultural and breeding techniques favored an exponential increase in the amount of available food: it is possible to feed a higher proportion of the population, reducing the effects of famines. The possibility to have a constant caloric intake during winter contributed to reduce the tolerance to coldest standard comforts that were once considered acceptable.

Between 1800 and 1900 the European population doubled, the average live quality increased, and food became more varied, thanks to the industrialization of agricultural processes and to the diffusion of techniques to conserve food. All of this adds to the increase of global commerce and the possibility of transportation, plus the introduction of modern processes to treat food, canning, dehydrating, and conservation with chemical substances.

The *history of clothing* is the other useful instrument to study past levels of comfort. Clothes give a layer of resistance to the transfer of heat from the human body to the surrounding environment. Increasing the capacity of insulation of clothes represents a strategy to increase resistance to cold temperatures. Hence, the perception of comfort depends on the available clothes, on the basis of the evolution of the techniques.

During Middle Ages the available materials were wool, linen, silk, and cotton, while all the procedures to produce clothing were manual: carding, weaving, and sewing, all of which required long times.

During Renascence begins a slow devolution concerning fabrics, with effects on social relations and fashion, as fabrics undergo longer processes of treatment, including bleaching, all of them manual.

Starting from the mid-eighteenth century, the production of fabrics is one of the fields in which the effects of Industrial Revolution are stronger. It concerns the automatization of the processes to produce the fabrics and the application to them of the power of the steam machines.

During the eighteenth and nineteenth centuries, all of the phases to produce clothes become automatized, with spinning, carding, weaving, and sewing machines. Automatization arrives inside the houses, and the whole industry is now able to dress people with several layers of clothes: socks, underwear, shirts, jackets, etc.

The aspects just remembered are just some of those in relation with Historic Indoor Microclimate, determining at different levels the goals of indoor microclimate determination, which are more or less those we know today. Some are the adoption of furniture elements that can modify small portions of indoor microclimate. These can be alcoves and canopy beds, the use of heavy fabrics insulating parts of the buildings, or other systems such as the stoves used in the alpine areas in Europe to warm small portions of the house. Some others are the availability of energetic resources, such as peat or remaining of agricultural processes, and the economic possibility to buy them. Moreover, the factors regulating the relations between civilizations, geography, and climate should be considered, described by Huntington (1915) and Huntington and Cushing (1920) since the beginning of the twentieth century.

In our opinion, the attention of people dealing with architecture has been until now too little in respect of this extended universe. The study of HIM would represent an opening to this universe, as we believe that these kinds of studies will be able to bring forward the knowledge on these as well as other fields, besides the fundamental use to improve our ability to preserve historic architecture.

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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.

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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

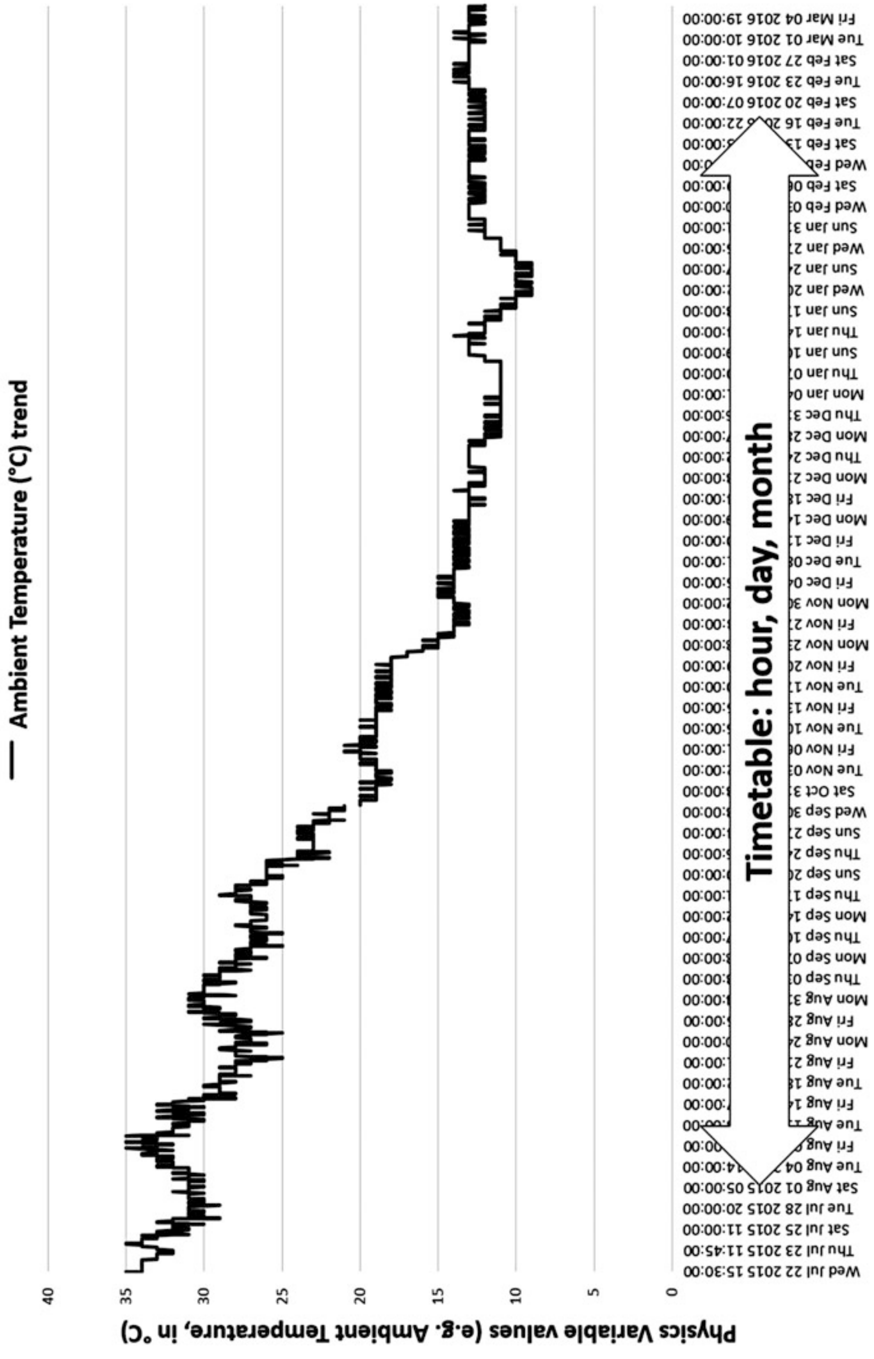

Fig. 2.1 Example of air temperature trend

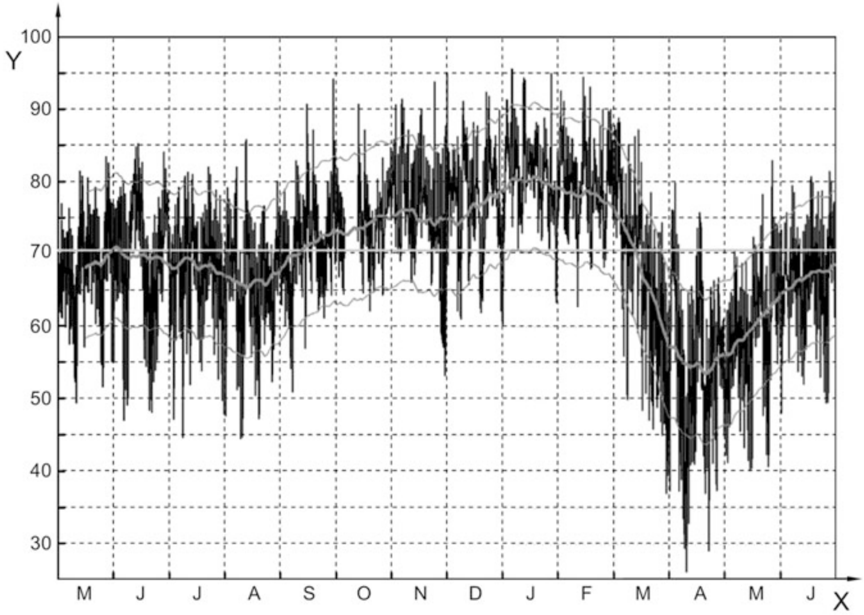

Fig. 2.2 Example of relative humidity trend. Target RH values for this sample set of RH readings (EN 15757 pg.17)

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:

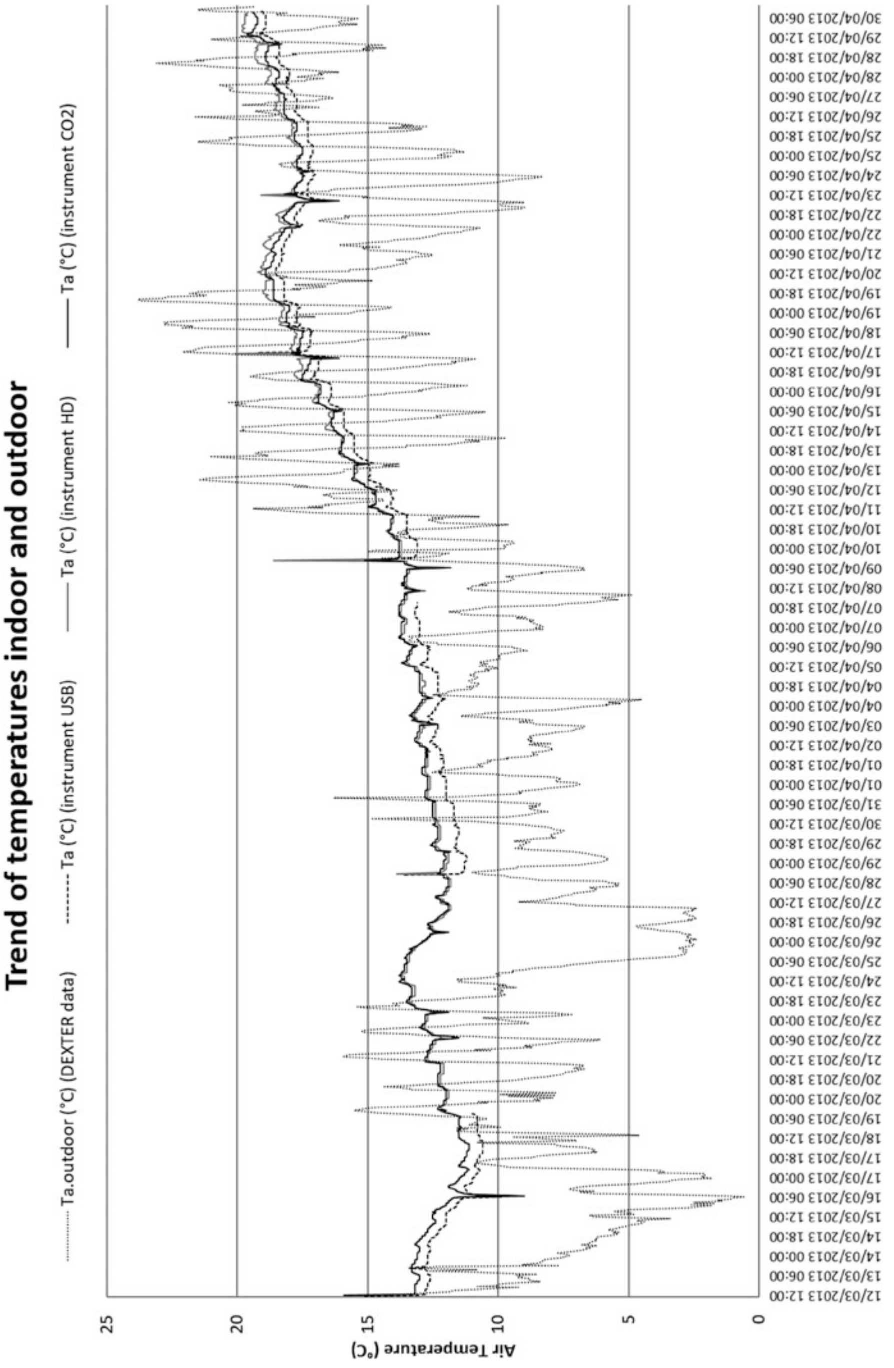

Fig. 2.3 Example of relative humidity trend with multiple probes

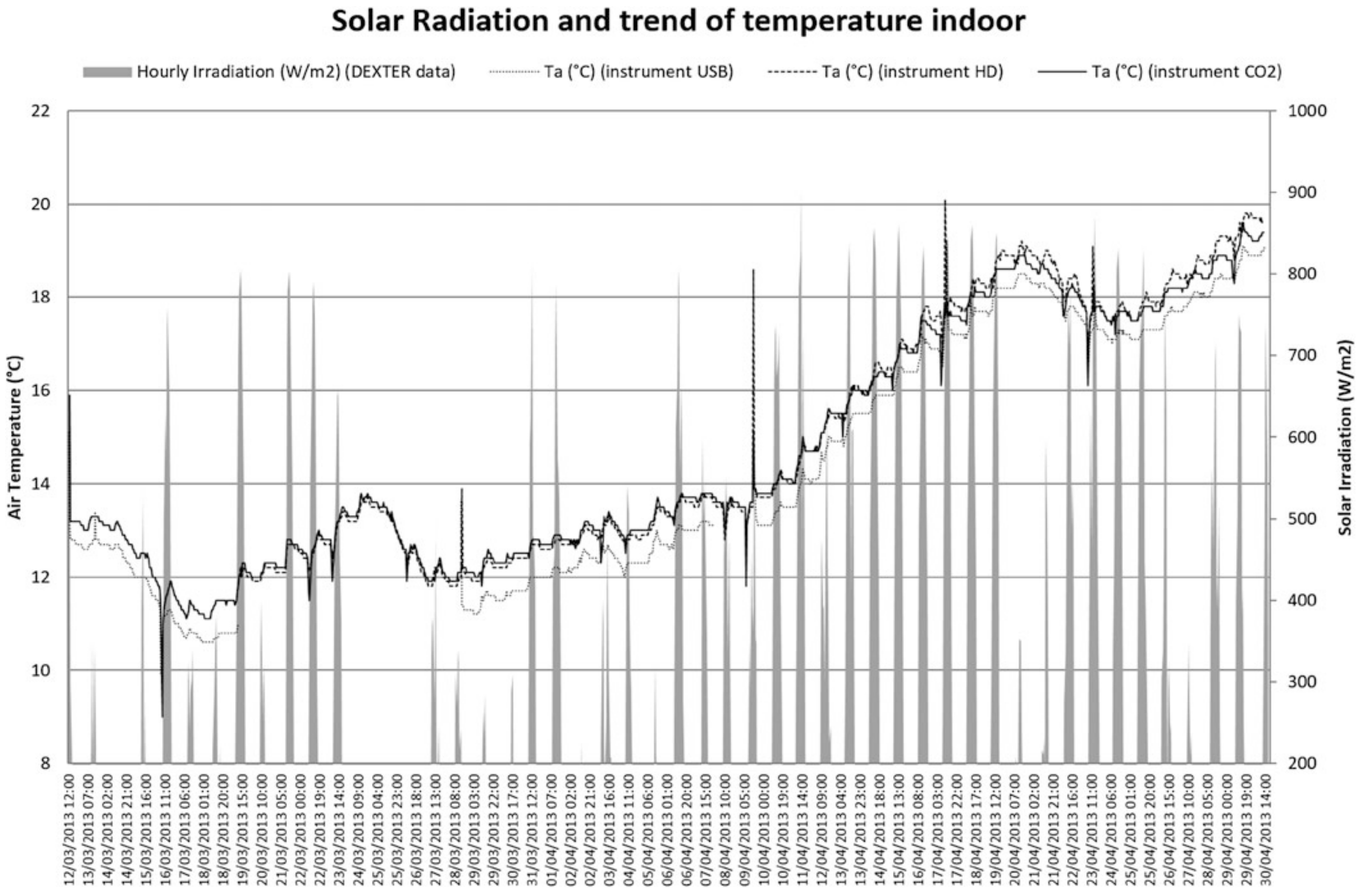

Fig. 2.4 Trends of two variables: air temperature and relative humidity

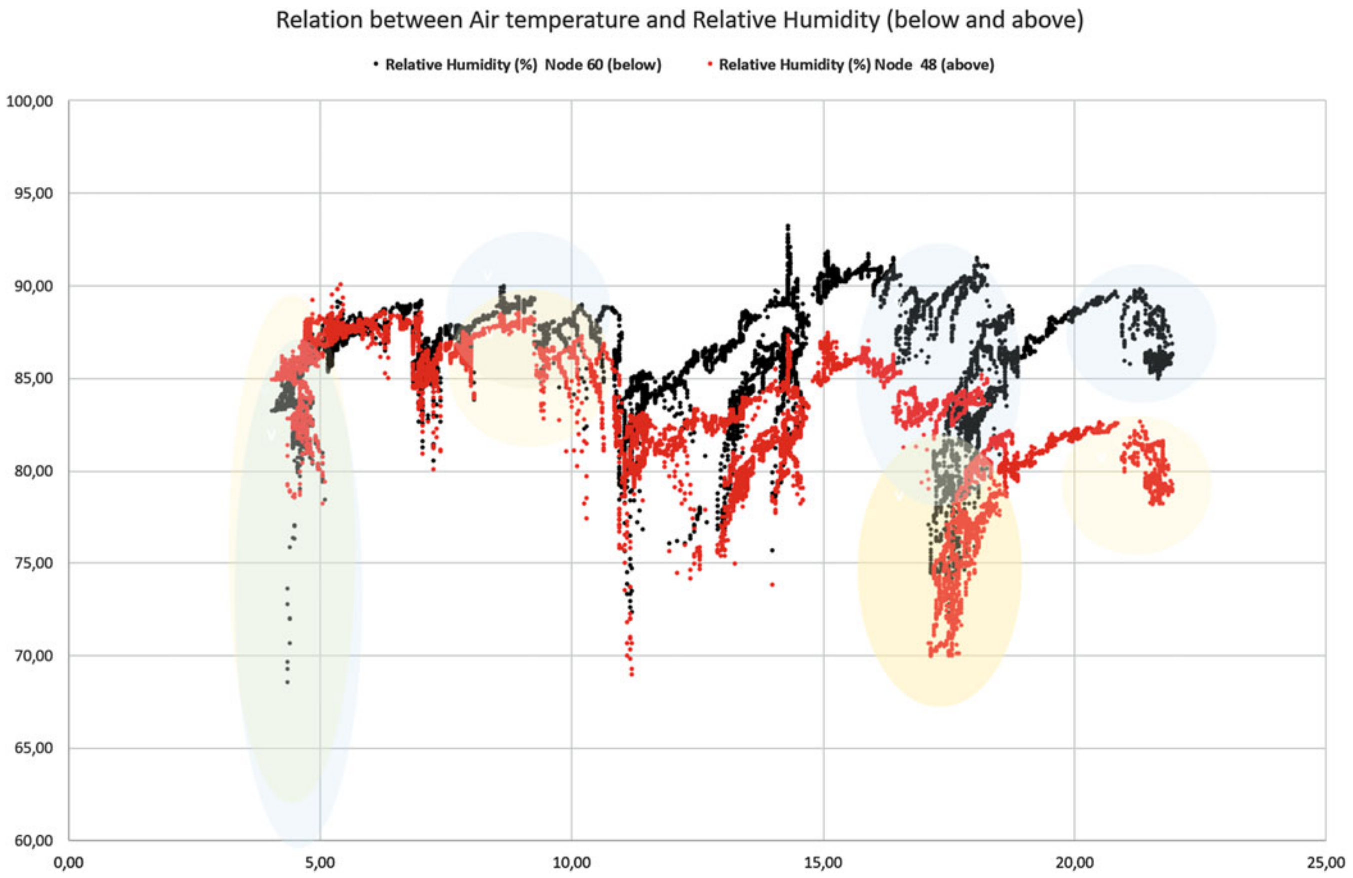

Fig. 2.5 Example of *x*/*y* graphic, with air temperature and relative humidity

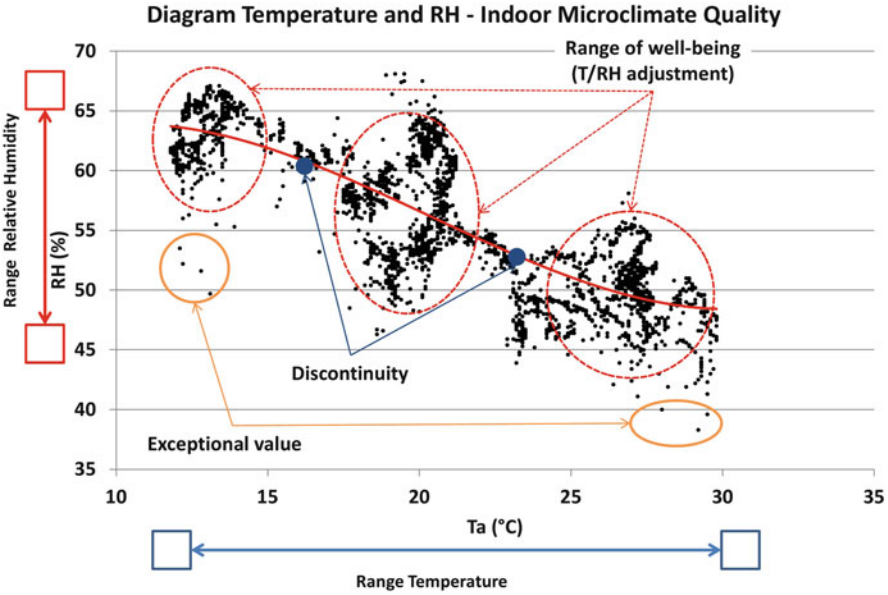

Fig. 2.6 Example of *x*/*y* graphic with air temperature and relative humidity or relative humidity matrix

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

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).

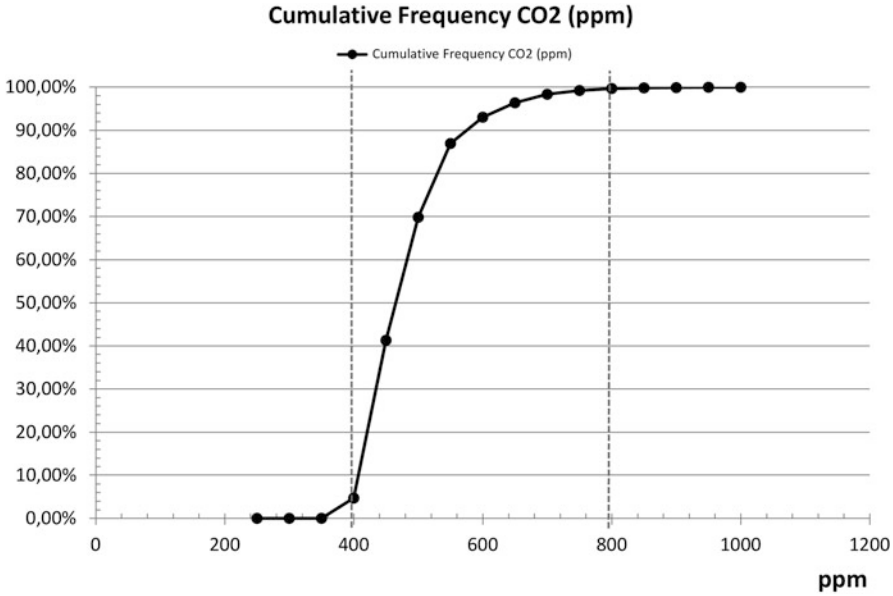

Fig. 2.7 Examples of single cumulative curves and relatives of the same variable measured in multiple spaces

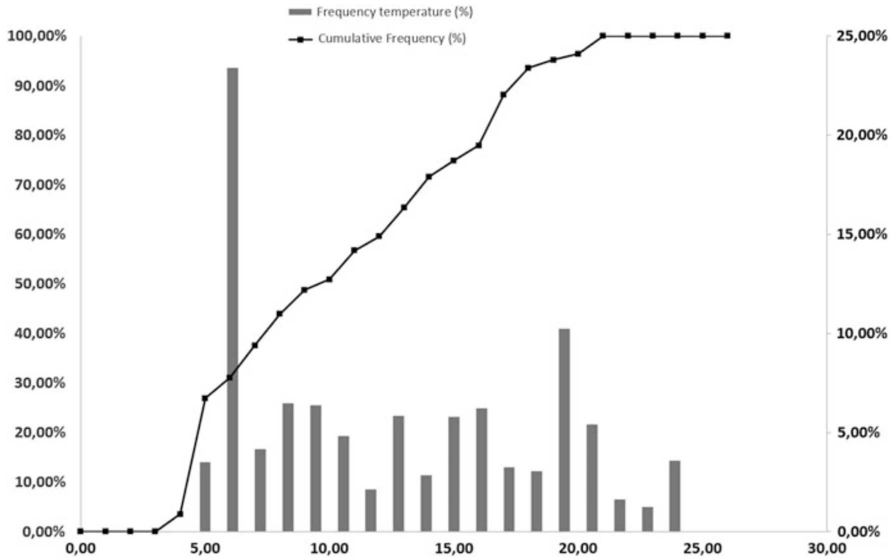

Fig. 2.8 Example of histogram of frequencies and cumulative curve

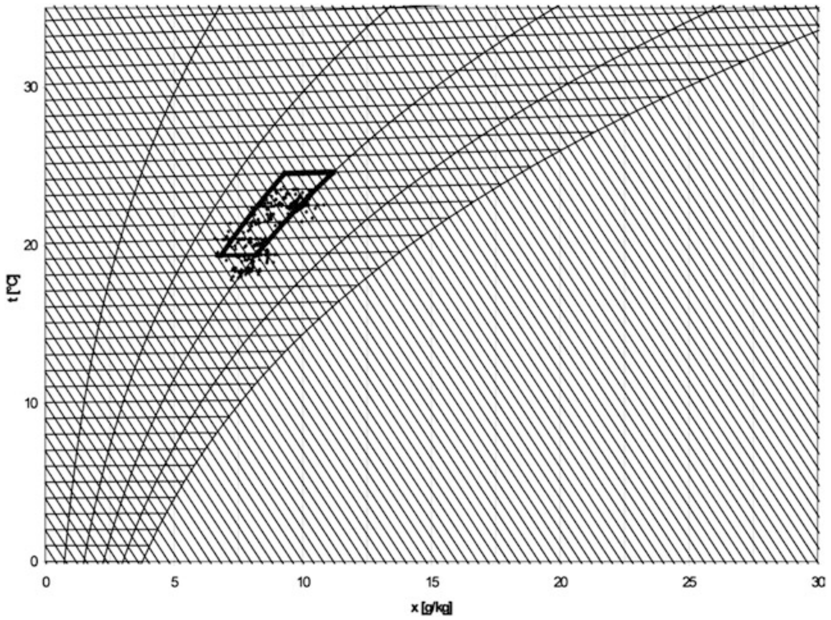

Fig. 2.9 Psychometric diagram. From La Gennusa et al. (2005)

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).

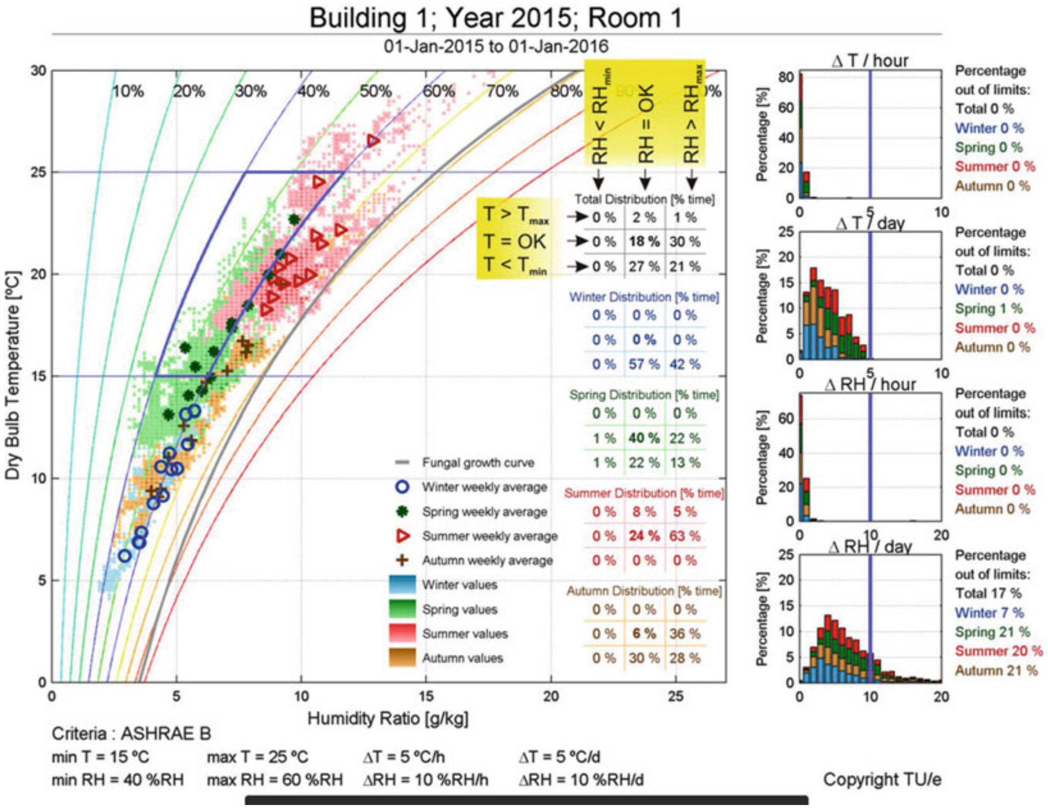

Fig. 2.10 Psychometric diagram. From Huijbregts et al. (2012)

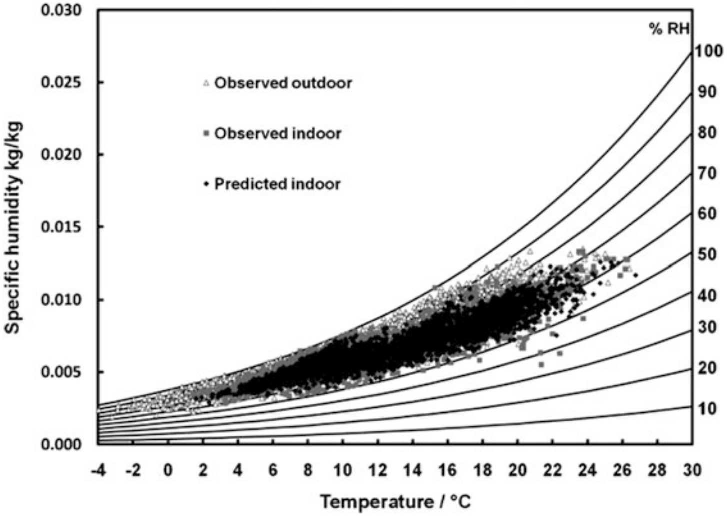

Fig. 2.11 Psychometric diagram. From Lankester and Brimblecombe (2012)

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).

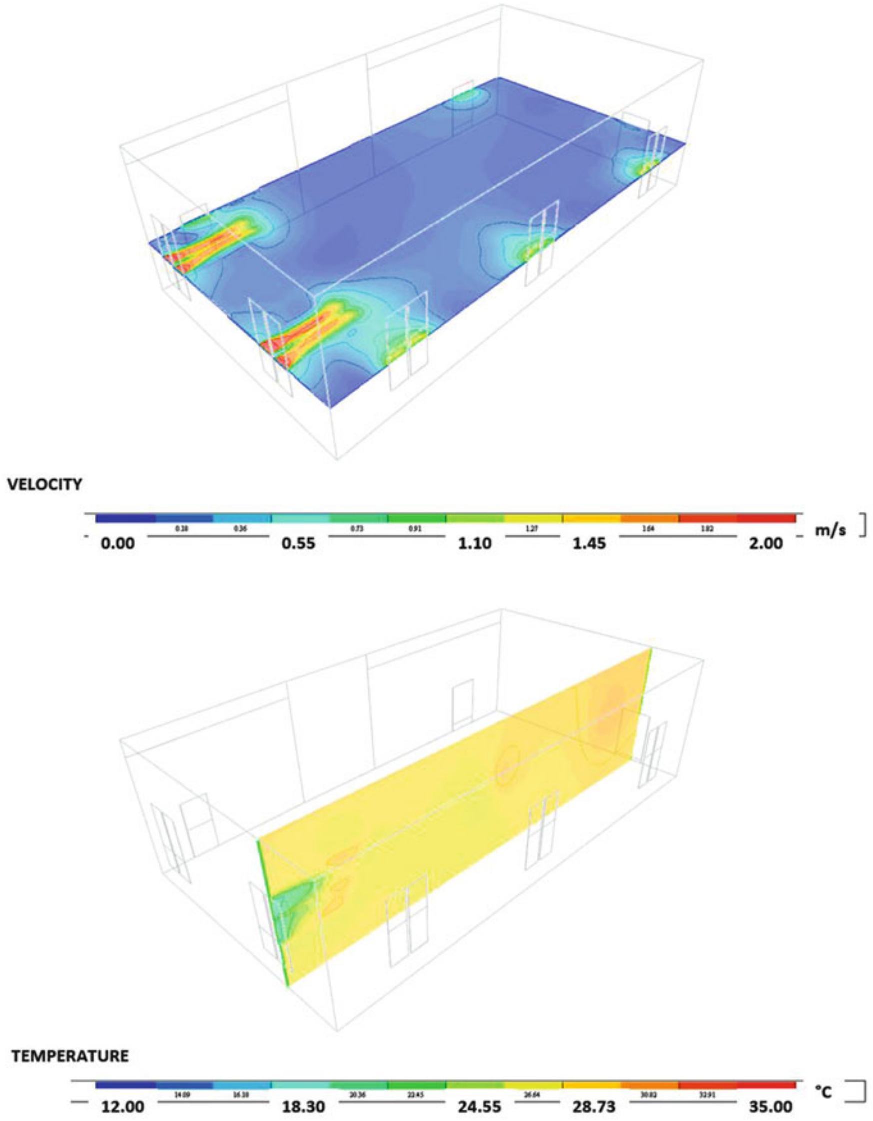

Fig. 2.12 Indoor microclimate map in 3D simulation

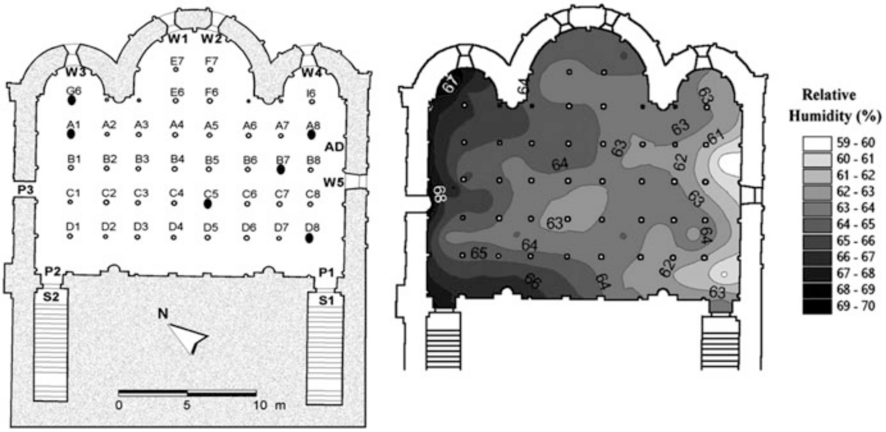

Fig. 2.13 Indoor microclimate map, Cattedrale di Otranto, from Cataldo et al. (2005)

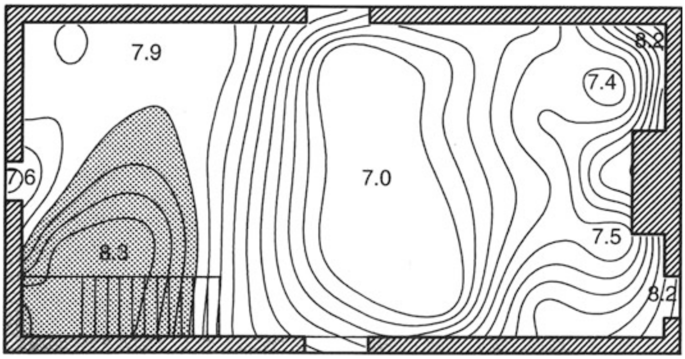

Fig. 2.14 Indoor microclimate map, S. Rocco Oratory, Padova (Camuffo 1998)

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

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Chapter 3
Historic Indoor Microclimate

Marco Pretelli and Kristian Fabbri

Abstract In this chapter are described the elements leading to the definition of Historic Indoor Microclimate, with a particular reference to the reference principles and goals of the study. The different fields of research defining HIM, the different sources that can be used, and the subsets of HIM (original indoor microclimate, OIM; subsequential indoor microclimate, SIM; actual indoor microclimate, AIM) are illustrated. Historic Indoor Microclimate configurates as aspecific research area, giving original and complete indications on heritage buildings.

3.1 Historic Indoor Microclimate (HIM): A New Research Area—Principles and Objectives

That of Historic Indoor Microclimate is a field of research defined by two main factors: first is the characteristic *indoor microclimate* of a building in a specific moment; the second factor is *time*, in its chronological sense, with the changes happening in a building along its life.

The study of indoor microclimate of a building concerns the study of the air volume included within a confined environment, described through physical variables (temperature, relative humidity, air speed, etc.), described in the previous chapter. The researches focus on energy and mass exchanges through the shell of the building:

(i) Directly, through the opening of doors and windows, or the entrance of people
(ii) Or indirectly, e.g., when heat flows in the building's shell: These exchanges depend on the geometric characteristics of the rooms and of the air volume, on the dimension and thermophysical qualities of the surfaces, etc.

The time factor is relevant in the history of any building as any architectonic organism has, somehow, a specific life, being subject to changes and modifications (Moneo 2004). These can have significant effects on the microclimatic behavior of

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buildings, so that, through the changes involving a building during decades and centuries, history interferes with microclimate.

The relation between indoor microclimate and architecture is evident: using different strategies and solutions, including proto-systems such as braziers, and in relation to the different climates and social contests, the architectonic solutions to develop livable spaces for human activities had the goal to determine a specific indoor microclimate in them.

Given the shortage of experimental data so far, we must assume that there has been an evolution in characteristic microclimates of buildings, as time and environmental conditions changed. Analogously to the researches on earth climate based on ice cores, indoor microclimate can be studied along the history of architecture. The goal of this volume, as well as of several contributions to meetings and journals, was hence to reconstruct the evolution of microclimate in single buildings and to extrapolate the main lines of this kind of research, which is highly useful to achieve the goals of building restoration.

HIM can be defined as the study of evolution in time of the characteristic microclimate of an architecture, in relation to the variation in fruition (conditions linked to food, clothing, and behavioral habits); to the changes involving the building in structural terms (destruction, changes or construction of walls and ceilings, addition or removal of new parts, opening and closing of windows, etc.); and finally to the introduction of new or successive HVAC systems.

Indoor microclimate is the result of strategies adopted to guarantee the usage of a building by people. These strategies concern different fields summarized in four groups:

(a) *Technical strategies*, specifically architectonic, concerning specific architectural solution contribution to the realization of a building
(b) *Energetic strategies* relative both to the modalities adopted to reduce energetic exchanges through the shell and referred to the type and use of energy to modify indoor microclimate with hearths, stoves, or other HVAC systems
(c) *Economic and social strategies* linked to the dynamic of the whole societies, discoveries and inventions, economic mechanisms (energy sources and prices), as well as the appearance of new social functions requiring the realization or modification of buildings, as a Church or a castle
(d) *Physiological and cultural* aspects, depending on the changes in human ability to adapt to microclimatic conditions, through the adoption of specific food habits or the performance of specific activities: All of these factors influence the energetic exchanges between man and its environment, in relation to cultures, traditions, and local habits.

Each of these aspects changed autonomously in time, while heritage buildings were undergoing the effects of such an evolution and suffering the modifications linked to it. Exempla are the passage from early heating systems to modern HVAC systems or, more recently, the introduction of new industrial products to insulate perimetral walls.

Indoor microclimate, in its immaterial essence, can, in the same way bricks and plasters do, register historic data and allow to decode them, as long as there are instruments to interpret the information.

The disciplinary sectors interested in the study of HIM can be grouped into three big families:

- The group interested in the conservation of heritage buildings, on which indoor microclimatic conditions and its variation in time have significant effects on the preservation of materials and of the objects conserved into the buildings.
- The group designing HVAC systems (heating, ventilation, and air-condition system): To properly design such systems the characteristics of the buildings must be taken into account, as well as the conditions of set point to achieve to obtain a comfortable indoor microclimate.
- Last, the area of researches interested in the study of comfort and thermal comfort in extreme and moderate environments, evaluating the comfort perceived by the users, as well as possible thermal stress or damages to human health.

Being somehow linked to HIM, these three lines of research are not completely separated; on the contrary, they are intertwined. In different contexts, they have to relate in order to find solutions to guarantee thermal comfort to the visitors of heritage buildings as well as the conservation of the building itself and of its content. These relations are at the basis of the studies of Corgnati et al. (2009), which compare and note the similarities between indoor microclimatic quality (IMQ) and indoor environmental quality (IEQ) as described in European Standard EN 15251 (2007), and of the studies of La Gennusa et al. (2008) and Ferdyn-Grygierek and Baranowski (2015) that highlight the conflict between adequate indoor parameters for people and for artifacts.

In a wide and mainly unexplored setting, museums constitute a specific subsample in which microclimate is highly studied, as reported in Thomson (1986) "*The Museum Environment*," or in the literature review from Pavlogeorgatos (2003) and in other recent studies such as of D'Agostino et al. (2015).

Among the studies dealing with microclimate in historic architecture, the work of Camuffo (2013) represents a detailed documentation, with different exempla, of the different instruments for the study of microclimate in historic buildings. Standards as EN 15759-1 (2011) or, in Italy, UNI 10829 (1999), define specific criteria for the microclimatic variables for the conservation of cultural heritages.

Recent studies suggest a new specific index for heritage buildings; see Litti et al. (2013, 2015), and in this book Chap. 6.

The goals of the study of HIM are different:

- *To investigate the history of architecture and, more in general, human behavior, as far as the habits related to architectonic indoor microclimate are involved*
- *Give useful data to evaluate the comfort of a building, as well as in relation to variations on the habits of its inhabitants and social contest*
- *Support an attitude to base the design of HVAC system on historic bases, evaluating the microclimatic performances of each architecture*
- *Deliver data in order to design conservation interventions in which space is given to what is called preventive restoration* (Brandi 1977; Urbani 2000)

3.1.1 Historic Indoor Microclimate as a Research Field

Following a common definition, a discipline is a field of knowledge with specific data and terms.

It appears evident that the study of HIM uses concepts and terms taken from different disciplines, some specifically scientific, others related to historic studies, and it cannot hence be fully considered a discipline. Anyway, it represents a field of research, given the originality of the combinations of disciplines coming from the two directions.

Among the more scientific disciplines, the evaluation of indoor thermal comfort is a growing field and implies the contemporary evaluation of different parameters connected to the relation between human body and environment. Among the aspects already studied and regulated there are the working environments with extreme conditions, such as very hot and very cold, while three other aspects are not developed:

a. The perception of comfort in hospitals, where hosted people are in different health conditions, metabolism, clothing, mood, and psychological situation. There actually are norms linked to patients with chronic diseases, but there is no structured work to describe the most adapt conditions in the different departments.
b. Comfort in schools and teaching environments, which has an effect on conditions and learning of students. These conditions are extensively studied; it is known for exemplum that they depend on age, but a specific normative lacks.
c. Comfort and microclimate in *heritage building*.

In both the first two applications, priority must be given to the best comfort of the users of buildings. On the contrary, in the third application of the studies on comfort, this logic must be inverted and priority must be given to the well-being of the heritage, i.e., the building or the artifacts it hosts, instead to that of the visitors.

Last, the study of microclimate in heritage buildings is correlated to the studies linked to tourism. Indeed, microclimate in these structures should be controlled in order to maximize the fruition of the building as well as the conservation of the heritage.

In this volume, Historic Indoor Microclimate in heritage buildings is not only the description of the physical components of microclimate in a specific moment in time, but also the comprehension of how this changed in time and how the interventions on the building, variations in the users' habits, and macroclimate influenced the indoor conditions. Learning from the past can help to understand how to act in the future.

3.1.2 *Historic Indoor Microclimate as an Immaterial Heritage*

> The term 'cultural heritage' has changed content considerably in recent decades, partially owing to the instruments developed by UNESCO. Cultural heritage does not end at monuments and collections of objects. It also includes traditions or living expressions inherited from our ancestors and passed on to our descendants (UNESCO 2017).

Despite the fact that its origin lies in the materialità of architecture, it is clear that HIM has several contacts with this definition. Already in the study on the Malatestiana Library, it appears that to the determination of HIM contribute many of the ICH of the people in charge of the heritage. Then, the level of comfort guaranteed by the building is correlated to the habits of those inhabiting it, in terms of clothing, usage, food habits, etc. Hence, as:

> . . .fragile, intangible cultural heritage is an important factor in maintaining cultural diversity in the face of growing globalization. . . (UNESCO 2017)

and

> understanding of the intangible cultural heritage of different communities helps with intercultural dialogue, and encourages mutual respect for other ways of life. (UNESCO 2017),

The study of HIM can contribute to the widening of our knowledge on habits and lifestyles very different from ours. In the case of HIM we think we can adapt the sentence:

> The importance of [HIM as an, NdR] intangible cultural heritage is not the cultural manifestation itself but rather the wealth of knowledge and skills that is transmitted through it from one generation to the next. (UNESCO 2017),

Given this, until now it probably lacked a point of view synthesizing different cognitive approaches, such as that of physicists, chemists, architects, and restorers. Hence HIM has never been interpreted before as an element to study in its historic development, and not only as a quantification of specific microclimatic conditions.

In other words, the question to be asked is why to study indoor microclimate in historic buildings, how does this differ from that of new buildings, which can be the consequences in other sectors, and what do we intend with *Historic Indoor Microclimate (HIM).*

Our point of view, as presented in the book, is to revert the perspective and not think to indoor microclimate as the result of the strategies determining it, but, on the contrary, as an object to study and on which to base those strategies. It is, indeed, a source of information, a document and a historic heritage to understand and preserve.

Once the definition of HIM at paragraph 3.1 is accepted, it appears evident that each building has a specific indoor microclimate and comfort level per each stage of its history (or more specifically, a OIM and several SIM), determined by:

- External climate, so that it is necessary to know the history of climate and the specific macroclimate in a specific time in order to understand indoor microclimatic behavior in that time, and to model it
- The habits of inhabitants, based on their economic and social level, which influences the clothing and other strategies to resist the cold and deal with heat, as well as metabolic activity, which is linked to calorie intake, activity, and health status
- Architectonical characteristics, depending on the availability of materials and technology for construction in each time

3.2 Definition of Historic Indoor Microclimate, HIM

The definition of Historic Indoor Microclimate (HIM), as written above (par. 3.1), is strictly related to the study of evolution and history of indoor microclimate in buildings, along with the variation of the following:

- A. Physical characteristics of the architecture, such as its geometry and shape, on the one hand, changing as the building was enlarged in roofs, walls, doors, or windows, partially demolished, etc. Or, on the other hand, as the presence of one or more subsequent proto-plants such as stoves and fireplaces, or, later, proper plants (heating ventilation, and air-conditioning—HVAC)
- B. Cultural characteristics that have an effect on the historic microclimate and on the building itself, as use of clothes, foods, functions, habits, and rituals of the inhabitants and even energy sources

These cultural characteristics, as well as the changes of costumes and habit registered along history, can be the result of the evolution of the social group, elegant changes, or novelties and discoveries in the field.

3.2.1 HIM and Its Articulation in Different Elements

Historic Indoor Microclimate (HIM), as a product of, on the one hand, interactions between temperature and relative humidity as the two main parameters with others (air speed, solar radiation . . .) and, on the other hand, of its changes during time, is to be studied specifically. It is indeed a multidisciplinary research concerning many areas of interest: from artifact conservation to comfort, building physics, plant design, history of architecture, down to history of culture.

HIM could be divided into the following:

- A. *Original indoor microclimate (OIM)*, which is the historically original microclimate, characterizing the building at the moment in which it has been built. This can be simulated and studied thanks to the historic, climatic, and architectural data, through the historical information and the information collected on the construction period of the building, found in the archives and by directly building survey. The knowledge of OIM is relevant not only to speculate on the possible reinstatement of the original microclimate, which is sometimes the one which ensures the best conservation conditions of the building itself, but also on what should be the best alternative conditions for ensuring the building conservation.

- B. *Subsequent indoor microclimate (SIM)*: as the microclimate present in historic times in the building, consequent to variations in the building. Variations as additions, partial demolitions, covering, etc. can be deduced from historic and architectural data as well as on researches on the phases of construction of the building, including early and proper HVAC systems.
- C. *Actual indoor microclimate (AIM)*: contemporary microclimate, determined by the state of the building in present times (the one that we can monitor nowadays). This can be recorded with instruments placed in loco during the monitoring phase and the data can be used during a modeling phase and even be validated. Two main methods are applied to perform these studies: research into historic archives and building simulation within virtual environmental building. This latter study method creates a virtual model of the building based on its original configuration, with no addition nor successive modifications, and uses it to simulate the past microclimate of buildings. The results obtained with this method allow to understand the characteristics of the original indoor microclimate and use this information to develop considerations useful to restoration project.

Here follow the specific characteristics of each. To be noted that in this study three parameters are discussed that could be part of HIM, i.e., light and sound comfort and indoor air quality.

3.2.2 Original Indoor Microclimate (OIM)

In most historic buildings, OIM precedes the addition of HVAC systems, which happened in almost all of this kind of architectures. OIM is the characteristic microclimate of each architecture depending on the used techniques, closing and opening systems and of windows and doors, orientation to the sun, and range of variation between seasons: in other words, the planning and management of the building, including the destination of some spaces to the only function of influencing microclimate, where the floors were rarely used. OIM was connected to punctual systems to control microclimate, such as braziers, hearths, and stoves, or to other strategies to confine environments, such as canopy beds.

The search for OIM, as a document of increased knowledge, allows to plan a series of specific competences, supporting the traditional methods of historic and architectonic analysis. At the same time, it can be a useful support for restoration, planning, and valorization intervention, as well as to divulgate knowledge for touristic promotion and so on.

It must be highlighted that OIM has been lost in almost any of the heritage buildings passed through time to us and the current microclimate is the result of many changes. First of all, the outdoor climatic conditions that the local context might have changed, such as e.g. new buildings or the conformation of cities and urban aggregates. Moreover, historic buildings underwent changes in the usage and occupation of the spaces, as well as in the technology and presence of systems to illuminate, heat, and ventilate or other elements alternating microclimate.

The study of OIM allows to individuate the characteristics, architectures, and technologies that were allowing to guarantee a sufficient thermal comfort in a specific historic time and social characteristics. This means that the standard thermal conditions expected in a renaissance court are different from those of a court from the eighteenth century, given the differences in clothing, social context, etc. Differences are obviously linked to social stratum of reference: noble family houses, religious centers of power, places belonging to common people, or bourgeois.

The study of OIM can be applied to buildings from Modern Movement in the twentieth century. Indeed thermal comfort was very different in houses from the 1930s, during the construction of the Weissenhof, and in the Unite d'Habitation of Le-Corbusier in Marsiglia, from the 1940s to 1950s. Obviously, in these cases, the contribution of HVAC systems planned by the architects must be considered when defining OIM for these buildings.

3.2.3 Subsequent Indoor Microclimate (SIM)

During their existence, most heritage and historic buildings have undergone several changes, and only few buildings remained untouched until today.

Most buildings are interested by restoration or other changes to adapt them to the habits and needs of the time. Indeed, changes of architectonical styles and uses of the buildings are always linked to changes in uses, costumes, and technological abilities of society. Just as an example, in many villae planned by Palladio as residences HVAC systems have been integrated in time to shape their indoor microclimate to the expectations of each historic period from sixteenth century until today.

Depending on the story of the building, there can be more than one SIM, as several interventions changed directly or indirectly indoor microclimate. Direct interventions include restorations, inclusion of HVAC systems, and architectonical changes; indirect ones are changes of usage, furniture, or other nonmaterial aspects.

Historic thresholds of SIM can be determined with different criteria, such as the following:

- *Architectonical thresholds (configuration)*, when the changes interest the conformation of architecture, the addition of rooms or demolition of parts, etc.
- *Technical thresholds* when are added or substituted technological elements.
- *Usage thresholds*, relative to the variation in usage of the building after the original or precedent one. Changing the usage of the building, the frequency and time of occupation, the number of people present and the expected thermal comfort change as well. The reasons can be different: sometimes are the requirements of the uses themselves to change, as it happens with the variation of religious rituals in time, but often the whole building changes its role, becoming a museum, being abandoned, and so on. Lack of use itself can contribute significantly to the decay of a building, partially because of the effect on microclimate.
- *Thresholds of HVAC and other systems*, different from the technical ones as they depend exclusively on these systems (heating, cooling, wiring, lighting, stove, fireplace, etc.).

The addition of a HVAC system, in particular thermal ones, obviously determines changes in indoor microclimate, as temperature and relative humidity are kept within specific ranges, independently of external temperature or presence of people. Moreover, they change the perception of thermal comfort from users. As the systems are added and microclimate becomes manageable, the users change their habits, such as clothing, and their expectations concerning indoor microclimate.

3.2.4 Actual Indoor Microclimate (AIM)

Actual indoor microclimate (AIM) is the only indoor microclimate we can actually get in contact with, to measure and evaluate. Hence, it constitutes the reference parameter for any analysis, in particular building simulation.

Modes of usage of spaces can be evaluated, compared to specific standards, analyzed with questionnaires and interviews to inhabitants or users. These interviews, in particular, allow to observe the habits, clothing, and characteristics of subjects, as well as the thermal comfort they perceive.

3.3 Which Are the Goals?

The study of microclimate in heritage buildings has the first goal of studying and evaluating the microclimatic conditions and comfort that could guarantee the conservation and the fruition of the building itself and other artifacts.

Historic indoor microclimate (HIM) wants to include other data to the mere microclimatic ones, in order to build models explaining how and why microclimate varied in time, which are the correlations with the changes in the building, the changes in its uses and in macroclimatic patterns. HIM, moreover, constitutes by itself a characteristic of the building, with an intrinsic value and useful to understand other phenomena linked to it.

In this perspective, it would be useful to plan strategies to preserve HIM, mainly where it is still consistently similar to the OIM. It must be considered that HIM, given its immateriality, is a fragile characteristic of buildings and few careless interventions are enough to destroy it.

It is known that it is possible to deduce many information on the civilization that built an architecture from its very same walls, bricks, and their textures, from the quality and components of mortars, etc. (mines for clays, cooking of bricks, their positioning, origins of sands, etc.; Febvre 1953). In the same way, starting from the HIM of a building many other information can be deduced, useful to comprehend the habits and lifestyles of its inhabitants, and how these varied in time.

Among the many information that can be collected thanks to the study of HIM, many are useful to the reconstruction of habits of clothing, activities, and rituals of people occupying the buildings, as well as their energy sources. Just as an example, in order to obtain the minimum comfort for the inhabitants of architectures during rigid winters between 1500 and 1600, complicated pre-HVAC systems were activated, such as braziers, hearths, and stoves. Behringer (2013) tells us about the importance given to the responsible of the hearth system in the Castle of Prague, as he was in charge of the health of the inhabitants. HIM could give a quantitative dimension to these studies, allowing to understand the initial microclimatic conditions, the effects of the sources of heat, the advantages of specific types of clothing, the energetic requirements, and the alimentary habits as well as the needs in terms of wood to burn to guarantee a minimal level of comfort.

The study of HIM allows to join different disciplines around the question of how microclimate varied in time, mainly those interested in the interactions between climate and society. Obviously, a mechanistic approach is not possible, as there is no univocal link connecting environmental aspects to the solutions developed in the architectonical field. This study, nonetheless, allows to determine the relations between the geometric and technological data on buildings and those coming from archival sources, such as climatic data, iconographic information concerning them, and literature ones. The final aim of such a research should then be to reconstruct the long-term phenomena influencing the life of buildings and of their inhabitants.

To conclude this chapter, it is important to highlight again that the study of HIM constitutes a specific research field and a multidisciplinary sector. The study cases of Chaps. 8, 9, 10, and 11 demonstrate how this HIM-oriented approach can be useful and how it allows to discover, understand, and adopt specific conservational and restoration strategies.

Finally, the management protocols of restoration projects should be planned considering the consequences on indoor microclimate and should follow the same logic used to define HIM in the first place. In particular, it could be useful to consider an additional type of HIM, apart from OIM, SIM, and AIM: the RIM, or retrofit indoor microclimate, or FIM, future indoor microclimate (for their definition, see Chap. 9).

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Chapter 4
The Study of Historic Indoor Microclimate

Kristian Fabbri

Abstract The study and investigation of HIM from the starting point of actual microclimate AIM is the subject of this chapter. This can be done through (1) direct investigation, with probes and measurements; (2) indirect investigation, with modeling tools; and (3) historic studies and surveys. Direct investigation allows to study actual microclimate with instrumentations, interviews, and questionnaires, given that the physical information is not sufficient to comprehend the modalities of management, affluence, and usage of the current spaces. Questionnaires are particularly useful to acquire information that wouldn't be otherwise accessible and to interpret the recorded data, with peaks and anomalies. Indirect investigation uses instruments and software of building simulations, and the main modeling tools and general indication to use them for the study of Historic Indoor Microclimate are described. Indirect investigation includes studies that can be conducted with the analysis of historical climatic data, calibration, and projection with respect to the needs or design and restorations of virtual environment.

The study of Historic Indoor Microclimate (HIM), of the architecture constituting its boundary, of the artifacts it preserves, and of the physical variables that describe it requires the use of direct and indirect investigation tools:

– Direct investigation is what we define when the data are obtained directly in the studied building. This happens with in situ surveys, the analysis of architectonic and technologic characteristics, and, for HIM, use of specific measuring tools and monitoring campaigns.
– Indirect investigations are those in which the information is deduced not in presence of the structure to study, but from virtual modeling (virtual environmental) and with archival and historic research.

To the first phases of direct investigation follows data interpretation, with the analysis of physical variables to characterize the microclimate, as it is described in Chap. 2, or of multicriteria indexes, described in Chap. 6, for every different HIM

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(OIM, SIM, AIM, as described in Chap. 3) with the goal to obtain information useful to the preservation and restoration of both the building and the immaterial heritage contained in it, Chap. 5.

4.1 Direct Investigation: Indoor Monitoring

Direct investigation of indoor microclimate includes recording of the physical and chemical variables characteristic of the space, with measuring environmental probes and data-memorizing dataloggers or similar instruments. The recorded data are analyzed and elaborated, or used to calibrate virtual modeling. Hence, the data must be enough to describe the whole indoor microclimate, with an accuracy level depending on:

- The accuracy of the probe
- The number of measure point recorded, from a minimum number of 1 to even 20 for the same variable
- The placement of the measure point in the space, both horizontally and vertically
- Period and duration of the monitoring campaign

Direct investigation requires a preliminary knowledge of the building and of the goal defined for the measuring activity. The first thing to do is to choose the variables to measure. Air temperature and RH give a minimum fundamental description of the air volume and of the energy and mass exchanges. Other variables such as mean radiant temperature allow to study comfort of spaces or the effects of radiation, illumination, UV radiation, radiance, etc. Air speed is an information relevant to the studies on comfort and dust distribution, as well as on how technological systems work. Finally, other variables such as CO_2 allow to study the pollutant dilution or the effects of the management of visitors, etc.

Besides this, it is important to consider the time or span of time defined for the monitoring campaign:

- If the monitoring happens in a single day, this must be chosen as representative and standard. The data must be coupled with outdoor values of the same variables to understand the behavior of the building. Data from a single day (24 h) or 2 days (48 h) can be useful to study the dynamic behavior of buildings, such as the phase displacement, or the dilution of chemical pollutant.
- If the monitoring can be run for at least a month, this should be chosen as representative of a specific climatic season (summer, winter, etc.).
- The ideal monitoring period is a whole year, or several weeks or months covering all the seasons, in order to understand the behavior of indoor microclimate in relation to different external variables.

- The duration of the monitoring can depend on the duration of the research activity, on the authorizations to access the locals, and on external causes leading to the interruption of the activity, such as the damaging of the probes and the change of use. In these cases it is important to find a way not to discard the data acquired.

To program the research activity, the role of planimetries, layouts, and sections is fundamental in order to describe and understand the building, even before the first inspection. This allows to individuate where to place the probes and how they can be placed. Their number and placement depend on several factors, as the number of available probes might be lower than optimal. The placement of the probes must be representative of the spaces and of their number, to describe appropriately the monitored space. For example, a single probe should be placed in the center of the main room, and two probes should be placed in different spaces, such as the main one and a relevant one because of exposition (north, south, east, or west) or its use. If wireless systems are used to connect the probes to a bridge, the exchange of data among the component of the system must be assured.

In situ inspections are fundamental to optimize the positioning of the probes and they should be done by the researchers who will afterwards analyze the data, in order to determine if any problem can be correlated with the positioning of the probes themselves. The inspection must as well give information on the technical systems, in particular HVAC systems, if present, and their functioning, activation, and position of devices.

To these activities must be coupled some specific attention to heritage buildings and museums, since there might be problems to place the probes in the best position, linked to the expositions, to the visitors' path, to electricity supply, to the thickness of walls disturbing the wireless signal, etc. Moreover, heritage buildings can include several rooms, irregular in shape, with variable content in artifacts and furniture.

The monitoring campaign must include the following:

- Some form of agreement with the managers and personnel of the buildings on how the monitoring campaign will be carried on, on the characteristics of the probes, their aesthetical impact, and the possible damage caused, in particular by contact probes.
- The position of the probes must keep into account the presence of collections and conserved artifacts, and the history of the building. This could lead to prefer to place the probes in non-visible points in rooms with historical furniture, while if there are works or restorations ongoing, the probe might not be a visual problem.
- Once the system is placed, it is important to inform all of the members of the personnel, from the keepers to whom takes care of the cleaning, and even visitors, of the presence of the probes and of things to take care of (one example is in one of the study cases presented in this book, at the Santuario del Valinotto, where a probe has been unplugged with the consequent loss of part of the data).

- The consideration of all of the operations that might cause punctual or periodic alterations of the microclimate, collected with the support of the personnel if relevant to the research. This might include:
  - The number of accesses and visitors
  - The opening of windows, doors, or other events linked to the management of the spaces
  - The maintenance and cleaning activities, etc.
- Collect information on the outdoor climatic parameters, from climatic stations nearby.

Monitoring consists of long-term measuring of one or more variables, with up to several instruments in different points of the area to study.

The characteristics of a monitoring plan or monitoring campaign can depend on several factors:

- Length and duration
- Number of points and rooms to monitor
- The accuracy of the instruments for the measured variable
- The cost and management of the devices
- Security of the placement against theft and damages
- The control and finding of data in situ or from afar, with online support

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

The monitoring activity must include report of other activities, in particular information on:

1. The location of the object of study (e.g., heritage building)
2. Observation on the conservation state of the object
3. Measuring of minimum and maximum values in a specific period of time

For a correct execution of the monitoring activity it is necessary:

1. To define the *physical* variables that are to be measured in relation to the aim of the research. To determine indoor microclimate, for example, air temperature and RH are necessary, while CO_2 is relevant to observe the dilution of pollutants and presence of people, air speed for dust distribution, and ventilation, mean radiant temperature might give information on comfort, contact temperature for single artifacts, etc.
2. To define the length and time of monitoring: typical day, week, month, season, year. Also the modalities of download of the information must be clear: direct download from the probe or through remote measuring system, with a Wi-fi net and online platform.
3. To define the type of monitoring, explorative, aimed at modeling, at improving the management, etc.

4. To choose the measuring devices, such as probes, dataloggers, and Wi-fi-managed system, that can work for the whole monitoring time.
5. To agree with the managers on modalities of access and download of data.
6. To find, on the planimetries and in situ, where to place the probes, in a secure and representative point, where they cannot be modified nor ruined.
7. To inform the whole personnel of the presence of the probes and relative alert system informing of problems, and add "do not touch" signs.
8. To use other systems such as questionnaires, mainly if comfort is evaluated or if the number of visitors is a relevant information for the research.

The monitoring must be done with a specific instrumentation to continuosly measure thermo-hygrometric values. These atypically are micro-recording such as dataloggers, which can be wireless and placed in relevant points to measure. Recording dataloggers are usually programmed to record values every 15 min.

Starting from the hourly mean of temperature and relative humidity values, per each of the variables, with respect to the observation time, these values are recorded:

- Maximum, minimum, mean values, and standard deviation
- Temporal profiles
- Distribution of frequency and cumulated one

From the elaboration of the acquired data, these other information are considered:

- Maximum, minimum, mean, and standard deviation values of hourly gradients (ΔTh, ΔURh)
- Maximum, minimum, mean, and standard deviation values of daily gradients (ΔTg, ΔURg)

UNI 10829 defines measuring range and accuracy of measure of the devices:

- Air temperature: measuring range: −20 and 60 °C; accuracy of measure: 0.5 °C, moreover every device must give the arithmetic mean of several measures done in a time of at least 1 min.
- Relative humidity (RH): measuring range between 10 to 90% at 25 °C, accuracy of measure: 2.5% (5% if hair tension hygrometers, or de Saussure hygrometers, are used).
- Surface temperature: measuring range: −20 and 60 °C, accuracy of measure: 0.5 °C.

The measuring devices can include probes and dataloggers which record data or which can have a transmission system through Wi-fi nets to a bridge, collecting and downloading the data, or uploading them on an online platform remotely controlled.

The first system consists of probes for in situ measuring, even with high security levels, with a single measure point, i.e., probe and datalogger constitute a single device. Generally, among these there are instruments to measure mean radiant temperature, hot-wire anemometer, surface temperature, as well as dry-blub temperature and wet-bulb temperature and the measure of volatile organic compounds (VOC).

The second systems use more measure points and probes with a lower accuracy level, placed in several points in the space or building, connected to each other with a wire or wireless. The devices send the data to a single datalogger working as a bridge and interface to download the data. In some systems the bridge uploads the data to an online platform that allows to visualize the data remotely.

In nets with devices linked to wireless (wireless sensor network), every single sensor is denominated node and can have one or more probes, and can send the information to the bridge, in a tree-shaped structure, or to other nodes, such as the closest one in a hot-spot system, and then to the bridge. In systems with batteries an alert system must be placed to have information on the state of the batteries. The transfer of data in the net and to the bridge requires constant transmission; hence the positioning of the probes must take into account screens and obstacles between nodes or nodes and the bridge. The higher the amount of obstacles, the lower is the receptivity and transmission of data, and higher the consumption of batteries.

The wireless sensor network is preferable if the monitoring is supposed to last for long periods, with few variables and many measuring points.

In the study cases described in the second part, both systems have been used.

In a general pattern, the cost of a monitoring campaign depends on the number and accuracy of the probes, increasing with these characteristics, and on the duration of the monitoring (Figs. 4.1, 4.2, and 4.3).

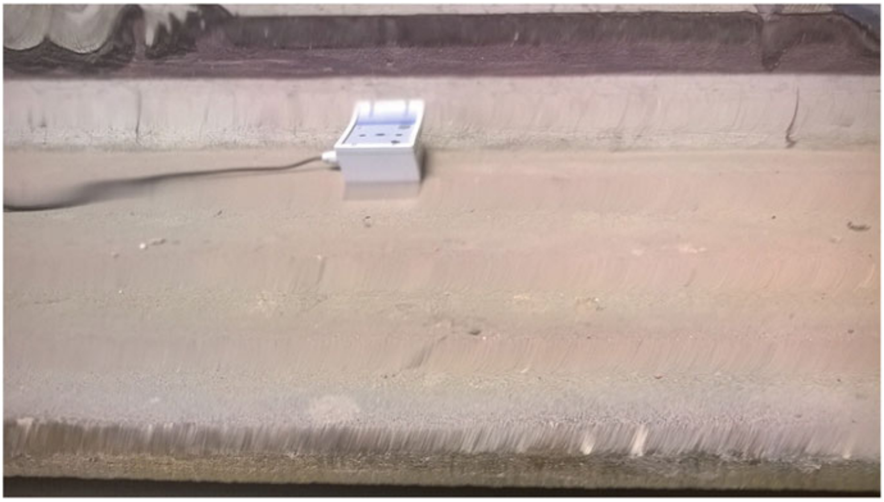


Fig. 4.1 Positioning of probe in Villa La Petraia

Fig. 4.2 Positioning of probes in Malatestiana Library from the left to the right: air temperature probe; CO_2 sensors; microclimate datalogger

Fig. 4.3 Positioning of the contact probes in the Santuario del Valinotto

4.2 Direct Investigation: Interviews, Reports, and Questionnaries

In the study of indoor microclimate, in particular of actual indoor microclimate (AIM) in heritage building, the monitoring activity is not sufficient, even if supported by virtual modeling. A whole lot of information, which can be deduced from the results of monitoring, needs the confirmation through other techniques of direct investigation, such as interviews, reports, and questionnaires.

Heritage building or historic building can host several activities, museums, host artifacts, and collections, or be used as residence or other destination, such as offices, libraries, and theaters. In all of these situations the presence of people getting in and out of the building and carrying on different activities is expected. These can usually be divided into the following:

- *Ordinary tasks* linked to the main activity of the building, mainly if not a museum, but hosts residences, offices, libraries, etc.
- *Activities carried on by workers, functionaries, and managers*, in particular administrative personnel, anyway people spending long time in the same position in activities not linked to the fruition of the building or involved in the visitors' welcome. In particular functionaries and managers, who should be involved in the management of the building and hence have detailed information on ongoing restorations, changes in the placement of objects, or acquisitions which can have an effect on microclimate.
- *Keeping and custody activities*, which include the permanence of the subject in the building for long period of times, with reduced movements, seated or standing. People carrying on these tasks are usually less tolerant to conditions of light discomfort for long period of time. This is because the prolonged permanence in a space with a condition of thermal discomfort (slightly cool or slightly hot) can lead to a chronic feeling of discomfort or even diseases, in the same way as it happens with the experience of clear discomfort for short periods of time.
- *Guides and company*, i.e., people getting into the building occasionally and for short periods of time, and walking along the path in the building. These people usually have a different opinion, of a less acute discomfort, compared to the keepers.
- *Cleaning activities*: People carrying on these activities are usually not part of the regalr staff and carry on periodic cleanings to guarantee hygienity of spaces (floor washing, removal of dust, etc.). Their permanence is linked exclusively to these activities and requires a moderate physical effort.

- *Ordinary or specialistic maintenance*, where ordinary are the whole of operations that allow to use the heritage and that can influence indoor microclimate, mainly:
    - Opening of windows, doors, etc., which favor natural ventilation and air leakage
    - Management of visitor's access, which has an effect on introduction of pollutants

  Special activities can be movements of furniture or collection objects or so on, which represent an exceptional event not representative of the standard microclimatic conditions. Their presence can be occasional, such as cleaning activities, or permanent, especially when they coincide with the keepers.
- *Users*, such as people entering the space in order to complete specific activities, if the building is not a museum, whose permanence is rare or anyway not recurrent. Their opinion on thermal comfort is hence linked to these occasional visits only.
- *Visitors*, i.e., tourists visiting the heritage building or the museum, who stay in the museum just for the time of the visit and are hence able to tolerate conditions of discomfort, sometimes even relevant discomfort for short periods of time, in order to enjoy the heritage.

In relation to the different subject inhabiting the building, in this Chap. we don't brought further the analysis of the priority to give to thermal comfort and artifact conservation, which will the subject of Chap. 6, and which is further debated in Litti et al. (2015), Martínez-Molina et al. (2016), and Lucchi (2016).

Human behavior (as management criteria and of access) and the use of the building (e.g., windows) can influence microclimate since they produce pollutants and modify the thermal charges, ventilation, etc., as well as the information on thermal comfort and perceived IAQ are important.

Instruments to develop direct investigation on subjects such as thermal comfort or to acquire information on the building are the following:

- *Interviews*, i.e., questions to some or all the figures listed above to know the reason of presence and the opinion of the different subject on the building, microclimate, management, etc. Interviews can give a relevant amount of information useful to plan the monitoring campaign, but as well as to study the actual indoor microclimate (AIM), to interpret the results of the monitoring and the transformations happened in time.
- *Report*, where possible, in particular during the monitoring, as well as information on the different ordinary or extraordinary activities happening in the building.
- *Questionnaires* where an opinion on the perceived thermal feeling and comfort (thermal comfort, visual comfort, visual comfort) of different visitors. Information on the preferred comfort and tolerance of discomfort are also interesting. All the information must be related to the moment in which the questionnaire is given.

4.2.1 Interviews

Interviews constitute of several questions, posed to a subject by the interviewer. These questions can follow standard procedures or, as it is more common for indoor microclimate in heritage building, be more like a chat on the feelings of heat or cold inside the building, on the decay of collections, on problems of management, on the difficulties linked to the distribution of spaces, and on the affluence of visitors, complaints, or suggestions. These noninformal conversations usually offer some useful insight into how to develop at best the monitoring activity or into the climatic behavior of the building.

The opinion of keepers and guides is influenced by the continuity of service, to the permanence of conditions of thermal comfort for long periods of time, and hence their judgment usually takes into account average conditions in the building. These subjects can as well give interesting information on seasonal variations of microclimate, on adaptive measure they use in their behavior to increase thermal comfort (such as heaters, ventilators, or other solutions where the spaces allow them), on the identification of the spaces where the problems are greater or that are more representative of average conditions, as well as on the different actions of ordinary and extraordinary maintenance.

Then it must be reminded that these people are usually taking care of different activities, from simple supervision of the spaces to guide or maintenance of the building.

The keepers themselves can constitute a nonmaterial heritage when, as in the case of the Malatestiana Library, they pass from one generation to the other the knowledge on how to preserve the building and its content. This includes the management of accesses to the opening of windows, with an oral praxis for the management of the buildings. Interviews can hence aim at understanding this nonmaterial heritage or defining a protocol to manage the heritage building.

At last, interviews can give useful information on the management of the building and collections, previous restorations or other interventions, and movements of collections and anecdotes that can be useful to understand how the buildings have been used in past times.

4.2.2 Reports

Reports are made with the compilation of appropriate register of operations and maintenance actions, regular or exceptional ones. It must be regularly filled by the keepers or other responsible subjects that can guarantee a daily presence. Minimum contents are per date and time:

- Opening time of windows
- Time and number of visits
- Ordinary cleaning operations
- Other notes

Frequency of visitors can be compared with the trends of CO_2 and of relative humidity, while opening of windows has effects on convective air motions and on temperature, especially in winter times.

The data from the reports must hence be compared and read along with the data from the monitoring (Fig. 4.4).

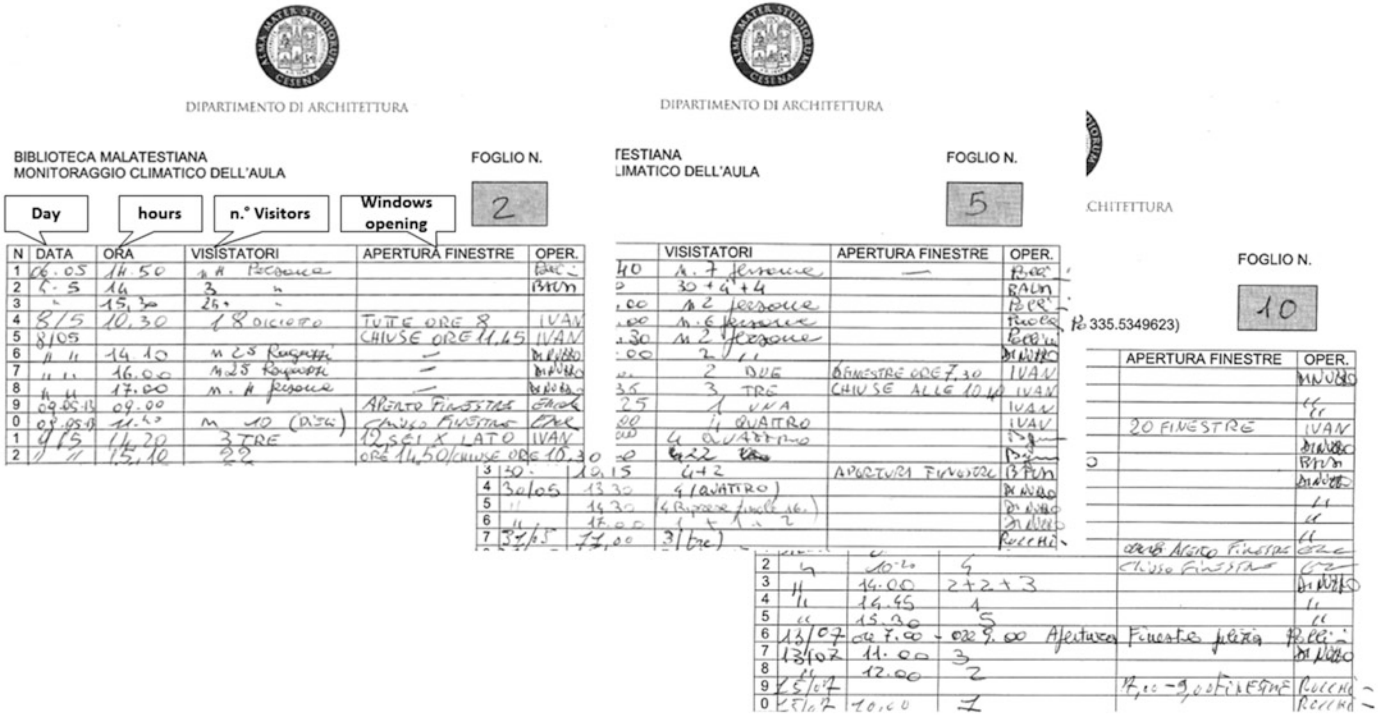
4.2.3 Questionnaires: Duration and Content

Comfort in buildings is a research subject that depends on people's opinion, and only through statistical interpretation of answers it is possible to understand general values of the considered microclimatic conditions. Despite the low level of objectivity, the high amount of literature on this subject allows to define technical norms. The questionnaires can be calibrated to take into account, apart from the actual feeling, psychological, cultural, and social aspects as well.

The use of questionnaires requires experience and competence to (a) elaborate, (b) formulate, (c) distribute, and (d) interpret the results. The phases, in detail, include the following:

(a) To elaborate a questionnaire it is important to keep into account its goal, such as to know the thermal comfort feeling of visitors, which usually count four different ambits: thermal comfort feeling and indoor air quality (IAQ), visual comfort, acoustic comfort, and tolerance level for discomfort situations in relation to the presence of artistic or historical heritage.
(b) The formulation of the questions must consider the cognitive level and number of possible subjects to hand the questionnaire out to, to calibrate the content, vocabulary, and grammar of questions and answers. In particular it must be taken into account that to be asked to fill a questionnaire can be annoying to visitors, and hence the number of questions must be limited (max ten questions, better if five with answers to check). Keepers or personnel can see questionnaires as an intromission in privacy or as a judgment on their tasks, and particular care must be paid to explain the research goals to them.
(c) Modes to submit the survey questionnaire can vary; they can be given by an interviewer, which would be the best option, or the questionnaires can be self-completed. The choice should take into account the surrounding conditions, the number of questionnaires give, etc. If possible it is suggested to collect data and feelings of the surrounding conditions while completing the questionnaire.
(d) The interpretation of the results and their statistic treatment is dependent on the abilities of the researcher to read the information contained in the data themselves.

Finally it is necessary to remember the statistical value of questionnaires, i.e., how many it is possible to hand out compared to the daily number of visits. As an example, in museums with little number of visits, less than 10 or 15 questionnaires



DIPARTIMENTO DI ARCHITETTURA

BIBLIOTECA MALATESTIANA
MONITORAGGIO CLIMATICO DELL'AULA

FOGLIO N. 2

N	DATA	ORA	VISISTATORI	APERTURA FINESTRE	OPER.
1	06.05	14.50	n 4 Persone		[illegible]
2	6.5	14	3 "		[illegible]
3	"	15,30	25 "		
4	8/5	10,30	18 DICIOTTO	TUTTE ORE 8	IVAN
5	8/05			CHIUSE ORE 11,45	IVAN
6	" "	14.10	n 25 Ragazzi	–	[illegible]
7	" "	16.00	n 25 Ragazzi	–	[illegible]
8	" "	17.00	n. 4 persone	–	[illegible]
9	09.05.13	09.00		APERTO FINESTRE	[illegible]
0	09.05.13	11.40	n 10 (DISC)	CHIUSO FINESTRE	[illegible]
1	9/5	14,20	3 TRE	12, SEI X LATO	IVAN
2	" "	15,10	22	ORE 14,50/CHIUSE ORE 10,30	

DIPARTIMENTO DI ARCHITETTURA

TESTIANA
LIMATICO DELL'AULA

FOGLIO N. 5

	VISISTATORI	APERTURA FINESTRE	OPER.
40	n. 7 persone	—	[illegible]
	30 + 4 + 4		[illegible]
.00	n 2 persone		[illegible]
.00	n. 6 persone		[illegible]
.30	n 2 persone		[illegible]
.00	2 "		[illegible]
	2 DUE	6 FINESTRE ORE 7,30	IVAN
35	3 TRE	CHIUSE ALLE 10,40	IVAN
25	1 UNA		IVAN
00	4 QUATTRO		IVAN
	4 QUATTRO		[illegible]
	22		[illegible]

N	DATA	ORA	VISISTATORI	APERTURA FINESTRE	OPER.
3	30	10,15	4+2	APERTURA FINESTRE	[illegible]
4	30/05	13.30	4 (QUATTRO)		[illegible]
5	"	14.30	4 [illegible]		[illegible]
6	"	17.00	1 + 1 = 2		[illegible]
7	31/05	11,00	3 (tre)		[illegible]

(Ro 335.5349623)

CHITETTURA

FOGLIO N. 10

N	DATA	ORA	VISISTATORI	APERTURA FINESTRE	OPER.
					[illegible]
					"
				20 FINESTRE	IVAN
					[illegible]
					[illegible]
					[illegible]
					"
					"
					"
			4	APERTO FINESTRE	[illegible]
2	4	10.20	4	CHIUSO FINESTRE	[illegible]
3	"	14.00	2+2+3		[illegible]
4	"	14.45	4		"
5	"	15.30	5		"
6	13/07	ore 7.00 - ore 9.00	Apertura	Finestre piena	[illegible]
7	13/07	11.00	3		[illegible]
8	"	12.00	2		
9	15/07			7,00 - 9,00 FINESTRE	[illegible]
0	15/07	10,00	1		[illegible]

Fig. 4.4 Registers of intervivwes in the research on the Malatestiana Library. Time and date, number of visitors, and time of opening of the windows are recorded. The records are filled from the keepers themselves along the whole duration of the research

might not be sufficient to guarantee a statistical relevance to the data acquired, but might be only an indicative information.

The interpretation of the results might be helped by diagrams or histograms, and other means of data analysis, as required from the standards. The focus can be on a central tendency, on arithmetic mean, average or mode of the answers, and often the standard deviation alone is an interesting parameter to interpret data on comfort.

4.2.3.1 Questionnaire Content

ISO 10551 is a standard giving knowledge on how to develop questionnaires on subjective evaluation of thermal environmental. This norm gives comparable criteria to obtain valid and replicable results from a research method that can be compared to those of the standards to measure and monitor thermal comfort in situ. The length of the questionnaire must be shorter than 15 min, not to bother the subject and to assure adequate attention. With respect to the formulation of questionnaires, see Fabbri (2015).

In the questionnaires can be asked evaluations:

- Perceived or desiderated
- Referred to the global context or local one (a specific portion of a room or of the building)
- (*Apart from visitors and users*) referred to a specific moment of the day or repeted in time, in the same day or in more than one period during the season or the year

To build judgement scales, the standards define three different types of questions:

- *Evaluative scale* of the sensation in the specific moment (*How are you feeling (in this precise moment)*?). In this case the two extreme values are specified, e.g., extreme A = very cold, and extreme B = very hot. This criterion can be applied to several judgment scales, such as dark-very light-too light-blinding or silent-noisy.
- *Perceptive scale* referred to the feeling of a sensation (*Do you find this …*?). This can be expressed as a percentage of an optimal feeling (100% comfort) or as a scale of values (e.g., from perfect to nontolerable).
- *Preference scale* referred to the preference of a sensation (*How you would prefer to be now*), which requires a judgment of the previous answers, and to the changes to be made to the environment, such as colder, warmer, in a gradient of desired perception.

  In the case of heritage building and museum it is good to add a question on priority of conservation of the artifacts and of the heritage building compared to the comfort of the visitor.
- *Discomfort tolerance scale* (or complaint scale) referred to the level of discomfort that the subject could stand to guarantee the conservaion of the cultural heritage or building. The goal is that control of the personal comfort is

Table 4.1 Example of contents of a questionnaire to study indoor microclimate in heritage buildings

Age	**Your clothes**
<18 years	(Light) shorts and T-shirt
18–35 years	(Medium) trousers and shirt
36–50 years	(Heavy) trousers, shirt, jacket
51–65 years	(Very heavy) trousers, shirt, jacket, coat
>65 years	
Right now, you are feeling:	**In relation to the thermal conditions, how do you consider this room?**
Very hot	Acceptable
Hot	Quite acceptable
Warm	Almost acceptable
Comfortable	Hardly acceptable
Slightly cold	Not acceptable
Cold	
In relation to the general conditions of comfort, how do you evaluate this space?	**In relation to the characteristics of the architecture, of the furniture or of the museum, how much discomfort coiuld you tolerate?**
Perfect	None. I need the best conditions during my visit
Passable	I can accept small technical problems
Not completely passable	I can accept moderate tecnica problems
Hardly passable	I can accept any thermal variation
Nonpassable	I can accept thermal problems only if the visit is exceptionally satisfying

considered more important than the preservation of the heritage, and which would be the limit in discomfort in order to visit the museum or heritage. To visit a museum, if people are not up to stand feelings of comfort lower than those at home, probably they do not give any value to the heritage itself (Table 4.1).

4.3 Direct Investigation: HVAC Survey

The last mean of direct investigation refers to technical sysyems, when present. In particular heating, ventilation, and air-conditioning (HVAC) systems, which modify indoor microclimate, and artificial illumination, since lamps and other devices, to illuminate constitute a punctual factor of radiation and influence the formation of powders and natural convective motions close to the lamps themselves.

HVACs constitute a specific object to research for different reasons. On one side, they act on indoor microclimate to guarantee thermal comfort; hence they modify air temperature, relative humidity, and sometimes even air speed. To study the actual indoor microclimate (AIM), the characteristics and modalities of activation and set point of these systems must be kept into account. This is why the monitoring should preferentially control the parameters during the seasons in which HVAC systems are off, or ask that they are switched off when the monitoring is ongoing.

Often, almost always, to guarantee the use of buildings in optimal comfort conditions implied the installation of HVAC systems without any care for the comfort of the building itself. HVACs modify indoor climatic conditions, introducing microclimatic stress conditions for the building and its content, completely absent in the original one, often thought as a specialist place (a real machina, in the Latin sense of the word) with a specific and clearly determined role.

On the other side, HVAC systems in heritage buildings constitute a particular phase of their history, and hence of the subsequential indoor microclimate (SIM), or they can be originally present in the building and hence have been part of the original indoor microclimate (OIM).

If HVAC systems have been added in a second moment, this might have happened in different steps: localized heating systems, such as hearths or stoves, or the first heating systems from the nineteenth century, to guarantee a normal usage of the building, or later systems from the twentieth century, or finally more modern systems guaranteeing the comfort levels required in modern times. As an alternative, the goal could be to maintain the adequate conditions to preserve the collections contained in museums.

Localized heating systems are a relevant threshold in the evolution of SIM, because they allowed to use several rooms for longer periods during winter and because they represented a variation in furniture of rooms. For example, a canopied bed, which main goal is to enclose a warmer small portion of space, might not be necessary anymore if the whole room is heated with a stove.

The last case is represented by the buildings of the nineteenth century where heating, illumination, or other plants are already present. In these cases, the plants themselves are something to be preserved, even if only rarely they are functional in the same original ways. If so, the OIM would coincide with the AIM, if variations in the external climate are excluded. It becomes quite interesting to observe how the plants themselves are cared for, and how they influence the physical variables and microclimate.

The plant system must be studied distinguishing (1) historical plant system; (2) contemporary plant system, with terminals and thermal exchange modality; and (3) distribution and effect on microclimate and probes during ongoing monitoring campaigns (with the possibility to switch off the plant during all or part of the campaign). The effect of HVAC systems on monitoring is relevant in particular when air temperature trends are considered, with a focus on indoor–outdoor relations.

Direct investigation of plants must include mainly the positioning of the plant terminals (radiators, fan coils, etc.) within the studied volume and the effects on monitoring and/or modeling of the building. HVAC systems have, indeed, an effect on several variables such as mean radiant temperature, radiant asymmetry, air speed, and production and movement of dusts.

The distribution systems (pipes, drains, etc.) and generation of HVAC plants do not have a direct effect on microclimate, but their knowledge is important to understand the type of plant, functioning conditions, and set points, aiming to a virtual building modeling.

Switching on and off of the plant should be reported in records as described above, as well as all of the information related to their functioning and technical characteristics.

The impact of artificial illumination should be studied alongside HVAC systems. Lamps, indeed, constitute an element leading to the accumulation, burning, and distribution in the space, through natural convection at laminar speed, of dust. When this happens, it is common to see over lamps, as well as radiators, the characteristic black shade, caused by smoke, on the wall.

4.4 Indirect Investigation: Building Simulation

Indirect investigation consists of the evaluation of the characteristics of indoor microclimate without measuring it or directly evaluating the variables in the building to study. To this kind of investigation belong historic researches and archival that allow to understand the different constructive and usage phases, and the use of building simulation software.

Building simulation consists of the use of virtual models, elaborated with computer simulation, that allow to evaluate some specific aspects of the building. To study indoor microclimate, in particular, building performance simulation (BPS) is used, a group of virtual models that study characteristics of the performance of the building: indoor microclimate, lighting, energy, human behavior, acoustic, indoor air quality, etc.

The main software simulations concern:

- *Building energy performance* (BEP), i.e., the simulation of requirements of thermal energy (energy need for heating and cooling) and of primary energy, to predict energy usage of the building
- *Virtual environmental*, which studies the characteristics of indoor microclimate
- *Computer fluid dynamics* (CFD), which consists of the simulation of the fluid behavior of air inside and outside the building, due to natural ventilation or controlled mechanical ventilation (CMV)
- HVAC system performance prediction
- Indoor thermal quality performance prediction
- Daylight performance predictions, illumination and daylight simulation
- Other specific software for architectonic acoustic and/or environmental acoustic (room acoustics performance prediction) modeling, to model thermophysical characteristics (transmittance, phase displacementc, etc.), sustainability software, energy labeling software, building simulation in building automation systems

Building simulation and building energy performance are wide sectors of research, first appeared in the 1960s, alongside the development of informatics and computers.

Scientific literature on these subjects appears on many architectural journals and conferences, with two specific journals: Building Simulation, by Springer, and Journal of Building Simulation by IBPSA (International Building Performance Simulation Association, which is a nonprofit international society of building performance simulation researchers, developers, and practitioners, dedicated to improving the built environment). As for the informatics sector and computer graphic, the evolution of these fields has been so fast in recent years that technical manuals are hardly up to date, and there are no manuals summarising the whole universe of building simulation.

In the following paragraph are given some instruments to find a path in the complex study of heritage building and Historic Indoor Microclimate.

Building Performance Simulation for Design and Operation, from Hensen and Lamberts (2011), constitutes a useful summary of different applications of building performance simulations, as Joe Clark, pioneer of studies on Building Simulations, states in the preface:

> Integrated building performance simulation has emerged as an apt means of addressing the above challenges while allowing collaborating practitioners to identify the action combinations that will be most effective in providing acceptable overall performance as a function of the unique climate, design and operational parameters defining specific buildings and communities, planned or existing. IBPS does this by modelling the heat, air, moisture, light, electricity, pollutant and control signal flows within building/plant systems and, thereby, nurturing performance improvement by design. The benefits of the power and universal applicability of the approach comes at a price however: application requires an understanding of design hypothesis abstraction, computer model building, multiple domain simulation, performance trade-offs, and the translation of outcomes to design evolution. (Foreword by Clarke University of Strathcyde - Glasgow, in Hensen and Lamberts 2011, p. XX)

The authors highlight that:

> Computational building performance modeling and simulation1 on the other hand is multidisciplinary, problem-oriented and wide(r) in scope. It assumes dynamic (and continuous in time) boundary conditions, and is normally based on numerical methods that aim to provide an approximate solution of a realistic model of complexity in the real world. Computational simulation is one of the most powerful analysis/analytic tools in our world today – it is used to simulate everything from games to economic growth to engineering problems. However, it is very important to recognize that simulation does not provide solutions or answers, and that very often it is difficult to ensure the quality of simulation results. (Hensen and Lamberts 2011, p. 3)

Building energy performance simulation (BEPS) can be applied to heritage buildings without any need to adopt specific algorithms or simulation models. The main difficulty is to find the inputs for the model relative to the geometric characteristics of the heritage building, and the thermophysical ones, as well as usage modalities (human behavior, air leakage, and ventilation).

In spite of the difficulties linked to the correct choice of the input data, including the climatic ones, BEPS software can be applied to study indoor microclimate to build the virtual environmental.

The virtual environmental constitutes the virtual model of air behavior in the indoor microclimate in the building, with the goal to simulate trends and values of phenomena (moisture, ventilation, convective, etc.) and physical variables (temperature, relative humidity, etc.). The relevance of the simulation is to understand how the building should be managed to guarantee the conservation of artifacts with or without HVAC systems and in relation to its uses.

The scientific literature dealt with this subject in different ways. Balocco and Grazzini (2007) focused on the addition of sustainable conditioning plant design, which is only one of the aspects of the thermophysical behavior of building performance in historical buildings. The study refers to the Hall of the Five Hundred of Palazzo Vecchio in Florence, where the actual plants and the CFD software simulations are compared. Corgnati and Perino (2013) studied a non-air-conditioned building through the CFD simulation of airflows. The study of Ascione et al. (2011) illustrates how reducing consumes and energetic costs is in the interest of associations dealing with heritage.

Ecclesiastic buildings have usually no plant system, and Bernardi et al. (2000) studied the specific microclimate of churches. The main effect on microclimate in these buildings is due to the wall structure, and hence the simulation focuses on phenomena of mass transfer in the internal microclimate.

The study of microclimate in historical buildings focuses on air-conditioned buildings, since HVAC plants modify the original conditions, as described in Camuffo et al. (2002) in energy retrofit (Litti et al. 2013a, b) and, in particular, museum buildings (La Gennusa et al. 2005; Camuffo et al. 1999).

Historical buildings have a specific characteristic in the fact of having been built before the introduction of plant systems; their climate was usually modified mainly with braziers, hearths, and stoves. Hence it is interesting to study the conditions which made livable places out of these buildings. Dynamic simulation allows to evaluate indoor microclimatic conditions and how these are influenced by surrounding variables: climate, presence of people, thermal charges, plants, etc. The comparison between actual indoor microclimate and the past historical condition allows to individuate the problems specific of the buildings and which are due to modernity, i.e., to an inappropriate usage of the building, different from the original condition.

In this paragraph are described the instruments to directly investigate microclimate through microclimate modeling.

Microclimate simulations of virtual environmental building are useful to understand original indoor microclimate. In particular the modeling allows to evaluate, after calibration of the model, the consequences of specific actions.

4.4.1 Modeling Software

Knowing that it is not possible to give a complete account of the scientific literature on the use of BEPS in heritage buildings, here is reported a general description of the main calculation software, of the process to simulate, and of the use of virtual modeling in the study of Historic Indoor Microclimate: calibration and simulations.

Before going on, it is importat to clarify the difference between methods using a steady-state method and the BEPS ones, which use a dynamic model.

Steady-state calculation models consider boundary conditions (indoor and outdoor temperatures, internal load, human behavior, ventilation, etc.) as constants and varying in continuity, i.e., the model is considered in continuous equilibrium conditions. These calculation models are derived from ISO 13790 and are used mainly to evaluate the energetic performance of the building in the respect of laws (minimum energy requirements) and of energy labeling. These software are not useful to the study of indoor microclimate because they refer almost exclusively to energetic needs. In this case, indoor microclimate characteristics are considered a set point information in design conditions and no more information can be acquired in this area.

Dynamic modeling calculations consider surrounding conditions as continuously variable, keeping into account both indoor and outdoor variations, in the presence or absence of HVAC systems. Once input data related to the building and to the outside climate are added to the model, indoor microclimate, by virtual environmental, results from the simulation itself, and its variables such as temperature can be known from the model.

Modeling software can be divided into as follows:

- *Building energy performance simulation* (BEPS) or building thermal behavior modeling. These models allow to simulate thermal behavior on the basis of geometric, thermophysical, plant-, and activity-related characteristics of buildings. They use multi-zonal or nodal models, applying thermodynamic equations, such as energy balance. In the multi-zonal approach, each area of the building is a homogeneous volume with uniform physical values, approximated as a node with a single temperature, pressure, pollutant concentration, etc. Generally speaking, a node represents a room, a wall, or the external part of the building, but it can represent heating/cooling systems, devices, and activities. Heat transfer equations can be considered as a dimensional approach.
- *Computer fluid dynamics* (CFD) use Navier-Stokes equations with a microscopical approach to the heat transfer model, with detailed resolution of airflow patterns and volume discretization in numbers of control volumes structured as mesh. The advantage of CFD models is in the accuracy of calculation equations, but they can require long simulation times and they imply a risk of incorrect evaluations.
- *Multi-physics simulation*, where BEPS or CFD models are coupled with energetic or mass exchange equations (Fourier equations, Navier-Stokes equations, etc.) (Table 4.2).

Table 4.2 Methods of CFD and multi-zonal

Method	Modeling criterion	Application	Advantages	Disadvantages
CFD	The building is discretized in control volumes, densier where greater turbulences are expected	Distribution of chemical pollutants, Indoor air quality, HVIAC systems (design and effect)	Detailed description of airflow	Long computation times, complex model, high-performance computer required
Multi-zonal	The building is discretized in thermal zones, usually the single rooms. Variables are considered uniform in each zone	Evaluation of the energetic total need (heating/cooling, energy load, etc.), energy and mass exchanges, indoor microcliamte variables (air temperature, moisture, etc.)	Energetic need and physical variable calculation, short computational time	Not adequate for local evaluations

Follows a list of the main software for modeling and a list of the main characteristics.

4.4.2 Energyplus

Energyplus—energy simluation software—is an open-source calculation code of building energy simulations. Engineers, architects, and researchers use it to understand the heating, cooling, ventilation, lighting, and process load requirements of buildings. It has been developed by DOE (U.S. Department of Energy Building Technologies Office).

Thermal charges are calculated by a thermal balance engine, at a user-specified temporal pace, and building systems are passed to the simulation module at the same pace.

Energyplus is the most widespread calculation code in research and professional applications, thanks to its modularity and to the wide range of possible simulations, among which:

> Integrated, simultaneous solution of thermal zone conditions and HVAC system response that does not assume that the HVAC system can meet zone loads and can simulate unconditioned and under-conditioned spaces;
>
> Heat balance-based solution of radiant and convective effects that produce surface temperatures, thermal comfort, and condensation calculations.
>
> Sub-hourly, user-definable time steps for interaction between thermal zones and the environment, with automatically varied time steps for interactions between thermal zones and HVAC systems. These allow EnergyPlus to model systems with fast dynamics while also trading off simulation speed for precision.
>
> Combined heat and mass transfer model that accounts for air movement between zones.
>
> Advanced fenestration models including controllable window blinds, electrochromic glazings, and layer-by-layer heat balances that calculate solar energy absorbed by window panes. (US DOE 2016)

Being it a calculation code, input data and the interpretation of output results must be done through manual insertion of data, and with no graphic interface. To simplify the procedure, some software houses developed applications to virtually model geometry of the building, its thermophysical characteristics, thermal charges, and so on, with a specific and user-friendly interface. These usually generate data input to insert in Energyplus, which is the engine, and its results are elaborated into user-friendly output graphics.

The most common applications using Energyplus as calculation engine are:

- DesignBuilder, developed by DesignBuilder software Ltd. (http://www.designbuilder.co.uk/)
- IES.VE, developed by IES, it has a module for CFD modeling (https://www.iesve.com/)
- Open Studio, an open-source Google SketchUp application, with plug-in to create input/output data for Energyplus (https://www.openstudio.net/)
- Simergy, an open-source application (http://simergy.d-alchemy.com/)

4.4.3 ESP-r

ESP-r is a modeling tool for building performance, open source, developed by Energy System Research Units (ESRUs) of University of Strathclyde, since 1974.

> the objective of simulating building performance in a manner that: a) is realistic and adheres closely to actual physical systems, b) supports early-through-detailed design stage appraisals, and c) enables integrated performance assessments in which no single issue is unduly prominent. (ESP-r Overview, website: http://www.esru.strath.ac.uk/Programs/ESP-r_overview.htm)

The software requires an expertise in thermophysics of buildings, airflows, environmental systems, and CFD assessments. It allows to include building geometry with CAD and an interactive interpretation of outputs.

More specifically, the goal of ESP-r is to simulate reality, describing the complex relation between plant systems and automation. The calculation code is based on a finite volume, and not multi-zonal, with an approach that allows to transform geometric and constructive problems into a system of equations of energy balance (conservation equations for energy, mass, etc.), with a time-step calculation process, starting from climatic data and from those regarding occupant configurations and control systems.

A specific characteristic of it is the flexibility in the scale of the model of simulation, which allows to study and model both internal structure of the building and specific technological solutions. In this, it shows to be an accurate software in the restitution of comparable results with in situ-measurable data, as it is evident in double-skin facade in Hoseggen et al. (2008) and in Rijal et al. (2007) for the study of window opening.

4.4.4 TRNSYS

TRNSYS (Transiet System Simulation Tool) is a software elaborated by the homonym TRNSYS (http://www.trnsys.com/, last visit 20 August 2016), which sells it for more than 35 years as a graphically flexible tool to measure the behavior of transient systems. The components are configured and assembled using an integrated graphic interface, TRNSYS Simulation Studio, while input data are built through a dedicated visual interface (TRNBuild). The simulation engine solves the system of thermodynamic equations which represent the whole energetic system. In the building simulations, all the components of HVAC systems are solved contemporarily to the thermal equilibrium of the building and to the air net at each time step.

4.4.5 Heritage Building and Virtual Simulation

Virtual modeling (BEP, CFD, etc.) of heritage building is identical to that of new and sustainable ones and to energy retrofit interventions. The software is a calculation tool which equations do not differ between new and historic buildings, expressing phenomena and physic laws applied to the specific contest of buildings and of human scale (within the order of magnitude scale between 10^{-2} and 10^{2}).

What varies is the methodology, the whole procedure, which includes:

- Collect input data
- Inclusion into the model, in relation to the geometric complexity of the building and to calculation speed and capacity
- Evaluation of errors and approximations to adopt
- Interpretation of results, in dependence to the criteria and errors adopted and to the goals of the simulation itself

In the study of indoor microclimate, the goal is to describe correctly the physical variables of the air volume in the building (virtual environmental). To do this, the model must be comparable with reality and represent it physically.

In this sense the comparison with models of cars used in wind tunnels might be useful. These models are a smaller version of real cars, and hence wind speed in the tunnel must be chosen in proportion to the scale of the model and of the phenomenon to study (still car, moving at different speeds, curving, braking, etc.). Moreover, the relations in sizes between model and wind tunnel must be taken into account, to eliminate edge effects of the model itself. The tunnel is much bigger than the model of the car so that it can simulate real physical environment, but its walls can generate turbulences and the fan itself cannot be too close to the model, to create an airflow similar to that in still air around a running car.

The same principles are adopted in a CFD model: the whole world cannot be modeled, but a portion big enough can be sufficient to exclude edge effect happening close to the limit of the model (boundary effect).

The virtual model is not the reality, but constitutes a representation of it to measure specific phenomena.

In the study of indoor microclimate, the boundary conditions must be specified. These are the conditions that determine exchanges in mass and energy of the building system. All of the models above apply the laws of thermodynamics and of thermokinetics, which describe the conditions of equilibrium in a system following changes in its boundaries. Generally speaking, just taking into account the boundary conditions it is possible to model the system considering variations in its surroundings.

Using architectonic terms, boundary is the geometry and the technical characteristics of the building, through which exchanges in energy and mass happen. These phenomena depend on internal proprieties of the system (modalities of occupation, thermal charges, initial conditions, etc.), and external ones, i.e., all of the phenomena acting from the outside, as outdoor climate.

4.4.6 Virtual Modeling Steps

Virtual modeling using software, such as those described above, requires the following phases:

- Building a geometric virtual model
- Giving thermophysical proprieties to the shell of the building, such as thickness of the walls, transmittance, stratigraphy of materials, and emissivity
- Attribution of thermal proprieties to the thermal zones: thermal load, ventilation, human behavior, etc.
- Definition of the outdoor climate data, relative to the location and following the standards of the software starting from weather data

Per each of them an error must be defined, as well as an approximation, in relation to the characteristics and complexity of the heritage building.

4.4.7 Building the Geometric Virtual Model (Architectonical Configuration)

A 3D geometric model must be built on the basis of in situ surveys, current planimetries (see Chap. 5), and historical ones, in order to evaluate microclimate in different constructive and restoration phases, including surveys on plant systems and their technical characteristics.

Depending on the 3D modeling software used, simulation software, and geometric characteristics of the building, some simplifications can be adopted. For example, the shape of openings and doors can be simplified, while the total surface should be kept constant to consider the effects of solar radiation and ventilation. Or specific decorations can be defined, unless the study focused on fluidodynamic effects of these surfaces, in which case they should be considered in detail. In any case, these represent an error to take into account in the interpretation of the results, but this is reduced if volumes and surfaces, orientation of the building, openings facing north, or any other geometric characteristics are kept constant with effects on exchanges of mass and energy.

The architectonical configuration used in the geometric model can be referred to any phase of the life of the building, the original construction, or the sequence of following changes, restorations, and adaptations. In any case, it is suggested to perform a simulation of the current structure at least, since real indoor microclimate is known only concerning the current building.

4.4.8 Thermophysical Proprieties of the Building's Shell

Thermophysical proprieties of the building's shell include all the physical and geometrical characteristics of the building as required in the model.

In case of opaque vertical or horizontal structures, walls, ceilings, or coverings, their stratigraphy must be considered, along with the proprieties of single materials (thermal capacity, density, conductance), their thermal transmittance, reflectance, etc. If the closing is transparent, the emissivity of glasses and geometry of the frame must be included.

In this book the procedure of calculation will not be explained, since manuals, scientific literature, and the software themselves give enough explanations to characterize the building. It is important to notice, though, that in the case of historical buildings compared to new ones, to find these information/data/knowledge can be hard.

These difficulties represent another source of approximation, of errors in the model. Compared to new buildings, technologies and materials in heritage buildings are usually few in number: bricks, stones, mortars, wood, and some other organic materials, such as straw or wool, and glass. This can be helpful, since their thermophysical proprieties are recorded in software databases and in standards.

Some specific factors, as thermal bridges or single discontinuities in the shell, can be ignored since they have a limited influence on energy and mass exchanges involving the air volume constituting indoor microclimate.

The biggest problem is to understand the technical and constructive solutions adopted, such as the number of heads in the wall, the construction of ceilings or of the covering, and all the elements which allow to reconstruct the stratigraphy of the building. It becomes hence fundamental to acquire as much information as possible from in situ surveys and archival research, coupled with knowledge of the history of the building and of the local building techniques.

4.4.9 Thermal Zone Proprieties: Energy Load, Ventilation, Air Leakage, Human Behavior

The proprieties of thermal zones depend on usage modalities and on the function hosted in the building and of single rooms, directly influencing exchanges in energy and mass and constituting part of the internal proprieties of the system.

Calculation software give standard values of thermal charges and of occupation profiles of single spaces depending on uses that will not be described further here. It is only highlighted that in calculation models BEPS and CFD it is necessary to insert the data relative to occupations of single environments (people/m^2 by hours), the presence of pollutant sources (crowds, devices), air leakage and natural ventilation (flow rate m^3/h, etc.), modalities of opening of the windows (which is important to know air speed, pollutant removal, RH concentration), and the accesses of people and visitors.

In new buildings, the standard profiles given by software can be an effective description of the use of the building, with small variations depending on destination and on accuracy of simulation (design, research, energy audit). In heritage buildings, given the different uses as museums, libraries, etc., these information must be recorded in situ with interviews and questionnaires as debated in Chap. 2.

4.4.10 Weather Data

Outdoor weather data are usually present in the software with respect to the different localities in the format defined on the basis of the typical meteorological year (TMY). This can be already present in the software or requested to societies which record data locally or internationally, or else they can be recorded with local meteorological stations. Weather data should be as close as possible to the real conditions close to the building, and hence recorded from the closest meteorological station, better if placed in a congruent urban contest. If, for example, the building is in an urban area, data from the airport can be not as accurate as those of an urban station, or better than those from a station placed outside the building itself. Data coming from less and less accurate sources, down to the least accurate record of data from the TMY software, constitute another source of error and approximation.

Weather data can be divided as:

- *Climatic data TMY*, i.e., the data representing a standard year, typical for that locality. This data are useful to simulate the behavior of buildings and of indoor microclimate in the future, predicting the effects of different design choices.

- *Climatic data of the current year*, i.e., the data of a specific microclimatic station or from monitoring for the specific current year. This is more accurate and allow to obtain a simulation where external climatic variation corresponds to the simulated one. This is useful to calibrate the model in the monitoring campaign.
- *Extreme weather data, simulated*, where it is assumed that the event of outdoor conditions is exceptionally extreme (heat wave, cold winter) and can have an effect on the indoor conditions.
- *Historical weather data*, i.e., weather data relative to specific periods in the past.

4.4.11 Historical Weather Data

Historical weather data are an interesting parameter of simulation because they allow to simulate indoor microclimate in specific historic times.

Accurate data are recorded only in recent times, starting from half of the twentieth century, but other sources can be accounted to have information on older times. Local historical climate archives and global climatic history of earth or of a specific territory can be used to understand the habits of people from the past and the effects on buildings. On these subjects, see Acot (2006, 2009), Behringer (2004), and Segrè and Cannillo (2005).

The study of historical climate, or past climate, constitutes a specific field of research, in particular as archival research is involved. The following journals and studies are considered reliable sources of information: Climate of the Past, http://www.clim-past.net/, Camuffo and Jones (2002), Moschen et al. (2011), Bradley et al. (2003), Brazdil et al. (2005), and Camuffo and Bertolin (2012). Among these researches, some give information on historic series of meteoclimatic data.

Historical climate relevant to Historic Indoor Microclimate researches are obviously referred to the last 2000 years of history, and more commonly to the last 400 years, when the first meteoclimatic station has been introduced in Florence. La Rete dei Medici, as it was called, was the first international net of meteorological information, with 11 stations, 7 of which are in Italy, the main ones in Florence and Vallombrosa. Readings were done every 3 or 4 h by Benedictine monks or Jesuit fathers following a specific protocol, day and night, on two thermometers exposed on the south and north walls. The Little Florentine Thermometer (LFT) has been invented by the Granduca di Toscana Ferdinando II de Medici about in 164 and it was the first thermometer with glass spirit, and the first instrument able to give precise readings of temperature after the invention of the thermoscope. Realized completely with glass, the bottom of an empty sphere constitutes the bulb, and a capillary tube where the thermal scale was recorded was hermetically closed in the superior end.

The insertion of climatic data in the software must take into account the characteristics of the data themselves. Generally speaking, past climatic data give values of air temperature but no information on radiation, which depends approximately on the latitude. The recorded temperatures should be hence adapted to the information on radiation, and the resulting values can be used to obtain simulations on past indoor microclimate.

4.5 How to Use Virtual Environment in the Study of HIM

Studying Historic Indoor Microclimate with modeling software requires some passages:

1. Geometric survey of the building and recontruction of the virtual model (e.g., *SketchUp*)
2. (If possible) installation of a continuous monitoring system in at least a room, to measure air temperature and relative humidity at least once per hour
3. Construction of the virtual environmental, a software to evaluate the energetic and physic behavior of the building, in a dynamic regime (BEPS, CFD). The model must take into account weather and usage data of the building, in relation to the monitored period.
4. Calibration of the virtual model, comparing the trends of real air temperature and relative humidity to those of the virtual model. Only if the values are less than 5–10% discordant, the process can move to the following and final step.
5. Simulation and construction of the scenaries, analyses of trends, average values, cumulative ones, etc. (see Chap. 2).

Following these steps allows to compare the model to reality, thanks to the calibration phase, considering the error given by outdoor climatic conditions and by occupation values.

Other variables can be simulated in the model, if not measured with direct investigation in situ. As an example, the virtual CFD model allows to simulate the distribution of air speed to evaluate turbulences, water vapor content, average illumination of spaces, and mean radiant temperature.

4.5.1 Virtual Environmental Calibration

If indirect investigation and virtual simulation are reliable and the virtual environmental is very similar to the real indoor microclimate, the model results in a useful instrument to build new scenarios and simulations.

Some papers have been published on BES calibration, focusing mainly on new buildings or recent ones, as Monetti et al. (2015), Yanga and Becerik-Gerber (2015), Royapoor and Roskilly (2015), Mustafaraj et al. (2014), Ahmad et al. (2016), and Giuliani et al. (2016).

In the case of heritage building and HIM, as in others, it is important that simulated and real indoor microclimate are as close as possible, in order to have a high confidence on simulations based on theoretical parameters. This is the reason why the calibration process is particularly relevant. It consists in the comparison of the trends of variables obtained from direct investigation, such as monitoring, with those resulting from simulation of virtual environmental in the same thermal zone. The calibration verifies a correspondence in the values coming from the two sources, directly comparing the values. The closest the values, the more reliable can be considered the model.

The comparison can concern different physical variables, such as air temperature, relative humidity, air speed, and CO_2. The minimum configuration must include a comparison of outdoor air temperature trends and usage modes in the virtual and real building, and relative humidity as mass exchanges is concerned.

Overlapping the trends of the variables from the two sources and observing the differences are the main goals of calibration. Building simulation must be calibrated with monitoring data. Compared to the results of simulations, the higher variability is originated in the higher variability of real climatic data, and not TMY, as well as occupation levels, affluence, and ventilation.

Up to a certain level, differences are not relevant, as they can be due to variation in the range of maximal and minimum daily values, anomalies due to problems in monitoring, specific days or periods with peculiar outdoor climatic conditions, etc.

The differences between the virtual and real trends that can be ignored are those that exclude minimum and maximum daily values, peak values, and monitoring suspension times.

If the two trends differ sensibly, i.e., the differences among the values are higher than 5%, or the peaks and flexes of seasonal or daily curves do not look alike, the trends are not comparable.

Once the model has been calibrated and considered reliable, its results relative to the physical variables in simulated scenarios can be interpreted with similar instruments to those described in Chap. 2.

4.5.2 Virtual Environmental of HIM Scenarios and Simulation

Once the virtual environmental model is calibrated, it is possible to build different scenarios depending on the goal of the research on HIM. The scenario is defined as a possible configuration of the model, different from the current reality. The model resulting from the calibration is modified depending on some parameters of which effects are to be studied.

These variables or parameters of the virtual model are the same input data of the model, such as:

- The architectonic and technological configuration, concerning different historical phases of the building and changes in the material
- Changes in the modes of use, crowding, and pollutant sources
- Changes in the outdoor climate

In building the scenarios, only one variable must be changed at a time, one element of the list above. If more than one variable is changed, it is harder to evaluate the effects of a single input. This is worth doing only if the simulations are relative to restorations or changes in the management.

The model representing the current conditions is the Scenario Zero, the reference as actual indoor microclimate (AIM).

The number of goals and scenarios is incredibly high. Here follows a synthetic list of the main goals in the study of Historic Indoor Microclimate. The use of software allows to obtain a relevant number of information and trials on the considered building.

4.5.2.1 Architectonic Configuration

In these kinds of scenarios, the geometry of the model of the building corresponds to the different constructive phases of its history. This way the phases of development of the building can be coupled to their indoor microclimate, since the initial construction, with its original indoor microclimate (OIM), to the following changes (subsequent indoor microclimate—SIM), in relation to the historically most relevant levels as revealed from archival researches.

With these researches it is possible to reconstruct the reasons behind architectonic, technical, and design choices.

4.5.2.2 Historic Climate and Past Thermal Comfort

In these scenarios, outdoor climatic data are the independent variable, modified to evaluate the effects on the other variables. The data used come from researches related to past climate and to HIM, or aim at predict the effect of changes of indoor microclimate in relation to future variations in outdoor weather (such as effects of climate change).

The results of simulations can be used in historic and archaeological studies. The simulation of PMV comfort indexes allows to understand the comfort level perceived by the users of the building in the past, but as well as to suggest the perfect clothing style to read in the library.

In the simulations for past comfort studies, apart from the climatic data and configuration, which must be those of the historic period considered, other relevant variables are:

- Resistance of the clothes (clo), as deduced by history of clothing, paintings, chronicles, or archival documents
- Metabolic activity (met), correlated with the different activities that were supposedly typical of each room, or to the kind of alimentation
- The crowding of the spaces (thermal charges of people) and use of heating systems (stoves, hearths, etc.)

In these kinds of researches it is possible to reconstruct with a method similar to the archaeological one, the habits, behavior, and life of people in the past.

4.5.2.3 Usage Modes, Occupation, and Management of the Building and of the Visitors’ Path

In these scenarios, the end use of the rooms and their use profile are changed. This allows to verify pathological conditions or pollutant concentrations, or to evaluate the origin of the decay processes, or else as an effect of the restoration processes, and mainly in the definition of protocols to manage the building, improve or define the role of the keepers, the visit tours, the crowding, etc.

4.5.2.4 Diagnoses of Audit of the Building and Lending Protocols

Virtual models are useful instruments to develop energetic diagnoses or environmental audits to verify specific decay conditions. These evaluations can be related to the current conditions of the building or to future design configurations. It is indeed possible to simulate specific conditions, such as moisture concentrations close to a wall, ventilation, still air, or turbulences.

The definition of indoor microclimate through virtual modeling can aim as well at assuring the best conservation conditions to lend artifacts or artistic collections to other institutions. The virtual model, in fact, can demonstrate the specific characteristics of microclimate in relation to the places where the artifact will be exposed, which is important if the information is required in the lending protocols.

4.5.2.5 Project Configuration

Project configuration refers to architectonical, technological, or usage changes in the building, as planned in restoration or other interventions.

These kind of configurations refer to architectonical, technical, or usage changes as planned in the restorations or in other kind of interventions, with the aim of evaluating the effects on indoor microclimate of project strategies. The simulation allows to evaluate the effects of the restoration on the conservation of artifacts and comfort, as well as on energy efficiency, as described in Vieites et al. (2015) and Ascione et al. (2011).

4.5.2.6 Strategies to Preserve Artifacts and Outfitting

The virtual model of scenario zero (AIM) and of possible future scenarios can be used in heritage buildings, and in particular in museums, to evaluate permanent or temporary outfitting.

It is possible to simulate the values of variables in the model to evaluate if the places designed to host the artifacts present suitable conditions for the preservation of the objects, i.e., the conditions are in the tolerance range of that specific object and are not going to pose a risk of decay for them.

The evaluation of the results of simulations in each room can be used to define the strategies of conservation and exposition of artifacts, with three goals:

- *Screening*: The annual average, maximum, and minimum values are simulated, for one or more variables, in each room of the building. This way it can be considered whether the conditions in the room designed to host an object are within the conservation range for that object, in accord with scientific literature or with the standards.
- *Aimed*: Once the room has been chosen, simulations can be useful to define the outfitting, visitor's path, needs of the curator, and so on. Factors to be considered to define if the conditions are adequate for the preservation of artifacts are the expected length of the exposition, if temporary or permanent, the expected level of crowding, etc.
- *Check*: In rooms where artifacts experienced some kind of decay, or where the conditions are considered not adequate in terms of comfort, or if there are doubts on some climatic parameter (air speed, dust deposition, water vapor content, etc.) the virtual model allows to punctually verify the physical variables of the space.

4.5.2.7 Individuation of Evaluation Indexes for Heritage Building

Thanks to direct and indirect investigation and starting from physical variables, it is possible to elaborate indexes allowing to evaluate with a single value the quality of indoor microclimate. The use of a single indicator is useful to evaluate the differences between the current and future condition.

4.6 Conclusion

Concluding, the tools of direct and indirect investigation can give information driving the choices of who is in charge of managing the building and visits, insuring the conservation of the building itself and of the artifacts, as described in Chaps. 3 and 7.

But here it must be reminded that, before dealing with restoration of Historic Indoor Microcliamte, two subjects must be developed:

- The use of archival research in catalogues and surveys (geometrical, technological, related to plants), to study Historic Indoor Microclimate, including virtual environment modeling (Chap. 5).

- Elaboration of indexes for heritage building, following a multicriterial approach describing with a single index the complexity of the aspects related to the fruition and conservation of historical buildings and conserved artifacts. Conservation multicriterial indexes can be used to define usage protocols in “buisiness-as-usual” conditions in the building or in “ideal” conditions (Lucchi 2016), or for lending protocols (Chap. 6).

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Chapter 5
The Investigation

Leila Signorelli

Abstract This chapter focuses on how to approach HIM investigations starting from the study of AIM. Investigations are divided into two main groups: (1) *indirect investigations* (archive, bibliography, iconography, modeling tools) and (2) *direct investigations*, which include all the survey on the monument (metric survey, mapping of technical systems, project of AIM monitoring). The data collected through each kind of investigation must be interpreted to sketch a frame through which to state how HIM has changed over time and how it may have affected the historic building and the artifacts inside it (*e.g.,* furniture, paintings, frescos). All these data (metric, environmental, material) will be collected and synthesized in a following phase through 3D and environmental modeling. This kind of method is a rigorous process which ensures that interventions on historic buildings will be in line with its cultural value, including intangible one.

5.1 Indirect and Direct Investigation

The knowledge of historic buildings, intended as a coherent and profound analysis, is crucial to determine the attitude in approaching historical heritage (Fiorani 2009; Musso 2010). It is essential in order to be able to take decisions on interventions modifying, even slightly, the material or immaterial component of the building itself. Indeed, if used adequately, it is an efficient tool to obtain reliable answers from a building, in terms of conservation and performances/potentialities.

These investigations are not a simple collection of information, but should be calibrated for the specific case and be relevant in the research.

Salvatore Veca, in the introduction to the Italian edition of *Technics and Civilization,* by Lewis Mumford, states:

> I believe that science, techniques and culture are tiles of a same mosaic, pieces of a puzzle, with no discussion. Hence, we should look at the whole puzzle, adopting and keeping an holistic perspective.

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> Sostengo che scienza, tecnica e cultura sono le tessere di uno stesso mosaico, i pezzi distinti di uno stesso puzzle, punto e basta. Dovremmo allora guardare al puzzle, adottando e mantenendo una prospettiva olistica (Veca in Mumford 2005, p. 19).

The kind of research that is described in this chapter should be part of this wider image, of the puzzle to look at, in order to maintain a correct approach to the study of Historic Indoor Microclimate (HIM). The holistic perspective to keep during the research is necessary to achieve correct interpretations, and helps to look critically at the "parts" of the puzzle"—science, techniques, culture—with the goal of bringing in intuitions worth more than the mere sum of the observations.

Sources from which it is possible to acquire information useful to study microclimate can be divided into:

- *Indirect sources*: such as archival, iconographic, and bibliographic research.
- *Direct sources* (from the historic building itself): control survey, architectural survey, mapping of technical systems, indoor microclimate monitoring

The difference between the two depends on the relation between the researcher and the object of the research, i.e., the historical building. Indirect sources give knowledge through an intermediate mean, while direct sources come through a direct contact with the heritage.

In the following paragraphs the useful information to study HIM are listed in relation to the two different sources they can be obtained from.

5.2 Indirect Investigations

5.2.1 Archives

The term *archive* includes the whole of documents produced by an individual (a legal subject or, more extensively, an organization) during its activity and, with the same word, the physical place defined to conserve these documents, as part of an authority, the documents collected by a single subject or a National Central Institute. Based on the clear division of the sources given by experts (Van Nieuwenhuysen and Peyceré 2000; ISAD(G) 1999), information on microclimate can be found in:

- Government Offices and Other Organization

> A variety of government offices and other public or private institutions have architectural functions or hold architectural records. Some national, regional, or local government bodies, including departments of public works, urban planning offices, and bureaus responsible for classifying and maintaining historical buildings and monuments are directly responsible for architectural projects. Large municipalities often have building construction departments established to design and supervise building construction. Professional associations of architects also may hold architectural documents or influence the creation or preservation of these materials. (Van Nieuwenhuysen and Peyceré, p. 21)

- Architects’ Offices

> Archives of architects are rarely complete. The preservation of an architect’s records depends on many factors, including the course of his career and the degree of independence of his work. In general, architects have systematically retained records for legal purposes, to discharge their liability with regard to the construction of a building. Beyond this, attitudes and practices have varied widely. Few architects have subscribed to Le Corbusier’s belief that architectural records artistic value in themselves. In fact, many, like Belgian architect Victor Horta, have taken the opposite view: that only the constructed work is worthy of attention. (Van Nieuwenhuysen and Peyceré, p. 23)

- Contractors, Engineering Firms, Engineers

> Other records also may document the construction process. Even though builders existed long before architectural firms, few established meaningful archives which have survived them. On the other hand, firms involved with fine crafts have tended to preserve preliminary graphic documents. Detailed design drawings, some of which were produced by established artists, survive for some art glass and metalwork businesses, for example. Conversely, a masonry or plumbing contractor is not likely to attach much value to his archives beyond their practical use or the period of liability. Such records may well be destroyed. (Van Nieuwenhuysen and Peyceré, p. 24)

- Private archives of single people or families, associations, etc. (Lodolini 1997).

The archives to which to refer with respect to HIM must be chosen considering several characteristics of the building such as:

- *Property*, which can be public or private. Public buildings can be divided into other subcategories, such as military buildings, which usually have specific archives. Private buildings, on the contrary, have reports conserved more often by the owners.
- *Chronology* of the evolution of the building and of the interventions to modify, maintain, or restore it, which can orientate the research to find documents in current or historical archives, or in private documents of architects or suppliers
- *Provisions on safeguard,* which can be related to the building, with the possibility to find documents on the procedure to determine the provision

Once the archives to consult for the specific case are defined, the documents available regarding HIM must be found, which can be of different types:

- Graphic documents, such as project designs, surveys, and drawings of interventions, even if concerning only a part of the building
- Estimated metric calculations, technical specifications, relations, account tables of works, liquidations
- Personal documents, such as correspondence, or legal ones, as notary deeds and passages of property
- In the case of heritage interested by specific protections, due to historical and artistic value, such as preservation bodies (e.g., Soprintendenze Belle Arti e Paesaggio in Italy, Service de Monuments Historiques in France, Historic

England in England). These sources often conserve documents related to the procedure to include the building as protected heritage, among which are historic reports.

Based on the coupling of the data emerged from this phase of the archival research, some points must be clarified, with the goal of studying microclimate:

1. *The construction stages*: The documentation on the building phases (e.g., parts added, demolished, open areas becoming indoor) allows to read the transformations that influenced HIM. An example can be represented by a space that was initially exposed to the extern on many sides, around which new parts are built, or, as in the case of Villa Petraia (Chap. 9) the effects of the covering of the central courtyard, originally open, in order to obtain a hall. The study aims at interpreting how, in the different building phases, the microclimatic behavior of single spaces and of the whole building changed.
2. *Changes in the use*: Changes in the function of the building or of single rooms furthermore characterize point 1. Changes in the use can be associated to changes of property, an information that is usually found in legal acts. This can increase the precision of the temporal collocation of events with an influence on HIM. The study of internal distribution of functions has a similar role. To clarify how the change in destination of a single room can influence indoor microclimate, let's imagine the kitchen of an ancient mansion, where a huge hearth was releasing high amount of heat to cook food. This heat had for sure an influence on the nearby rooms, and if the kitchen is not used as such anymore, but is used as a storage room, both this specific room and the neighboring ones will suffer the effects of this change in their microclimate.
3. *Presence of heating systems, original or added*: The sequence and times of addition of technological systems to the architecture must be clarified. From archival documents it is possible to acquire information on the works done to add the systems (such as drawings of demolitions, insertion of pipes or cables) and to use the relative documents that might be conserved by the suppliers. Heating and other systems are relevant to understand the changes of HIM as an answer to the changes in the comfort needs of the inhabitants, which is one of the main reasons to add new technical systems, or to change them.

Here it is relevant to highlight that the "times of the machine" are different from those of the architecture. The rhythm of evolution of technical systems is often faster than that of the building that hosts them. Architecture follows its own "narrative line," parallel to that of the systems, determining a continuously changing interaction among them.

5.2.2 Iconographic and Bibliographic Research

Iconographic and bibliographic research concurs to add other pieces to the puzzle, completing aspects crucial to the study of HIM.

Iconographic research is the collection of images, as medals, paintings, pictures, etc., representing the building, both internally and externally.

Bibliographic research consists of the study of texts or librarian sources referring specifically to the building or the area it is placed. To these more relevant sources, others can be added regarding the information from literature on habits and uses of past times.

> Experience did teach not only that it is impossible to decide beforehand if apparently disinterested speculations will not reveal themselves incredibly fecund for practice.
>
> L'esperienza non ci ha soltanto insegnato che è impossibile decidere in anticipo se le speculazioni in apparenza più disinteressate non si riveleranno, un giorno, straordinariamente feconde nei confronti della pratica. (Bloch 2009, p. 13).

Data on daily life in past times can appear not very relevant, but, if coupled with the other data related to microclimate, can enrich and increase substance to the research, giving valuable information.

With this respect, in the study of indoor microclimate, researches can focus on the following:

- *Food habits:* Such information can be found in many images and reports of daily life in past times. A food code (Le Goff 2014) can constitute a source for different researches—historic, symbolic, etc.—as well as in the case debated here: the description of a banquet could give information on the food and on its thermal conditions. The cloche covering many dishes is often related to hygienic and service-related reasons (Flandrin and Montanari 1996; Montanari 1993), but it can as well indicate that the rooms through which that dish was passing were probably not heated.
- *Cloth description:* It can give lots of information on indoor microclimate conditions, from the amount and characteristics of the clothes needed by the inhabitants in the different seasons. Thanks to these observations it is possible to suppose a range of temperatures in the indoor spaces (Muzzarelli 2008, 2014).
- *Information on indoor and outdoor microclimatic conditions:* Literature can give information on years of particularly cold winters or of abnormal heat waves. As an example, many reports concern the exceptional cold wave that hit Europe in 1709, the so-called Great Frost, when the thermometers dropped even 30° below zero in many countries (Churchill 1938).

The interpolation of these data allows to indirectly delineate a picture of the conditions and uses of buildings and rooms in the different phases of their histories. Moreover, it allows to foresee the strong and weak points of the architectures, which are useful if the building is to be restored (Chap. 7).

Indirect investigations are needed to obtain all of the information above (e.g., chronology of the construction phases, changes in use, historic climatic conditions, indoor comfort levels), which would be verified through direct investigation.

It is as well possible that the information acquired is not sufficient to understand the evolution of HIM. The required documents might not be available, dispersed, or destroyed.

The phase of direct investigation, more extensively debated in the next paragraph, represents the verification of a correspondence between the material obtained through archival research and the current situation. But if these materials are lacking, partially or completely, the direct investigation becomes the main source of information, with the building becoming the most reliable documentation of itself (Docci and Maestri 2009; Musso 2010).

5.3 Direct Investigations

Direct investigation consists of surveys, verifications, and monitoring on the historical building itself.

To carry on direct investigations it is important to continuously correlate wide and specific perspectives: an analytical approach where a final synthesis acts as a control and verification of the methodology. It can be divided into main phases:

1. *Control survey*, or simple survey if other detailed designs are already known
2. *Mapping* of technical systems
3. *Monitoring* of actual indoor microclimate (AIM) using probes (Chaps. 2 and 3)

5.3.1 Geometric Survey

Control survey—or its check—is needed to understand the precise characteristics of the building. The mapping of technical systems is based on it as well as the modeling phase, which follows. The check consists of the comparison of the dimensions reported on the drawings found in the archives with the real ones. With this goal, only designs reporting length of room walls, diagonals, position of windows and doors, etc. must be used to compare the real measures. Instruments are: laser distance meter, measuring tapes, and sticks (Musso 2010), the latter useful as well as length reference in pictures. The survey itself uses the same tools, but has the goal of giving information useful to model graphically the building; hence it should be more accurate.

The geometric conformation, together with the technical constructive characteristics of the building, influences many microclimatic behaviors of the rooms: the proportion of windowed surface, the presence of skylights or glass coverings, the type of window fixtures, as well as the thickness of the walls are important information to give details to the modeling (Chap. 4).

In the graphic render of the survey, as well as the most common data (length, wideness, diagonals, heights), each room should be identified by a univocal number in the building, which will be useful in the following steps.

The code should include an identification of the floor where the room is (ground floor can be identified as “GF-. . .” or “0-. . .”) and a number following a logic in the floor, e.g., clockwise from the main entrance. The most detailed this phase is going to be, the most likely will be the interpretation of the data obtained from the modeling.

5.3.2 Mapping of Technical Systems

Technical systems are all the equipment included in the building along time, useful to guarantee comfort and livability to the building. Among these we remember heating, cooling, ventilation, illumination, and electricity. These can have undergone changes, stratification, and destruction in time, with technical innovations bringing new comfort needs. Today a house lacking heating in any of the rooms, or with toilets placed outside the building, probably appears unacceptable: the quality of Western lifestyle is nowadays incomparable to that of few decades ago, let alone the one peculiar to the historical architectures here described.

A map and survey of the technical system is important in the study of Historic Indoor Microclimate. This because it allows to know the type and location of the sources of energy or of humidity, which contribute to define indoor microclimate. Radiators or stoves imply a nonhomogeneous distribution of heat, as well as system of mechanic ventilation, or toilets have an effect on relative humidity.

The mapping of technical systems stratified in the architecture must be done with direct observation, systematically checking the building and writing down on an "*eidotipo*" (preliminary sketch), per each room, the placement of conditioning systems: hearths, flues, stoves, etc.

An "*eidotipo*" is a sketch on a working map on which other notes and relevant measures are reported. This can be done during the survey or prepared after the first survey. Through the observation of the operator, each of these technical elements must be surveyed for the dimensions and described through apposite record, where are reported:

- The code given to the room (e.g., GD-01)
- A navigator with the collocation of the room in the general design
- The detailed designs in an adequate scale (larger than 1:50) with the measures (map, perspective, and cross-section drawings)
- An adequate photographic documentation to comprehend the surveyed object nature
- A description of the last use of the room and, if possible, of the past ones, as well as the type of analyzed thermal exchange (e.g., direct radiation, recover of heat from the smokes).

Mapping and survey of technical systems constitute the basis from which to start transversal observations.

After the survey and organization of the data, these information must be reanalyzed, from a smaller to a bigger scale, giving order to the systems on the planimetry and grouping them based on the similarities that could suggest their common temporal origin.

The technical system must hence be divided into the following:

- *Historical technical system*, of which the temporal sequence must be determined. Thanks to this it is possible to reconstruct HIM and individuate its changes.
- *Current technical system*, with the specific devices and type of thermal exchange (e.g., radiating radiators, convective fan coils) and the changes in the building that have been necessary to install it. Current systems determine AIM, marking the difference with HIM.

5.3.3 HVAC Systems

Heating, ventilating, and air-conditioning (HVAC) systems are systems that allow to directly modify indoor microclimate of buildings. This acronym includes single heating systems, as fireplaces and stoves, or other systems typical of different historic times to heat or cool the spaces. Their position in the building and their effect on microclimate and, mainly, on the probes that will be placed in order to monitor indoor microclimate must be considered.

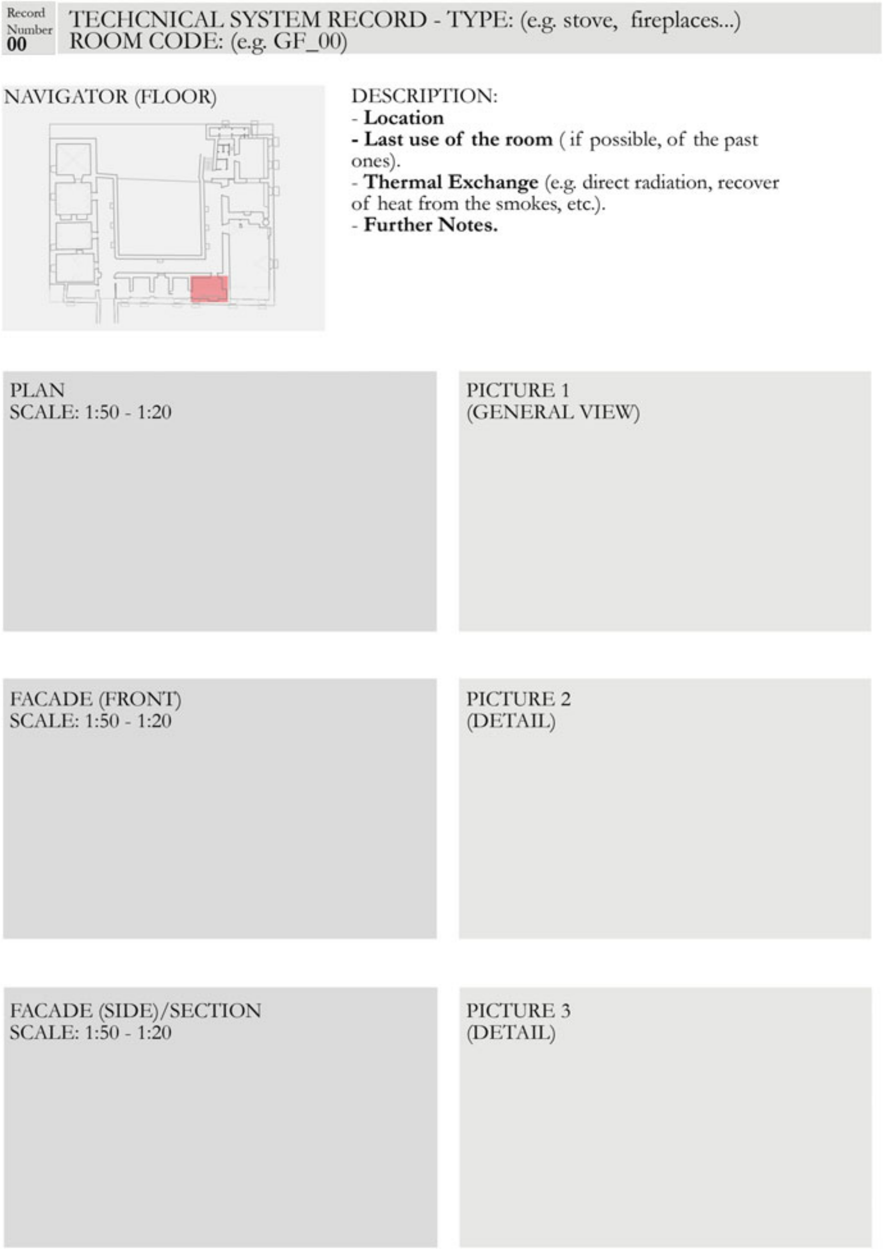
HVAC systems, when absent in the original conformation of the building, change indoor microclimate, introducing "*climatic stress*" conditions for the building and its artistic content (furniture, paintings, sculptures, frescoes, etc.). This was often due to the need to guarantee the fruition of historical buildings, of adequate comfort conditions for visitors, and most of the times the comfort of the building, originally planned as a "*machina*" to perform a specific function, is not taken into consideration.

Appears then a new concept of comfort, not only the one of visitors and workers, but also the comfort that tells of the effect of microclimatic transformations on the conservation of the cultural heritage, both as the container and content.

The monitoring of AIM follows this first investigation and must adapt itself to the normal fruition of the building, which includes often the use of HVAC systems. To this goal it might be useful to plan days with no HVAC systems working during the monitoring, in order to have data on indoor microclimate in the absence of HVAC systems.

5.3.4 Project of Monitoring of Actual Indoor Microclimate

The placement of probes to monitor indoor microclimatic conditions (Chap. 4) should be defined during the survey or even during the mapping phase. Indeed, the probes should be placed in relevant points to give reliable data, but as well they should not interfere with the normal activities of the building. In a museum, for example, they shouldn't be in the visitors' path; they should be easily accessible and not visible to the public.



Record Number **00**

TECHCNICAL SYSTEM RECORD - TYPE: (e.g. stove, fireplaces...)
ROOM CODE: (e.g. GF_00)

NAVIGATOR (FLOOR)

DESCRIPTION:
- **Location**
- **Last use of the room** (if possible, of the past ones).
- **Thermal Exchange** (e.g. direct radiation, recover of heat from the smokes, etc.).
- **Further Notes.**

PLAN
SCALE: 1:50 - 1:20

PICTURE 1
(GENERAL VIEW)

FACADE (FRONT)
SCALE: 1:50 - 1:20

PICTURE 2
(DETAIL)

FACADE (SIDE)/SECTION
SCALE: 1:50 - 1:20

PICTURE 3
(DETAIL)

Fig. 5.1 Example of a record for the mapping of technical systems. From above: identification of the technical system and its location (code and navigator), description of the unit. *Column left*: drawings (plan, facade, section). *Column right*: representative pictures

This is relevant on the one hand to avoid accidental movements or theft of the probes, but as well as, on the other hand, not to spoil the cultural heritage. It is suggested to define adequate surfaces to place the probes and to avoid to fix them to the walls, in order to limit as much as possible the consequences of a temporary intervention on the building itself.

The choice is influenced by different factors, such as the type of devices (e.g., the maximum distance among devices, their need of electricity) or the maintenance they require during the monitoring (e.g., change of batteries). Hence the position of the probes is an important aspect to plan, in consideration of the complexity of the involved factors (Fig. 5.1).

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Chapter 6
Buildings' Indoor Microclimate Quality (IMQ): Assessment and Certification

Giovanni Litti and Amaryllis Audenaert

Abstract Ensuring satisfactory indoor climate quality is a fundamental aspect of building management for both newly constructed and existing buildings. Moreover, as indoor microclimate quality (IMQ) plays a driving role in building energy consumptions and movable heritage preservation, its assessment and certification are fundamental in order to allow building control and optimization. In historic buildings, museums, or where indoor climate requirements should simultaneously satisfy people comfort and movable heritage safety, it is essential to propose assessment and certification methodologies capable of capturing the multidimensional nature of this management problem. Currently, a framework for guiding during IMQ assessment and certification, especially when different microclimate needs coexist, still lacks; this makes often the certification process inconsistent and arbitrary. In this contribution, after an overview on the collection microclimate management evolution, the critical aspects of the methodology to be taken into account during IMQ assessment and certification are discussed. Finally, an IMQ certification model is introduced.

6.1 Introduction

The main purpose of a building assessment or certification is to allow a structured evaluation of a given building performance, e.g., indoor climate performance and energy performance. The quantification of the distance between a current building performance and an ideal one as well as a trustworthy comparison between buildings can also be considered a practical advantage of building certification schemes; see Kalibatas et al. (2011, 2012).

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Moreover, not only can a building certification be supportive for external use, meaning the comparative assessment between two or more buildings, but also for internal one, meaning the regular performance assessment of a single building. Indeed, because buildings are intended to fulfil multiple performances, a certification process can be an important facility instrument for their management and control.

It is worth noting that, in this chapter, the terms assessment and certification are meant as a structured evaluation of one or more building performance, such as the indoor microclimate. However, conversely from the assessment, the certification process includes also the development and/or application of a model for delivering a synthetized metric expressing the quality of the assessed performance.

It is clear that certifications for building evaluation or management are more relevant when not limited to the assessment of one performance criteria but when extended to the set of the different performances the building is supposed to simultaneously satisfy. This is because performance effectiveness concerning one criteria can strongly conflict with one of another, proving the implicit multidimensional nature of building management (Medineckiene et al. 2014).

The potential mutual exclusivity of the several building performance requirements is widely discussed in the literature with respect to different optimization (or decision making) problems including, among others, indoor microclimate management (Zavadskas et al. 2015). Penna et al. (2014) highlighted the existing conflicts between people on thermal comfort and energy saving in a multi-objective optimization evaluation of retrofit alternatives for existing buildings; Camuffo and Chiara (2012) and La Gennusa et al. (2008) highlighted the conflicts between thermal comfort for users and artwork preservation; Yu and Tai Kim (2011) highlighted how the fulfilment of the airtightness requirement, according to the BREEAM certification scheme, would enhance the indoor concentration of pollutants as well as the risk of biological infestation in buildings.

Given the mentioned independency and potential conflict between concurrent aspects of building performance, it is advisable within any certification to adopt models capable of capturing this complexity. To allow this, the global building performance can be broken down into different (more controllable) performance indicators.

According to the scope of the assessment, different modeling approaches may be opted: multicriteria models consider simultaneously different assessment indicators, while single-criteria models consider only one indicator of performance per time. The first kind of method aims at providing a comprehensive building evaluation considering not directly comparable items, while the second one aims at providing a stand-alone performance certification of a specific building aspect.

Attention should be drawn to the use of stand-alone certifications with external comparative purposes as the certified item is often dependent on other ones excluded from the assessment. With this regard, the comparisons of buildings based only on energy performance might be inappropriate because of the exclusion of parameters still having a bearing on the building energy consumption. For instance, a comparison of different museum buildings only based on the Energy Performance Certificates (EPCs) is at risk to be inconsistent, as the energy consumption variation between the considered museums can be triggered by different indoor climate performance requirements and not necessarily by building-plant system inefficacies.

Therefore the need of providing a certification of the building indoor climate performance next to the energy one is unneglectable as clearly stressed by the EN 15251 (EN 15251). This imposes a mind-set shift in evaluating the building performance: from a single-objective to a multi-objective problem.

However, in specific circumstances, also the building indoor microclimate performance can be in its own a multi-objective problem. This occurs because of the diversity of the comfort aspects and subjects involved. Indeed, in case of historic buildings or wherever artifacts have to be preserved, the indoor climate quality should satisfy both: users' comfort and objects' microclimate safety.

The indoor microclimate performance certification for users and collections is discussed in this chapter together with methodological issues that might arise during its development due to the current lack of a coherent methodological framework.

6.2 Why a Microclimate Certification for Historic Buildings and Museums?

Indoor climate requirements in buildings affect energy consumption independently from the building performance itself; therefore an indoor climate certification is worthy being considered in both building control and optimization process.

In the specific case of historic buildings and museum, a microclimate certification, if iterated in time, can be a facilitating tool for identifying installation failures, improper user's behaviors, and risk of damage for collections and materials or it can be used as decision support during HVAC system design.

Moreover a certification, developed with the aim of delivering a real-time (and long-term) rendering of the microclimate comfort for building users and artifacts, can be a practical instrument for undertaking mitigation actions or immediately intervening in case of hazards. Below is reported a more detailed, though not exhaustive, list of milestones that a microclimate certification in historic buildings and museums can allow:

- Identification of people and collection microclimatic dissatisfaction or hazards (considering the specific building space requirements).
- Analysis (per building space) of hygrothermal needs overlaps between people and artworks for seeking at optimizing exhibition safety, building energy use, environmental emissions, and management running costs.
- Quantification of thermal satisfaction fraction that can be eventually allocated to minor building user's thermal adaptive behaviors.
- Assessment of building microclimate quality as a function of the HVAC schedule and operational costs.

- Identification of local microclimate failures possible to be solved by implementing passive or active air mass exchange between building spaces.
- Analysis of the environmental parameter interrelation and relative incidence on the overall microclimate satisfaction for undertaking target-specific improvement actions.
- Comparison of microclimatic quality between different buildings for facilitating (and making safer) artifact loan procedures.
- Optimization of the exhibition outline considering the relation: indoor building microclimatic conditions and artifact deterioration response factors.
- Assessment of museum institutions on common and comprehensive performance criteria.
- Definition of energy retrofit or renovation strategies according to a bottom-up strategy.

In the practice, a microclimate certification becomes meaningful only if the *assessment phase* is followed by the *action phase*, meaning that the labeling should not be the final aim of the certification process.

The first phase refers to the steps during which the building is scanned and a certification of microclimatic quality is obtained, while the second phase refers to the necessary set of actions to be implemented for correcting or mitigating the source of the potential microclimate problem.

The two phases can be either automatized by a control system or not. In any case, they should be iteratively undertaken for eventually rectifying occurred deviations from the expected microclimate ranges.

6.3 From a Single-Objective to a Multi-Objective Microclimate Management for Collections

The issue of managing microclimatic quality in historic buildings, especially in museum or where exhibitions or artifacts are housed, is still an open international scientific debate.

In the past (and often yet now) safe microclimate quality for artwork preservation was supposed to be achieved by tightly controlling the indoor hygrothermal fluctuations. Departures from aprioristically defined steady-state hygrothermal thresholds were not allowed. This praxis was undertaken regarding less to the specific building microclimate history or building geographic location. Also the economic and environmental running costs of such a microclimatic management were often disregarded. A microclimate management such as the mentioned one was characterized by a single-objective decision-making problem represented by the unique need of ensuring stable microclimate for collections.

However, the difficulty in the daily practice of such a microclimatic control, as well as the high running environmental costs and also the not always justified meaningfulness of a tightly controlled microclimate, resulted in the complete revision of the microclimate management approach for organic and hygroscopic objects. This new approach was introduced within the European standardisation by the EN 15757 (EN 15757).

Material deterioration has started being considered in function of the climatic conditions already experienced by the object. Thus, a material that has already experienced certain hygrothermal fluctuations is supposed not to further deteriorate if fluctuations lower than the past ones will occur. Therefore, the hygrothermal variability calculated on the basis of the historic climate for a specific building (or building space) can be, after the approval from a conservator, considered safe.

The EN 15757, admitting a dynamic physical interactions between building and collection rather than predetermining hygrothermal bounds, allows also to save energy and to contain the conflicts between hygrothermal requirements for material preservation and building users' thermal comfort. Evidently, the initial single-objective decision-making problem evolved into a multi-objective one. Indeed, objectives such as building energy consumption, microclimate safety for object conservation, and people thermal comfort have started being considered concurrent aspects of a unique, decision-making process.

However, despite the introduced temperature and relative humidity dynamicity, still conflicts between people and collections may rise especially with regard to building thermal comfort management.

6.4 Critical Aspects of Microclimate Certification for Historic Buildings and Museums

A multicriteria-based microclimate certification aims at delivering a representative image of indoor microclimate quality (IMQ), based on a set of criteria. Each one represents an aspect of the indoor climate in relation to both people and collections.

Considering that a certification procedure consists of two methodological phases, (1) certification model development and (2) preparatory data acquisition, the final results can be biased either by inappropriate model hypothesis and limitations or by inaccuracies during the data acquisition process.

Following the methodological order from an IMQ certification (for people and collections), theoretical and procedural issues emerging during data acquisition and model development are discussed in the following two sections.

It is worth noting that the following observations do not refer to a specific microclimate certification model, but rather to a general model. Indeed, although currently several microclimate assessment and certification models already exist, a robust methodology on the basis of which they should be developed still lacks.

6.4.1 Critical Aspects of Microclimate Certification for Historic Buildings and Museums: Preparatory Activities

The indoor microclimate certification of an existing building can be performed either on the basis of an onsite building environmental monitoring (instrumental or subjective) or on the basis of a calibrated dynamic building model simulation. The first option is here termed *instrumental (or subjective) measurement-based indoor microclimate certification* and the second one *simulation-based indoor microclimate certification*. It should be noted that building monitoring takes on a fundamental role in both the certification options and not only in the first one. Indeed, in the second option it is essential for allowing model calibration. However, a standardized procedure for monitoring the physical parameters to be inputted in the indoor microclimate certification model still lacks. This unavoidably results in dissimilar assumptions and undertakings during onsite measurement activities, especially when the certification is meant at providing an evaluation of people and collection indoor microclimate comfort and safety. Spatial and temporal representativeness and data resolution of the sampled parameters often differ from certification to certification, hindering a straightforward comparison of the results. A summary of the mentioned issues is listed at points (a) and (b) and discussed below.

(a) Temporal representativeness and resolution of the environmental monitoring for users and collections
(b) Spatial representativeness and resolution of the environmental monitoring for users and collections

As the environmental parameters are time-spatial dependent it is necessary to define the characteristics of the monitoring campaign in order to interpret the IMQ certification results.

With *temporal representativeness* the authors mean the monitoring period duration. This interval elucidates the temporal representativeness of the certification results but it does not necessarily coincide with it; indeed, a monitoring campaign can be longer than the period to which the certification refers.

With *temporal resolution* the authors mean the level of details (in time) of the acquired data, thus the sampling interval of the parameters. This might have an influence on the certification results especially if outliers occur; see later on in this section.

With *spatial representativeness* the authors mean the space representativeness of the measured building part in relation to the whole building.

With *spatial resolution* the authors mean the level of details (in the space) of the acquired data within the monitored space(s). An analysis of the spatial homogeneity of the hygrothermal patters might be supportive with this regard.

With the purpose of indoor microclimate assessment for collections made of hygroscopic materials, EN 15757 is largely applied (Vyhlidal et al. 2013; Silva and Henriques 2015). The standard does not propose predefined microclimate quality categories indicating levels of microclimate safety, but it rather suggests a methodology for defining the target microclimate on the basis of the building historic climate, which is obtained after a building environmental monitoring of minimum 1 year and 1 month with 60 min of minimum data resolution.

Next to issues related to the temporal representativeness when establishing the target microclimate on the basis of a short interval of the building historic climate (Litti and Audenaert 2016), issues with regard to the spatial representativeness should be evaluated if considering the EN 15757 for artifact indoor microclimate certification purposes.

By knowing that in historic buildings, the indoor microclimate may differ room by room, it might be worth to undertake a monitoring of all the climatically governable spaces in which objects are (or will be) kept. This approach maximizes the spatial representativeness of the measurements and allows to provide a *per-space* microclimate certification.

But, because the elements of a collection might be scattered in different points of the space, it might be necessary to deal with microclimate heterogeneities even into the same space (EN ISO 7726).

Theoretically the monitoring of the historic climate should be foreseen in vicinity of each object to be preserved. However, when more objects (with equal conservation state) are located in a building space, it is often considered to monitor room microclimate.

If the space is homogeneous, one measurement point in an undisturbed (possibly centered) position of the space or the averaging of the readings from different loggers located in the room might be a sufficiently accurate approach; but, if the space is heterogeneous, the option of averaging the readings from two (or more) parts of the room should be cautiously evaluated. Indeed, this praxis does not always offer a more accurate understanding of the indoor climate (due to the flattening of the microclimate heterogeneities). As an example, during the continuous monitoring of a room with well-mixed air mass, heat and vapor of a peripheral part dynamically interact (towards the equilibrium) with a more centered one. This interaction is registered if two loggers are located in both the spots. If peripheral environmental heterogeneities occur, the averaging of the readings from the two loggers would provide information about a climatic condition that does not exist in reality. Moreover, the calculation of the target microclimate based on this average would unduly result in a more permissive hygrothermal variability for the entire room even if departures from the environmental stability were registered only in one localized part of the space. Obviously what is above mentioned refers to parts of the monitored space where local environmental conditions constantly differ from the rest (due to, e.g., peculiar building geometry, orientation, building envelope deterioration, or specific architectonic features) rather than outliers caused by, e.g., temporary solar glare on the logger. If the peripheral areas evidence constant variation from the rest of the room space, it might be considered a separate certification and management of the parts.

With the purpose of indoor microclimate assessment and certification for building users, the EN 15251 is generally taken into account in the existing models.

However, the standards recalled in it do not provide complete information on the instrumental or subjective monitoring of temporal and spatial representativeness and resolution to be considered.

For the purpose of long-term certification, EN 15251 specifies that the environmental parameters should be measured for a whole year or for a representative interval of time within 95% of the building spaces or within representative building spaces. The double option offered by the standard in terms of temporal and spatial representativeness makes the certification praxis highly variable.

When considering a certification of the indoor climate based on subjective evaluation, the standard prescribes to obtain user's response for a representative number of times during the year within each representative space of the building. The term representativeness is never defined in the standard, neither in numerical terms nor in a theoretical definition. It is after all not surprising, as reported by Heinzerling et al. (2013), that current proposals for buildings' indoor climate certification (some of them based on EN 15251) consider monitoring periods ranging from 1 day to 5 years. Obviously, such results cannot be compared to each other even if developed on the basis of an identical certification model. The certification of a building thermal quality might differ if it has been calculated on 1-week measurements or on the whole heating season monitoring.

Furthermore, the standard does not specify how to deal with temporal data resolution; this is not a marginal problem as data acquired with different sampling intervals might bring to different certification results. For instance if calculating the weighting factors for certifying the thermal discomfort on the basis of the degree hours criteria (see method B, Annex F in EN 15251), the results can differ if room-operative or dry-bulb temperature has been sampled each 15 or 60 min and outliers have occurred. The occurrence of rare extreme events does not change the local climate but affects the average values (Camuffo 2013). If these average values are used for determining weights within a certification process, the result can be altered. The alteration of the certification results, when utilizing the degree hours long-term assessment method, can also be caused by an (un)intentional variation of the assessment time interval, as discussed by Nicol et al. (2009).

The issue of temporal representativeness and resolution is also relevant when certifying people environmental satisfaction on the basis of subjective evaluations based on regression models. Indeed datasets with low representativeness and resolution can cause a large part of the variance not to be explained, meaning not robust certification results.

With regard to the spatial resolution, EN 15251 and the quoted EN ISO 7726 do not give information on the appropriate monitoring instrument location, despite their importance within the measurement process (Camuffo 2013).

Spatial resolution is a relevant issue also when considering a simulation-based microclimate certification. Indeed, building dynamic simulation software solutions simulate the physical parameters of a space, as the mean value of that space. Possible microclimate heterogeneities existing in the reality are thus neglected. The onsite measurement, aimed at registering the environmental parameters to be utilized for a further building model calibration, should be planned in coherence with the calculation and visualization capabilities of the used software.

To measure room air temperature with a data logger in contact with a wall is not only methodologically wrong in itself—because the obtained data might be biased by local boundary conditions, for instance absorption or evaporation of the wall itself (Litti et al. 2015)—but it is also misleading if the building model is supposed to be calibrated on that data.

6.4.2 *Critical Aspects of Microclimate Certification for Historic Buildings and Museums: Certification Model Development*

Next to inaccurate methodological undertakings during the data acquisition process, also assumptions within the certification model development may affect the reliability of the results. The potential sources of inaccuracy, discussed below, are (a) model design and criteria selection, (b) weighing procedure, and (c) aggregation procedure.

(a) Model design and criteria selection

As already mentioned elsewhere in the chapter, microclimate certification models are structured into a family of criteria where each of them responds to a specific aspect of the microclimate certification. The set of criteria should answer exhaustively to the certification problem without being redundant and incoherent with the certification object. The criteria for an indoor microclimate certification model can be either aggregated indexes of performance derived from existing comfort models, such as predicted mean vote and percentage of people dissatisfied or physical attributes, such as operative temperature, relative humidity, CO_2 concentration, and illuminance. Although no limitations are advisable in the concurrent use of aggregated index of performance and physical attributes, the use of physical attributes should be avoided both as single criteria and within aggregated indexes since by doing so the requirement of no-redundancy might be violated.

Moreover, when selecting the criteria for long-term indoor microclimate certification, it can be practical to consider indicators that relate a given criterion occurrence to a time interval (such as percentage inside or outside the range) instead of considering criteria mean values. However if the frequency of performance is linked to performance categories, the model function is characterized by discontinuities.

If the model is meant to deliver a single score, the use of averaged physical attributes should be discouraged. Indeed the certification based on average values does not provide any meaningful understanding of the microclimate quality. This is because the simple mathematical averaging flattens the dataset. Consequentially, a certain space with high upper and lower, say, temperature fluctuations, might obtain identical marginal value as another one with more constant temperature.

Furthermore, if the marginal value of each criterion is supposed to be aggregated, the final score is unavoidably biased, especially if a (high) weight is attached to the biased criterion.

It is worth noting that in case of simultaneous certification for people and artifacts, although the certification results are generally delivered with regard to the same reference time period for both, the time standardization is based on two separate time intervals: the occupation time and the entire reference time period for people and artifacts, respectively. The reference time period should be declared as well as the start and the end of the considered warm and cold periods (if discretization of the criteria for thermal assessment is considered); doing differently can lead to unclear certification results (Nicol et al. 2009; Carlucci 2013).

(b) Weighing procedure

Another significant issue to take into account when developing a certification model is the methodology for the priority selection. In the specific decision context, two steps of weighing can be identified: in the first one, the priorities for balancing between people and collection comfort needs (generally hygrothermal comfort) are set and in the second one the importance for each criterion (in which the certification object is subdivided) is agreed.

The first weighing stage, although highly significant, is the one with higher risk of uncertainty. The weighing at this stage can be performed on the basis of *risk assessment* or *panel of experts* (PoE).

In the second weighing stage, each criterion within the certification domain (both for collections and people) is weighted by means of *panel of experts* (PoE) or regression analysis techniques. With regard to the environmental criteria prioritization for people, the following should be considered:

- b.1 The marginal importance attributed to each criterion of indoor comfort sensation is personal and not always constant. This varies on the basis of, among others, building location, typology of activity, time permanence in the space, clothing thermal resistance, etc. Whenever possible, these weights should be based on infield subjective or experimental investigation results rather than on experts' judgment.
- b.2 Despite that fact that methodologies have been developed for reducing the uncertainty during the prioritization procedure within a panel of experts (Kim 2010), issues such as number of participants and affiliation, professional experience on the specific management topic, possible conflict of interests or independency from the decision-making process, etc. should be clarified as they are not trivial aspects that can bias the weights.
- b.3 When defining the weights on the basis of statistic models, such as regression models, principal component analysis, and factorial analysis, the observations with regard to onsite subjective or instrumental monitoring time and spatial representativeness and resolution should be taken into account.

The prioritization process of the environmental criteria concurring in the definition of the object safety can be based on experimental data. The analysis of the material response factor at different environmental conditions can be considered a good praxis for establishing the weights.

(c) Aggregation procedures

Another issue to consider when developing a microclimate certification model is the aggregation of the criteria scores. The score aggregation, according to the certification aims, can be considered in two (not compulsory) steps as listed at points c.1 and c.2 and below discussed.

- c.1 Aggregation of the single microclimate criteria scores into a synthetic certification score
- c.2 Aggregation of the certification scores from each building space into a global building score

The aggregation mentioned at point c.1 refers to the models deemed to provide a final labeling of the global quality by combining the marginal criteria scores. This aggregation can be supportive for rapidly scrutinizing, e.g., the indoor climate quality of a space and calling for more detailed investigations only if a defined threshold value is surpassed (this operation implies performance threshold definition). The inherent problem of such a model is the implicit interchangeability of the criteria, meaning that if a given criterion gains a low score and another gains a high score, the final result flattens the specific score contribution. This weakness can be solved, as in multi-attribute utility theory (MAUT), either by tuning the weights for each criterion or by providing next to the global score a breakdown of the single criterion score.

Another aggregation possibility, mentioned at point c.2, refers to the certification of a whole building on the basis of the aggregation of each single space score. Methodologies for allowing this aggregation are given in Annex I, EN 15251.

However, there exists a remarkable difference of points of view with regard to this aggregation, meaning that standardization of the comfort sensation at a building scale, before being a matter of the certification models, is a theoretical concern. The fundamental problem is this: "*How the comfort (or discomfort) quality expressed with regard to each space should be averaged for obtaining the comfort quality of a whole building?*" The current methodologies propose a weighted average based on either the space geometry (first approach) or the space occupancy (second approach).

The first approach considers that each space score should be averaged and weighted in function of the net surface (or volume) of the space, while the latter considers that the single space score should be weighted in function of the given occupancy rate. In other words, the first approach relies on the fact that the bigger is the certified space, the larger should be its influence on the total building certification, while the second approach relies on the fact that the more occupied is the certified space, the larger should be its influence on the total building certification score. Limitations within both the methodologies can be highlighted.

The first aggregation method implies that the certification of small spaces, even when highly occupied (or with several objects to be preserved), is less meaningful than the one of big ones. At the same time, the second aggregation method implies that the certification of less occupied spaces (although big and with several artifacts) is less significant than the one of highly occupied spaces. Moreover, another issue with regard to the second aggregation approach should be pointed out.

If the certification is developed on comfort criteria indexes based on mean (dis) comfort percentages, it might occur that the given comfort score does not represent the actual occupant comfort sensation; this inconsistency (if the second weighing approach is opted) is amplified in spaces with high occupancy rate.

In the author's opinion, it might be worth to consider a weight in function of the occupancy if the certification is based only on infield subjective evaluations as in this case it is possible to account for the actual score variance.

Another point to be considered in the aggregation process is how the certification with regard to the artifacts should be integrated into the aggregation function. As the process of aggregation implies a clear understanding of where the comfort sensation should be allocated (to occupants or to building spaces?), this process becomes even more tough if considering also the artifacts within the certification domain.

When considering an aggregation procedure also including the artifacts, the question becomes this: *"Which weighing process is more indicated for them? Amount of objects per room? Object importance? Object sensitivity to the microclimate variability?"* The answer is not straightforward as there might be a risk of simplifications that brings to nonconservative microclimate management that should be avoided.

In view of the observations above, it might be worth to introduce, instead of a weighted average of the spaces score, a graph (such as a radar) which allows to show the distribution of the score variability for the entire building. However, if a single value for the entire building needs to be compulsorily provided, the simple average (without weights) of all the space score with an indication of the deviation from the mean as well as the best and worst score might be preferable. A table providing the specific results for each space should also be provided.

6.5 Simultaneous Indoor Microclimatic Certification for People and Artifacts

In this section a proposal to simultaneously certify the indoor microclimate quality (IMQ) will be briefly introduced with regard to both people and movable heritage. With movable heritage, the authors mean either single objects from a collection or artifacts integrated into the building components (frescos, painted surfaces, etc.).

An applied example of the discussed certification model is given in Chap. 11.

The proposed model is developed on the principle of comfort neutrality for people and for objects (meaning non-harmful microclimate for the latter). Comfort neutrality is considered the optimal microclimate conditions to be maintained. This condition is numerically represented by zero; therefore any positive or negative deviation from it is indicated with a (symmetrical) stepwise numerical and linguistic alteration, such as good conditions (±1), moderate conditions (±2), and unacceptable conditions (±3). If the hygrothermal quality of a space is evaluated with a final score zero, it means that the environmental readings in that space were registered into the neutral and non-harmful region.

The criteria included in the model refer to percentage inside the ranges. This allows to verify with regard to each assessment criterion, for people ($\mathrm{IMQ}_{(P)}$) and movable heritage ($\mathrm{IMQ}_{(H)}$), the cumulated time frequency of each criterion ($\varphi_{(k)}$) in the category intervals; see (6.2):

$$\mathrm{IMQ}_{(H,P)} = \sum_{k_i=1}^{n} \varphi_{(k_i)} \text{ where } \begin{cases} \varphi_{(k)} \leq \mathrm{Cat}_{(\partial)} \text{ upper limit} \\ \varphi_{(k)} \geq \mathrm{Cat}_{(\partial)} \text{ lower limit} \end{cases} \tag{6.1}$$

It is worth mentioning that the assessment criteria and their category intervals should not be seen as characteristic of the certification model but of the specific assessment problem.

In the first certification step, two dimensionless time frequency matrices, for people ($T_{(P)}$) and heritage ($T_{(H)}$), are built considering, respectively, the frequency of time during which the (${\varphi^{\text{th}}}_{(P)}$) or (${\varphi^{\text{th}}}_{(H)}$) criterion (in rows) falls in the (∂^{th}) category interval (in column) as calculated by Eq. (6.1):

$$T_{(\alpha)} = \begin{bmatrix} t_{1,1} \ldots t_{1,\partial} \ldots t_{1,n} \\ \vdots \\ t_{\varphi,1} \ldots t_{\varphi,\partial} \ldots t_{\varphi,n} \\ \vdots \\ t_{m,1} \ldots t_{m,\partial} \ldots t_{\varphi,\partial} \end{bmatrix} \quad \varphi = \overline{1,m} \quad \partial = \overline{1,n} \tag{6.2}$$

where (α) refers, respectively, to people (P) or movable heritage (H); (m) refers to number of (φ) criteria; and (n) refers to number of (∂) category intervals. In this study ($m_{(P)} = 1$), ($m_{(H)} = 2$), while ($n = 7$).

The magnitude of the microclimate deviations from the neutral comfort is expressed by a stepwise numerical perturbation of 0. With the purpose of expressing this magnitude, the vector (β) is introduced. The incidence vector (β) is a (7×1) matrix, with elements ranging from $\{-3,\ldots,+3\}$. Nota bene, in this study symmetrical importance is given to upper and lower deviations; however a weighted or asymmetrical incidence might be considered according to the specific building and collection requirements.

In the second step of the certification, the incidence matrices for heritage ($P_{(H)}$), and people ($P_{(P)}$), are calculated as the product of the time frequency matrices, ($T_{(H)}$), or ($T_{(P)}$), and the perturbation (β) vector, considering its elements in absolute value. The result is a ($m \times 1$) matrix describing, for each considered criterion, the severity of deviation from the microclimate neutrality. Therefore, the severity of the deviations is evaluated by the product of the deviation time frequency (time frequency matrix) and the deviation magnitude (perturbation vector); see Eqs. (6.3) and (6.4):

$$\left(P_{(H)}\right) = \left(T_{(H)}\right) \cdot (\beta) \tag{6.3}$$

$$\left(P_{(P)}\right) = \left(T_{(P)}\right) \cdot (\beta) \tag{6.4}$$

Because the different aspects of the indoor climate may play a different role in the global comfort perception and even more in the hygroscopic material deterioration, see EN 15757, it should be considered their weighing.

In the third step of the certification, the weighted incidence matrices for people $\left(\overline{P_{(P)}}\right)$ and heritage $\left(\overline{P_{(H)}}\right)$ are calculated as the product of the transposed incidence matrices, $(P_{(P)})^T$ and $(P_{(H)})^T$ the theoretical weighting vector $\{\overline{\varpi}_P\}$ or $\{\overline{\varpi}_H\}$. See Eqs. (6.5) and (6.6):

$$\left(\overline{P_P}\right) = (P_P)^T \cdot (\overline{\varpi}_P) \quad (m = 1) \tag{6.5}$$

$$\left(\overline{P_H}\right) = (P_H)^T \cdot (\overline{\varpi}_H) \quad (m = 2) \tag{6.6}$$

The results of the matrices can be interpreted as single scores for each microclimate criteria representing the current performance with regard to people or heritage, considering at the same time the severity of the occurred deviations and the importance of the single involved environmental criterion.

Finally, by bearing in mind the drawbacks of the aggregation processes, a simultaneous index of performance (simultaneous performance index—SPI) can be calculated for each building space in order to deliver a complete picture of the current microclimate quality with regard to movable heritage and building users; see Eq. (6.7):

$$\mathrm{SPI} = \frac{\sum_{m=1}^{n} \overline{P_{(H,P)}}}{\sum m} \quad (m = 3) \tag{6.7}$$

where m is the number of criteria considered with regard to both heritage and people. At this point, an adjunctive weighing process, for distinguishing the importance between heritage and people comfort according to the space requirements, may be introduced. As above mentioned, the optimal microclimate quality coincides with the microclimate neutrality (0). The obtained SPI, other than 0, represents the deviation from the optimal microclimate comfort. The calculation of SPI in case of spatial heterogeneity or in case of aggregation for a single building should follow the observations discussed in this paragraph.

6.6 Conclusions

Given the implicit relationship between building indoor climate and other aspects of the building management, microclimate certification can be an essential control instrument especially in historic buildings, museums, or where different indoor climate requirements should be simultaneously satisfied.

However, even if numerous models for assessing people indoor climate comfort exist, there is still lack of models that allow a simultaneous microclimate quality certification for movable heritage and building users making tedious the process of indoor microclimate control and optimization in heritage buildings and museums. Moreover, a consistent framework to follow while simultaneously monitoring the microclimate quality for collection and people does not yet exist leaving unaddressed fundamental methodological problems.

An analysis of the methodological aspects to consider during microclimate monitoring and certification model development as well as a proposal for indoor microclimate quality certification for people and artifacts have been addressed in this chapter.

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Chapter 7
Design Criteria and Strategies

Marco Pretelli

Abstract This chapter is dedicated to three aspects of HIM research. First of all, an analysis of the great step forward in the microclimatic functions of architectures, between the eighteenth and the nineteenth centuries. This is at the basis of the conflicts that more and more often we see between physical architectures and their microclimate, which end up into slow but inexorable decay of buildings. Second, the nature of these phenomena, due to the imposition of an inadequate microclimate to a building, with an adequate support of literature. In the third and final part, strategies and interventions to reduce the risk of decay are presented along with evaluation criteria to intervene on historic indoor microclimate when this is needed.

As has been demonstrated in the past chapters, the study of HIM and its correlates, OIM, SIM, and AIM (Chap. 3), finds its place at the conjunction of different researches, from the purely historical ones (history of civilization, of life conditions inside buildings, etc.) to those linked to applied restoration (which starts from historical and physiochemical analyses to define strategies and interventions to preserve the architecture) and to the most practical ones (such as building physics, which studies indoor microclimate to get useful information to improve modern design of HVAC systems).

The main interest of this research is as follows:

1. The possibility to understand causes and decay phenomena from the materials of architecture along with history itself
2. The capability to individuate, through indoor microclimate analysis, strategies to restore in advance buildings, in order to avoid other, more invasive, restoration works in the future
3. The reduction of risks for the conservation of the buildings due to HVAC systems, which modify indoor microclimate of architectures and exclude the ideal microclimate of the specific architecture

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In this chapter we try to focus on these subjects, defining the most appropriate approach and strategies to deal with indoor microclimate of historic buildings. This will start from the description of the main approach that prevailed for thousand years in determining a specific microclimate.

7.1 How to Create a Particular Microclimate (in Past Times, and Now)

Before the introduction of modern heating and cooling systems, indoor microclimate was intrinsically correlated to the architectures and not a characteristic indifferently attached to any building. In it, the most physical part of a building, walls and ceilings, and the physical one, represented by energetic flows, interacted. Only the intertwining of the two phenomena constituted the architecture. It was a factor planned along with the foundations, walls, ceilings, etc., as each of these elements contributed to determine the specific indoor microclimate.

In the many essays on architecture published in Europe between the end of Middle Age and the start of the Industrial Revolution, indoor microclimate was one of the aspects considered in the indications on how to design new buildings. Not only specific materials were indicated to obtain some specific microclimatic conditions, but also the orientation of the rooms was considered, as well as the relation with the ground (ground floor for summer spaces, higher ones for winter quarters, etc.) and some other tricks was given, to influence indoor air temperature and humidity straight with the design of houses.

Architecture was designed and realized to assure specific indoor microclimatic performances (Litchfield 1991; Pretelli and Fabbri 2016a, b; and, in this volume, the cases presented in Chaps. 8, 9, and 10). In Tuscany, the Cascina di Tavola represents a clear example. Placed today between the municipality of Prato and the one of Poggio a Caiano (Foster 1992), this extraordinary building has been planned to accomplish the desire of Lorenzo de' Medici, the Magnificent, to import in Tuscany the know-how of Lombard cheese makers, as Lombard cheese was considered of higher quality. The complex was supposed to recreate the whole cheese production cycle, starting from cattle raising, the beasts coming from areas close to Milan, to milk conservation and manufacturing, which requires specific microclimatic conditions. The correspondence between the Magnificent and his ministry plenipotentiary for this project, Antonio Marchetti, shows how much attention both of them paid to the microclimatic characteristics of these buildings, inspired by the Lombard *cascina*. Many of their observations were based on *Liber ruralium commodium* from Piero de' Crescenzi and to the descriptions of farms that Francesco di Giorgio Martini gave in his essay from 1478 (di Giorgio Martini, 1478, edition 1967). To conserve milk and produce cheese, it is necessary to assure conditions of temperature and humidity as constant as possible, in any season. This is why a ditch had been dung around the complex and many rooms were built close to it, in the basement: despite the difficulty of making waterproof walls and to manage the ditch, microclimate was held constant in the “lattaia,” “caciaja,” “lattaia per l’inverno,” and “luogo dove si cuoce jl cacio” (respectively, the place to store milk, cheese, a special room to conserve milk during winter, and the room to cook cheese, as they are labeled in the drawings).

Besides the already mentioned essays, further interesting information come from *L’Architettura*, written by Leon Battista Alberti in the mid-fifteenth century, where he describes a rustic villa (Alberti 1485-edition 1966), as well as from many other texts that, from the Renaissance to the eighteenth century, deal with this subject.

All these sources highlight that specific indoor microclimate characteristics can be obtained only if this is pursued right from the beginning of the designing process, when the place for the new building is chosen. L. B. Alberti (Alberti 1485, Book V) is particularly clear on this, as well as Francesco Milizia (Milizia 1785, edition 1991, second volume pp. 12–23), who dedicated chapters II, III, IV, and V, second volume, to the conditions to obtain the most adequate microclimate for each building and their rooms. The author suggests to adopt technical solutions to improve environmental characteristics, which we would nowadays call microclimatic, depending on outdoor conditions (p. 35) and on ventilation and illumination (pp. 72–74).

All the parts of the buildings are described, including the characteristics of the main and “ignobili” (secondary, dedicated to the movement of supplies, being the mean dedicated to arrival of people and guests) courtyards. These must be open to wind and sun (pp. 79–81), as much as stables and coach houses must have a specific orientation (for the sun not to ruin carriages) and of all the other areas of the building. The *Princìpi di Architettura Civile* (principia of civil architecture) are one of the clearest instruments to understand the relation that linked microclimate and architecture.

A holistic conception of architecture emerges from these essays, where all the parts contribute to shape a single, unitary result in the building, unique as the product of those specific shape, materials, place, etc.

The specific microclimate constituted one of the most relevant characteristics of each building, quite an immaterial one but nonetheless highly considered while developing the design.

The very same concept of HVAC system, which in here would be a proto-system as illustrated in Fabbri et al. (2013) and Fiorani (2001), in its different declination (hydraulic, thermal, ventilation, illumination), was already known, but its contribution to indoor microclimate was only limited, being only able to establish a synergic collaboration with the building.

Another relevant aspect of indoor microclimate is its mutability. Microclimate is subject to consistent variations that can depend on the introduction of new heating or other systems (i.e., intervention specifically aiming at changing microclimate), or on modifications in any of the many aspects of architecture that influence its microclimate (composition of ceilings and walls, presence of windows, etc., i.e., interventions changing microclimate only as a by-product). Each of these interventions influence the indoor microclimate of what formally remains the very same building.

The main effects of Industrial Revolution on indoor microclimate are not only the development of new HVAC systems, but also their distribution and the growing interdependence between architectonic complex and HVAC systems, which has lately become complete.

OIM (original indoor microclimate) is described as the characteristic indoor microclimate of an architecture at the time it was built. This value is not only relevant as part of the history of the building: it represents a starting point to determine the best conservation conditions of its architecture. It is a fundamental information to define the best indoor microclimate that allows to preserve the building itself and, as such, it must be kept into adequate consideration, mainly if systems to influence indoor microclimate are to be built.

7.2 Decay Due to Indoor Microclimate Changes. Origin of the Phenomena and Effects on Historic Architecture

Scientific literature of restoration knows nowadays quite clearly the risks of changing indoor microclimate of historic buildings, mainly if the change is brought by HVAC systems indiscriminately introduced, as was commonly happening up to few years ago. On the contrary, scientific literature focusing on HVAC systems has these risks much less clear.

Mario Piana (Piana 2001) is the professor of building restoration and designer of relevant interventions on historic buildings. He reports several specific cases of damages in old buildings due to changes in indoor microclimate, with the goal of explaining the best strategies to reduce the impact of new systems being introduced.

Among these, there is the *Church of San Samuele* in Venice. From the microclimate analyses preliminary to the restoration, the effect of the heating system appeared clear. When it was switched on, during mass, indoor microclimate was varying incredibly fast, with an instantaneous fall of relative humidity and increase of indoor temperature. These fast daily changes repeated for decades had led to a consistent decay of the frescoes in the apse, because the indoor air, becoming relatively much drier than the walls, was increasing the phenomenon of water migration within the wall itself, which brings substances leading to the formation of saline excrescences on the frescoed surface.

In the *Church of Santa Maria dei Miracoli*, again in Venice, similar effects of saline efflorescence due to the heating system led to the detachment of the pavonazzetto marble sheet (a prestigious material imported from ancient Asia Minor, now Turkey) covering the internal walls of the church. To solve the problem coherently with the microclimatic data recorded, the designer of the restoration project chose to remove the heating system, going back to a microclimatic situation substantially similar to the original one (OIM), apart from macroclimatic changes (Behringer 2010).

Mario Piana illustrates a vast record of damages connected to changes in indoor microclimate of historic architecture with respect to buildings mainly located in

North Eastern Italy, but these can exemplify the cases of most European architecture.

Among the effects he focuses on, there is the movement of particulate powders connected to radiators and lamps, such as incandescent or halogen (while with new LED lamps the problem is going to be substantially reduced). These powders deposit on walls and ceilings near and above the devices, staining them on the long term. This is one of the most evident effects of the presence of these systems, and it might not become a serious damage as long as it doesn't affect frescoes, plasters, or decorations. But if the particulate is rich in dangerous pollutant, as often happens in industrialized regions, delicate materials can suffer heavily from this phenomenon.

In old buildings, damages more relevant than this can be linked to heating or other systems, even with dangerous consequences. As in the exempla reported above, many problems are connected to water migration, rising within the walls from the fundaments, which are in contact with the ground and the water in it, whether it comes from superficial reserves, rain accumulation, leaks in pipes, or sewage. Water present in the walls evaporates in the rooms with a rate inversely proportional to the relative humidity within the rooms (this is why when heating systems reduce relative humidity this problem increases), with consequent appearance of saline efflorescence.

Wood parts are damaged when their water content decreases below tolerance limit: gaps can appear on windows and doors or fractures and deformations can damage beams and planks until their resistance is compromised.

Frescoes and plasters can be seriously damaged or can even detach from their support if this is represented by a wooden ceiling. Centine and cannucciati can change dimension or be attacked by biological threats because of inadequate humidity levels and this can cause the detachment of the decorations.

A further risk is connected to the difference in temperature between internal and external parts of the building. In this case it can happen that oxides forming on metals transfer to the plasters and stain them, but as well as the stability of the building can be compromised. Indeed, chains and metal tie rods, that have high thermal conductivity, tend to have in their extremities a temperature closer to the external one, with which they are in contact through punches, with consequent formation of dew on these parts and hence oxidation. This causes an increase in the section of the metal, which stretches the materials around it; on the contrary, the resistant section is reduced. In extreme cases, this can become so small that the tie rods stop accomplishing their function at all.

These last phenomena can happen in many different kind of buildings, even those very different from the European tradition. Sharon C. Park (Park 2004), in the US Government's Official Guidelines for Preserving Historic Homes, recommends care when adding new systems to North American traditional houses, mainly because of disequilibria between internal and external temperature and humidity. For example, an increase in indoor humidity and its migration through the walls cause many problems: "moisture migration through walls can cause the corrosion of metal anchors, angles, nails or wire lath," as it was happening in the cases reported by Mario Piana. As far as efflorescence is concerned, North American architecture presents analogous problems to the European one, e.g., saline deposits on surfaces, mainly brick ones, that can go to the extent of endangering the whole structure or appearance of blisters or peeling in the external painting cover, especially where the superficial details are less permeable than the wall (i.e., oil paintings; Weeks and Look 2004). Moreover, the freeze-thaw cycle that typically, in cold climates, interests the water present within the walls and close to the surface can cause relevant damages to external surfaces, especially if they are thin, as Park states (Park 2004).

It is evident that these problems are linked to the functioning of the systems controlling indoor microclimate, but their installation is no lesser source of problems. Tracing distribution networks, placing electric, hydraulic, and thermohydraulic pipelines requires trenching, cutting, opening gaps, holes, and lacerations in the structure of the building, which can end up having an effect on the supporting structures and compromising the stability of the architecture. These problems are due to lack of care when the relevant systems are installed, as it would be quite easy to avoid them in many cases.

What often happens is that inadequate microclimatic conditions due to the functioning of system cause more serious decay on the long term than the works to install the systems. This kind of decay is usually harder to recover, as it causes profound and widespread alterations mainly in wood, which is one of the main building materials in historic architecture, but as well as in apparently less sensitive materials, such as mortar, plasters, bricks, stones, and metals. The long span of time in which this decay develops makes it harder to perceive or, lacking the perception of the problem and misinterpreting the visual clues, it might be interpreted as physiologic decay of an old building.

Only a long-term, in-depth, and well-aimed analysis of indoor microclimate (Chaps. 4 and 6), including a monitoring campaign, interpretation of data, and development of hypotheses on the evolution of the problem along the life of the building, can help interpret correctly these phenomena.

7.3 The Goals and the Tools (for Interventions Aiming at Modifying Indoor Microclimate in Historic Architectures)

A premise to the following paragraph is that any restoration on a historic architecture must aim at defining and preserving the specific values of the object of the restoration.

The studies on historic, archival, and iconographic bases, those based on the building itself (Chap. 5) and determining its physical, material, and immaterial elements (among the last ones would be erroneously included indoor microclimate), all have a single goal: to help the designer to define the most adequate strategy to assure the conservation of the building it works on. The materiality of it is the unique and irreplaceable vector of any value recollected in the architecture.

Consequently, HIM acquires a second relevance, as it depends strictly on the materiality of the building:

A. It constitutes one of the values of the building, as it represents a relevant facies among those that the building carries.
B. It is a fundamental corpus of information to understand the architecture itself and assure its conservation.

It is evident that the task of the designer is not limited to the preservation of the materiality of the building. Indeed, to assure a socially recognized function to the architecture, it is necessary to associate the planning of new functions for the building to these interventions.

Usage and fruition of architecture are intertwined in an architecture, as the finances and attention to restore and maintain the building are assured only if an adequate value is given to its use.

When giving a new function to an architecture, the overall intervention program determined by this choice must undergo a control, and be judged in order to assure its compatibility with the building (Palmerio 2001; Shopsin 1986). The designer is supposed to evaluate the impact of the technical proposal to recover the specific architecture, besides developing the design itself.

He is supposed to evaluate the compatibility of the intervention program with the effective conservation of the architecture. In this, a relevant weight must be given to the impact of HVAC systems, concerning both its installation and the effects of its functioning on the building. It is evident that the requirements of the systems must be reduced by limiting their impact or excluding some needs, e.g., avoiding to use air as energy vector or summer conditioning systems (Park 2004).

The insertion of HVAC systems should be always intended as a supplementary addiction to the historic substrate and have the goal of reducing as much as possible any risk for the preexisting building.

This could appear a redundant observation, as restoration is obviously intended to preserve a building, but it becomes sensible if it is considered as HVAC systems have been installed until now as an invasive “stratigraphic” insertion. This “layer” has become in the last two centuries the most extensive, intrusive, and expensive intervention (Koolhaas et al. 2014) and intrinsically short lived. Indeed, HVAC systems are doomed to be substituted every 15–30 years, as Sharon C. Park and others report (Park 2004; National Trust for Historic Preservation in the United States 1982; Shopsin 1986).

These are anyway short periods of time, mainly if compared to the architectures’ age, which implies that a single building is expected to undergo many modifications linked to the installation of many generations of HVAC systems in sequence. And this is unavoidable because of the fast capability of renovation intrinsic to the engineering-technological field of research that studies these systems.

As already stated, the peculiarity of HVAC systems is that it is able to cause damages to the structure actively and in the long term. This is, obviously, as long as the impact on the building of the functioning of the system and of the other factors influencing microclimate is not considered, or if the designer is biased from an optimistic view, with HVAC systems being incapable of bringing any negative side effect (Litchfield 1991; De Santoli 2001).

In this perspective, the study of HIM represents an extremely useful piece: by defining the original microclimatic conditions and studying the following evolution, in relation to the physical changes introduced in the building (demolitions, constructions, changes in the coverings, insertion of systems), it is possible to give a complex and exhaustive perspective to the analysis of the interaction between microclimate and decay, in order to orient the designing choices.

Through this analysis, it is indeed possible to understand how changes in indoor microclimate are linked to the appearance of decay phenomena along centuries of history.

7.4 Criteria and Modalities of Intervention on Microclimate of Historic Architecture

This study should be part of what Carbonara (2003) was defining as

> direct survey of the building, of its structures, materials, building techniques, decay... associated with usual critical-historical analysis of the artifact, founded on preventive bibliographic and archival research... ("il rilevamento geometrico, strutturale, dei materiali, delle tecniche costruttive, del degrado... associata alla consueta indagine archivistico-bibliografica ed alla lettura critica...", Carbonara 2003, p. 17).

On the contrary, the data collected should be considered as carefully as the other survey data, because it is interesting in a diachronic perspective and fundamental in the conservative one.

General goal must remain to be designing and realizing interventions inspired to minimum intervention concept, as well as of authenticity, compatibility, and reversibility, on which further considerations follow (Fiorani 2015). All of the terms are considered essential to define a restoration up to date. It is hence important to understand how the building manages to mediate the differences between internal and external microclimates, opposing the interference of the outdoor on the indoor. These are the performances of architecture in the absence of modern HVAC systems that allow to understand original microclimate (OIM) and the subsequent ones (SIM). Overall, HIM is a relevant aspect and cannot be ignored.

Restoration as a discipline agrees on how important it is to pay particular attention to the sequence of events concerning a building, in order to understand, firstly, how and when decay phenomena appeared (MiBAC and Moro 2006) and, secondly, to interpret these phenomena and find out the most adequate solutions, coherently with the building's history. Unfortunately, restoration is far less unanimous in according equal relevance to the study of indoor microclimate and its changes along the history of the building, when changes in its structure likely affected microclimatic characteristics. This would be particularly relevant in order to define the ranges of microclimatic parameters to obtain with restoration in order to preserve the architecture.

On the basis of existing data and surveys, it appears that OIM of a building is usually highly compatible with its conservation. This implies that to restore OIM conditions should be considered, when possible in accordance with the functions that are assigned to the building.

Obviously, this is not always possible, as often it is necessary to improve the comfort of people using the building or to guarantee different conditions in order to preserve particular heritages contained in the building.

With respect to this subject, though, we believe that a new concept should be introduced, in analogy with what happened with supporting structures in historic architecture. Studies on supporting structures changed their focus in the last few years, moving from adaptation to improvement (Carbonara 2001, 2003; Dall'O' 2003). Improvement must be intended as the act of getting closer to the best conditions for the building without subverting the whole structure. A similar approach would apply to microclimate by finding the best trade-off between the optimal comfort to use the building and its preservation, which should have a bigger weight. This is, indeed, to intervene on microclimate without the aim of adapting completely to the standards of modern architecture, which are often dangerous for the building, but to get satisfied with a less extreme solution which can as well preserve the structure.

In historic architecture, main attention should be given to the conservation of the building, verifying the possibilities of improving it in consideration of its actual physical conditions and of new microclimatic needs. In other words, interventions not establishing microclimatic conditions prescribed by the standards should be allowed in historic buildings, as far as the expected conditions are supposed to ensure at best the survival of the architecture itself (Fabbri et al. 2013). In particular, traditional measures using the characteristics of the building to define microclimate should be adopted in order to assure its compatibility with human activities.

The concepts of reversibility and compatibility mentioned above have been developed within a wider perspective of restoration, where their applicability has been tested (Dalla reversibilità alla compatibilità 2003). Compatible is an intervention that does not add materials interacting negatively with preexisting ones, such as common lime in historic walls. A reversible intervention includes the possibility of removing what has been added, i.e., the possibility of going back to the exact pre-intervention conditions. Obviously, these concepts must be carefully evaluated when speaking of microclimate.

As we have seen, the effects of microclimatic variations can appear only on the long term, so that it might be difficult to observe them. What then happens is that the damage gets to the extent that it is very hard to recover it, as in frescoes destroyed by efflorescence or with beams damaged by humidity. HIM analysis allows to evaluate the aspects of compatibility and reversibility with high detail and to plan interventions and the installation of systems in order for them to be really compatible and reversible.

Literature on microclimate in cultural heritage and how to preserve it is nowadays quite vast, starting from the monumental work of Dario Camuffo (Camuffo

2014). His contribution clarifies the relations between the values of temperature and relative humidity and their effects, such as condensation, biologic phenomena, solution, and dispersion of pollutant, which are associated to decay.

The criteria to take into consideration to design the microclimate of historic architecture (Della Torre and Pracchi 2003) are a part of the project that is often completely delegated by the architect to the professionals responsible for installing the systems, who are usually not aware of the specific characteristics and risks of historic architecture. These criteria, though, cannot be decoupled from the management of architecture and must take into account the microclimatic characteristics of the building at the time it was built and with the following modifications.

Attention must be paid to avoid extreme microclimatic phenomena happening in short periods of time, which impose fast changes on the building in order to adapt to these different conditions. An exemplum is represented by the Church of Santa Maria dei Miracoli as described by Mario Piana with the support of graphics (Piana 2001).

Equal consideration must be paid to longer, if less extreme, values which are inadequate for the preservation of the architectonic materials.

The results of the monitoring described in this book (see Chaps. 8, 9, and 10) show how architectures built before industrial revolution contain within themselves many clues on how the microclimatic values should change. Well-built architectures from the past, such as the Malatestiana Library, have an incredible ability to reduce the extreme values of external climate. They are remarkably effective in buffering the extreme peaks of variation both in summer and in winter, in a logic of partial adaptation to these seasonal conditions and, almost incredibly, always keeping the parameters within the favorable ranges for the conservation of the building and of the contained heritage (Fabbri and Pretelli 2014).

Only an erroneous perception of indoor microclimate would want for buildings a set of microclimatic values constant along summer and winter and could define these changing microclimates not suitable (And not suitable to what? Inhabitants? The building?).

To reach such a result, it is necessary to refer to the whole set of instruments which we know about, from present and past history. Passive effect of external shell is an aspect that should be usually improved, but keeping into account the external esthetic quality of the building, which is not always easy in historic architecture. Insulating performances of architectonic materials has always been considered important in many architectonic cultures, from European to North American. To improve these performances in existing historical buildings, however, might be hard if using only the strategies developed for nonheritage buildings.

HVAC systems should be efficient and adequate, guaranteeing the conservation of architecture (as we do not get tired to repeat) in order to reduce the risks connected to them, as exposed in Sect. 7.2.

The main component of these risks is linked to the choice to modify temperature and relative humidity, which was considered unavoidable until recent times, and modify these parameters in the shortest time possible, in relation to the punctual uses of architectures. It is on the contrary evident, nowadays, that this choice should be abandoned and new systems preferred in order to ensure the use of the buildings. In this sense radiation heaters should be preferred to fluid ones, which influence mainly the users and spare the whole construction: radiant panels or other elements should be positioned in order to warm the visitors and spare the heritage.

In this perspective, fixed elements should sometimes be preferred, such as radiant floors or walls, or on the contrary sometimes smaller less invasive elements are better, such as totems or platforms, connected to electricity or with fluid. It is useful to remember that radiant surfaces do not cause fast movement of air and transport of dust and have a reduced effect on general parameters of temperature and humidity, so that they can be used as well to condition microclimate in summer (but paying attention to risky concurrent phenomena such as water vapor condensation).

All of the possible historic and modern solutions should be used to solve problems linked to inadequacy of indoor microclimatic conditions to visitors' comfort. This is true mainly during cold seasons, distinguishing solutions for the visitor and for the building. Historically, some buildings, such as churches, were using wood platforms to insulate the user from the cold surface of the floor, or elements similar to wooden boxes were used to insulate small portions of the space in order to warm it, such as alcoves.

Among the specific historic solutions, often mentioned in this kind of study, the main one concerns clothing adequate to face low temperatures, considered below the comfort threshold. It should be considered as the opportunity to require or to equip the visitors with specific clothing to compensate the climatic disadvantage of historic architectures during winter. In buildings where the permanence of users is temporary, such as museums or churches, the problem of cold temperatures might be solved by giving and recollecting personal heating devices, as hot water bottles, handwarmers, or electric heaters.

There are other levels acting on this sector to consider and to use, among these the modalities of visits in the building (e.g., with a reduced permanence in the building or with other dynamics reducing the cooling of visitors) and the differentiation of microclimate per areas (i.e., the creation of warm paths, such as the installation of heating floors only in the parts of a church where people stand). This separation between areas with microclimate comfortable for visitors or for the building might be necessary to preserve those parts hosting:

> climate-sensitive objects, when they can be accomodated in special areas or climate controlled display cases. (Park 2004, p. 263).

Moreover, it is important to consider the number of visitors present at the same time inside a room, which can have positive effects (such as an increase in temperature), but which negative effects must be strictly controlled (e.g., increase in relative humidity, up to extreme peaks causing unfavorable conditions, or others).

In any case,

> before deciding to introduce a heating system into a building or to add an air conditioning system (in other words, putting any HVAC), be sure to check the effects of the new microclimate you are imposing to an old building, mainly if its humidity and temperature

> have not previously undergone a fast change due to a mechanical system (Park 2004, p. 263)

This check has to be done even if the building has already hosted a HVAC system.

The most advanced technological aspect positively characterizing any restoration intervention should aim at monitoring indoor microclimatic conditions. This would improve significantly the efficiency of the restoration, since only continuous monitoring and an alarm system (signaling possible appearance of extreme conditions endangering the conservation of the architecture or of its content) would enable the designer or the manager of the building to individuate solutions to these problems and preserve the heritage.

To plan continuous monitoring technical systems post-intervention would allow to confirm the relevance of indoor microclimate, which is to be considered as scientifically important as the other physical/architectonical aspects of a building.

To conclude, to widen the historical knowledge on modalities of interaction between the physical part of the building and the energetic flows that sweep it would not only allow to better comprehend architecture itself, but it would also make clear how the first step to plan the preservation of an architectonic heritage should be though before actually acting on the physical part, by acting on microclimate itself. All of this acknowledging that useful clues to define strategies to intervene in accordance to the thinking of Giovanni Urbani (Urbani 2000) on preventive conservation of monuments would definitely come from the comprehension of the historic evolution of a building and of its models.

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Chapter 8
Malatestiana Library in Cesena, Italy

Marco Pretelli and Kristian Fabbri

Abstract This chapter debates the first of the case studies: the indoor microclimate of a heritage building, the Malatestiana Library in Cesena. This building is particularly important as it represents a "*unicum architettonico*" (unique architectonic piece); since the year of its construction until today it did not change in the architectonic or technological configuration nor in the usage or contained heritage. It is almost a time capsule, survived until today with an indoor microclimate which is comparable to that of past times, excluding climate changes outside the building. And this is even more relevant considering that the role of this building is that of a library, where books require a specific range of microclimatic parameters for their conservation. Thanks to these analyses of microclimate, it has been possible to explain the peculiarities of the architectonic cross section of the building, which is perfect to guarantee an adequate indoor microclimate to preserve the books conserved there. The Malatestiana Library hence constitutes an interesting object to study, and part of this research has been described in journals and conferences.

The Malatestiana Library, a UNESCO Heritage, constitutes the first study case for Historic Indoor Microclimate, and is actually the one thanks to which this concept, as well as the tools and methods of analysis, was first developed.

The Malatestiana Library does not possess, and never did, any kind of technical systems, heating nor others, and the regulation of the indoor microclimate characteristics is done exclusively managing the opening of the windows, as it was happening in the year of construction of the library.

Evident consequences on microclimatic indoor conditions are due, first of all, to the climatic variations happening on global, regional, and local scales, which include both daily meteorological variations and seasonal ones; therefore the variations produced by global warming and development of greenhouse gases represent a risk factor for the conservation of historical buildings, as reported in several studies, among which are Fabbri et al. (2012) and Lankester and Brimblecombe (2012).

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The damage produced by outdoor pollution, particularly that deriving from particulates, as in De la Fuente et al. (2013), adds to these problems.

Because of its peculiarity, the building was the object of indoor microclimate monitoring, during 2013 research. Results and discussion on the research have been published in Fabbri et al. (2013), Fabbri and Pretelli (2014, 2016), Pretelli et al. (2013), Pretelli and Fabbri (2016) and Tronchin and Fabbri (2015).

8.1 The Building: Geometry and Structure

The Malatestiana Library (Figs. 8.1 and 8.2) was the first Italian civic library. Commissioned by the Lord of Cesena, Malatesta Novello, the works were directed by Matteo Nuti from Fano (probably a pupil of L. B. Alberti) and works lasted from 1447 to 1452 and was completed with furniture and manuscripts in 1454.

This Library has preserved its structure, fittings, and codices for more than 550 years, since its opening. The aula has a basilica shape (40.87 m × 10.47 m) with three naves which are divided by ten rows of white, local stone columns and the central nave is higher (6.30 m) than the aisles (4.10 m); the span is 11 for each aisle, pole vaulted. The central nave is barrel vaulted and ends with a rose under which is the grave stone of Malatesta Novello. The fittings are composed of 58 desks; light comes in through the 44 windows.

Fig. 8.1 Malatestiana Library, Aula del Nuti

Fig. 8.2 Malatestiana external view

The Library itself has been conceived and designed exactly as a book consulting/conserving machine.

The room in which books (better still, manuscripts) are conserved has:

- A large number of windows (light, exchange of air)
- The minimum amount of wooden structures (just the windows and the desks, no wooden beams or planks), to avoid fire risks

The fittings are composed of desks, made of larch wood (one of the less inflammable). Also from a structural point of view, the building is absolutely singular, with a high resistance to earthquakes:

- The particular internal structure, with a large two-naves lower level, and barrel vaulted
- A three-naves middle level, really light in its structures, superimposed over the two lower level naves
- A totally free third level, with the large trusses, the bonds of which are very far from the superior part of the vault
- Tie rods at every level, linking together all the internal and external structures, pillars, columns, and walls

The Malatestiana Library (Fig. 8.3) is separated from direct contacts:

(a) From ground level and other rooms (the space occupied by the archaeological museum isn't air conditioned) and so is isolated from thermal exchanges.
(b) From incident solar radiation, direct or diffused, on the attic floor, because it isn't involved in these energetic exchanges due to the air volume of the attic (also in this case there aren't any HVAC systems) and the air has the same outdoor temperature.

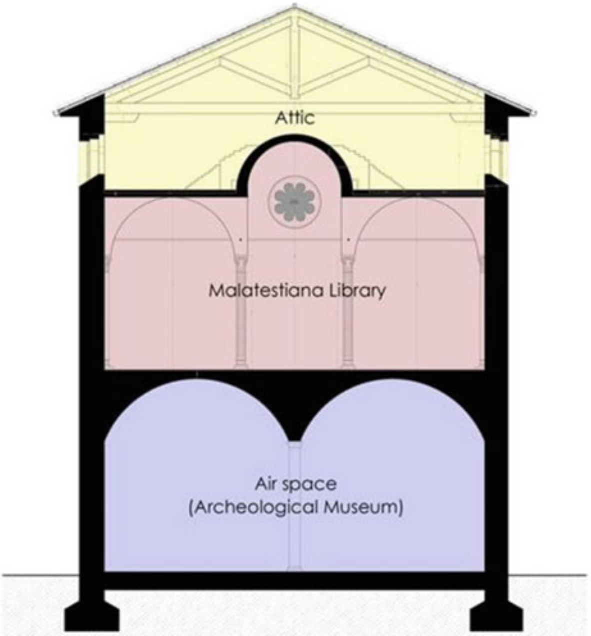

Fig. 8.3 Malatestiana Library, cross section. Ov iner, the attic, and below, in the archaeological museum, the air volumes guarantee insulation

The attic, over the Library, has the same geometry and structure with brick wall. The total surface is 427 m^2, with three windows, of 0.48 m^2, without frame, for each longitudinal side. The roof structure is a wooden truss, with wood splines and brick tiles. The roof does not have any insulation. The ridge is 15.60 m above the ground floor. The attic volume is 1386 m^3.

The space under the Library houses the archaeological museum, where once the San Francisco Convent refectory stood. It has the same geometry as the library (obvious) with a volume of 2142 m^3. The structure is a brick wall, column, and barrel vault. The ground floor has two naves, with a cross vault, a central nave, and two lateral aisles, with a cross vault of the upper Malatestiana Library. The ground floor has seven windows on one sidewall and six on the other, with wooden frames and glass. The access door is wooden and all windows have wrought-iron gratings.

8.1.1 The Manuscripts

The manuscripts conserved in the library are monitored and controlled and subject to periodic assessment, and if necessary conservation. The manuscripts, reproduced and available in digital format, can be consulted in exceptional cases by historians; in such cases the requested manuscript is withdrawn from the library by the librarian and consulted in another part of the library. At present, the manuscripts have not been subjected to particular restoration, at least in the internal parts, nor have there been found any coincidences regarding the position of the book and the cadence of the restoration/maintenance interventions (each of them is connected to a *plutea* and so their place is fixed inside the room). From this we can deduce that the range of microclimatic conditions inside the room varies in a homogenous way and the collocation of each single object has no influence on the conservation process.

Malatestiana Library constitutes a unique case study due to the fact that the building up to the present has not been subject to modification neither from the architectural point of view nor from the destination of use. Since its construction the building has been used as a library and the *plutea* and manuscripts contained in the library are the same ones chosen by Malatesta Novello. The building does not possess heating system or any other technical systems. The control of indoor microclimatic conditions takes place exclusively through the opening and closing of the windows exactly as in the year of its construction.

The Malatestiana Library constitutes a "zero case" of confrontation because it has not been subject to any alterations.

This is why it has been included among the Memoires of the World from Unesco (UNESCO), with the following explanation:

> The Library of Malatesta Novello, the last ancient library dating from immediately before the invention of printing, embodies the very concept of a humanist library. (UNESCO Memory of the World – The Malatestiana Novello Library).

8.2 Indoor Microclimate Research

The initial goal of the research was to study air temperature, relative humidity, and CO_2 concentration in the building, in order to verify that those parameters were suitable to the conservation of ancient books. This had been done following standard literature procedures. The results of the analyses, united to the constant dialogue with the keepers, the director, and the surveys in the ground floor and attic, allowed to obtain a complete frame of information to the variation of microclimatic characteristics.

The results of the research showed that the cross section of the Malatestiana Library had been planned following not only the aesthetic tastes of Renaissance, but also a specific criterion aimed at creating an adequate microclimate to the conservation of manuscripts. It is important to highlight that this microclimate was specifically due to the choices of the designers and, from this specific case, it was possible to give to microclimate a specific identity, to study even under the historic profile.

The study of microclimate, to avoid misplacing in data *dedalus*, must be carried out carefully, with the intent to individuate the single variables influencing the conservation of the objects and then connecting data to better understand possible iterations. These exchanges produce the better modalities for conserving rather than damaging slowly or quickly the object.

The indoor library volume is protected from the effects produced by the horizontal component of solar radiation. The area occupied by the vertical walls is less than that occupied by the horizontal elements of the roofing and flooring. Therefore the effect of direct solar irradiation on the vertical walls and the incidental heat transmission from outside to inside is reduced. In any case heat flow by solar irradiation depends on wall thermal displacement due to thermophysical and thermal capacity of the walls.

Our hypothesis was that the temperature trend and the indoor RH are influenced exclusively by the outside temperature. The results of monitoring demonstrate that the hypothesis is correct.

8.2.1 Malatestiana Library Management

The observation and analysis of the management of the Malatestiana Library has been the first step of our research. It was important to determine the boundary conditions, apart from climate and geometric structure, that could have an influence on the indoor microclimate. The two main boundary conditions are:

- The management of the access of visitors
- The management of the opening of the windows

Both tasks are competent to the keepers.

The control over those indoor microclimate parameters which affect wooden and paper artifacts, such as temperature and relative humidity, has been performed in the Malatestiana Library only through the management of the window opening and of the accesses since the times of its construction. Accesses are limited in numbers and spaces, and the windows are opened regularly, about daily, following a pattern determined by common sense and conservation logics. Indeed, there had never been any instrumental monitoring of the parameters to understand the benefits of this pattern on the indoor microclimate of the library before.

The access to the library is allowed to no more than 20 people at the same time and each visit is about 15/20 min long. Visiting hours and days are not restricted, but the space of the visit is the sole area in front of the first line of plutea. This way the heat and humidity released by the about 300 visitors per month have a nonrelevant effect on the conservation of the artifacts.

We are looking for relevant differences within the library compared to temperature, RH, and external solar radiance.

To this are added considerations on a characteristic microclimate in the Malatestiana Library that would guarantee the preservation of artifacts, and manuscripts specifically. The variation of such a microclimate demonstrated to be deleterious to these tomes, for example in some occasions when they have been lent and showed in other museums, where they were exposed to different parameters from what we will onward define as Malatestiana Microclimate.

8.2.2 Role of the Keepers in Maintaining the Indoor Microclimate

Discussing with the keepers about the registers, there emerged a lively curiosity and debate between them on the benefits of their care for the artifacts. Access to visitors to the Malatestiana Library has no specific times nor dates, with a maximum of 20 people at the same time, in a space limited to the area in front of the plutea. This is because the conservation restrictions allowed in the last 50 years a limit to the access of visitors equivalent to that of researchers visiting the Library in earlier times.

The opening of the windows in the morning and the visitors are the only pollutants of the internal microclimate. There are reasons to believe that those conditions remained constant since the year the Library was built, in 1454. This means that the current microclimatic characteristics are the same as those of the historic microclimate present in the Library for more than five centuries.

The only parameters to change have been the outdoor climatic conditions, due to pollution, urban growth, or global warming.

Even if not inherent to the research, it is relevant to highlight the debate that has been held with the keepers at every data collection. Access to the Malatestiana Library is allowed only if accompanied by a keeper, and this was held true even to place the probes and to download the data. This way many situations arose to discuss with them the habits of the Library management. From such talks emerged the care they take in adapting the opening of the windows to the weather conditions, opening the windows preferentially in the morning all the year long. The Library is cleaned regularly, simply dusting the plutea and washing the floor with tap water.

Manuscripts within the library are regularly monitored, their conservation status checked and, if necessary, restored following a specific protocol. The tomes can be consulted by researchers, previously authorized, and they are collected by the keepers and consulted in a specific area of the Library.

Here we want to conclude thanking the keepers and the vice director Paola Errani, for the help and for making the Library available to us, and for the kindness, the attention, and cure they constantly show in managing and conserving the Malatestiana Library.

8.2.3 Managing the Opening of the Windows

The windows are regularly opened by custodians for an interval of time which goes from half an hour to several hours. The warders open three windows on each side: the 2nd, 7th, and 17th side towards the inside courtyard of the building, and the 3rd, 12th, and 22nd, on the left side towards the outside. The window opening is the only active natural ventilation mode, of course, if we exclude the movement of air through the two openings on the entrance side which are always open.

Fig. 8.4 The Malatestiana Library, Cesena

The Malatestiana Library environment is enclosed between two air spaces (Figs. 8.3 and 8.4):

- a) Underneath exists a large vault place, actually used as archaeological museum. The space is 5.30 m high; therefore the level of access to the Library is 5.70 m from the ground, so indoor environmental of Library doesn't have an influence by ground temperature variation, and also other correlated phenomena (rising humidity, flooding, etc.).
- b) Above there is an attic, a space at present not in use; its maximum height is 2.70 m, and it has an outside ventilated opening (without window or frame) with wooden roofing and truss covering, secondary beams, small beams, and earthenware tiles.

The attic reduces the solar radiation effect on Library ceiling, because there isn't any continuity in heat transmission, by irradiation, which strikes the outside roofing going towards the environment inside the Library. The air-ventilated attic guarantees the convective exchange of air inside the room, in order to avoid all overheating and air stratification phenomenon.

The indoor section of the Library is separated from direct contacts:

- a) From ground level and other rooms (the space occupied by the archaeological museum isn't air conditioned) and so is isolated from thermal exchanges
- b) From incident solar radiation, direct or diffused, on the attic floor, because it isn't involved in these energetic exchanges due to the air volume of the attic

(also in this case there aren't any HVAC systems) and the air has the same outdoor temperature

The indoor Library volume is protected from the effects produced by the horizontal component of solar radiation; so only the vertical walls exposed to the east, the south, and the west according to solar diagram. The area occupied by the vertical walls is less than that occupied by the horizontal elements of the roofing and flooring. Therefore the effect of direct solar irradiation on the vertical walls and the incidental heat transmission from outside to inside is reduced. In any case heat flow by solar irradiation depends on wall thermal displacement due to thermophysical and thermal capacity of the walls.

To perform the monitoring activity and data collection, it has been necessary to interact with the keepers of the Malatestiana Library, and it has hence been possible to discuss with them some problems and questions that have been posed for a long time on the current "common sense-based" managing of the Library. A first point concerns the times and modes of the window opening that depended until now on external climatic conditions. During rainy or foggy days the windows stay open for shorter times, while when the weather is good, this time increases. Secondly, the problem of the access and permanence of visitors inside the Library has been addressed, as they represent a source of pollution in the environment. To this subject, the measure of CO_2 concentration has been used to evaluate whether the effect of the visitors' presence can be diluted in the air volume of the Library.

8.3 Indoor Microclimate Measurement In Situ

The object of the study is the microclimate constituted by the volume of air inside the Malatestiana Library, which exchanges energy through the opening of doors and windows and the admittance of people. Specifically the object of study is the "mass of air" (or air volume) inside Malatestiana Library which exchanges mass and energy in a framework of relationships between the outside microclimatic conditions in particular temperature and relative humidity, and the presence of visitors.

The indoor microclimatic monitoring campaign regards the measuring of the two parameters, which can alter the conservation of the objects. These are air temperature (T in °C) and relative humidity (RH in %). The *indoor air temperature* trends, in the absence of HVAC system, follow outside temperature trends. The temperature trend could be influenced by heating exchange and/or temperature variation due to visitor presence inside Library. The relative humidity trends follow both temperature trends combined with the humidity due to the opening of windows and the little increase of vapor caused by visitors. RH measurement allows to monitor water vapor quantity inside the air environment of Library. These parameters have an influence on the preservation of *plutea* and manuscripts. The temperature and the RH indoor change according to local weather conditions, ventilations, and air ventilation through window opening, entrance door, visitors and to regular cleaning interventions.

The increase or decrease of concentration of vapor, the relativity humidity, for example, governs, at the change of temperature, the development of condensation on fresco or lime plaster surface—event at the root of specific chemical or biological behavior, like the salt development (efflorescence) or mold. The same event appears in other materials such as wood, influencing mechanical performance and hence heat capacity. Temperature and content of vapor are conditioned by factors going beyond the external climate of the building: first, the internal climatic variations of architecture, where objects are conserved, caused by the presence of people or HVAC systems etc., aspects related to the disciplines attending to the study of indoor microclimate.

Indoor microclimate monitoring probes have been used for the research, plus register for the keepers to record time and number of visitors and time of the window opening, that have an effect, respectively, on CO_2 concentration, relative humidity, and dust, and on ventilation, pollutant dilution, and relative humidity.

8.3.1 The Monitoring Campaign

The monitoring activity of the indoor microclimate conditions of the Malatestian Library mainly concerns two parameters that are the most relevant for the preservation of artifacts: temperature and relative humidity. Temperature and indoor RH vary in relation to the trend of local weather conditions, the ventilation and air volume exchange through the windows and entrance door, the presence of visitors, and the regular cleanings.

Indoor air temperature follows the trend of external temperature, given the absence of any kind of technical systems. The temperature can be influenced as well from the presence of visitors, releasing heat.

Relative humidity is dependent on temperature, because its changes are due to the same causes as those of temperature, such as window opening or visitors' affluence. Measuring relative and absolute humidity allows to monitor the variation on the amount of water vapor present within the Library, a parameter with a relevant effect on artifacts, plutea, and manuscripts.

To clarify the goals of this monitoring activity, in relation to the tools used, we point out that:

1. Variables such as the effect of external temperature and of solar radiation in relation to the dynamic behavior of the air volume internal to the building and of its thermal aeric capacity *are among the objects of this research.*
2. *Among the objects of the research there aren't* phenomena or dynamic modeling of energetic behavior of the building, nor of thermal loss of phase, nor the variation of the internal superficial temperatures and convective phenomena, nor even the phenomena of detriment that can be caused to the artifacts by the detected microclimatic conditions.

Fig. 8.5 Picture showing the positioning of the probes

8.3.1.1 The Microclimatic Probes

The monitoring activity referred to the present work was carried out between March 12th and April 30th 2013. As previously explained, this activity required the collaboration and the formation of the keepers, both for data compilation and in order to guarantee the power supply to the instruments (Figs. 8.5 and 8.6).

The monitoring activity requires the use of three dataloggers:

(A) *Instrument HD* – WBGT – PMV HD 32.3—the instrument is designed for the analysis of moderate environments and it can contemporarily detect: the globe thermometer temperature (T_g in °C), wet-bulb temperature with natural ventilation (T_w in °C), ambient temperature (T in °C), relative humidity (RH in %), and air speed (w in m/s). The HD probe is adopted for the conditions of PMV well-being in moderate environments, and so can be applied to the conditions in the Malatestiana Library. The downloading and exportations of data in Excel are carried out with the dedicated software Deltalog 10. The data acquired is updated every 20 min.

(B) *Instrument* CO_2 – HD37-AB17D are instruments suitable for research and for monitoring the air quality in internal environments. Typical applications are the examination of the air quality in all buildings where there is a crowd of people. The instrument measures the following: Relative humidity (RH) is obtained with a sensor of capacitive type, and temperature (T) carbon dioxide (CO_2) measurement is obtained with a special infrared sensor (NDIR Technology (Nondispersive Infrared Technology) that guarantees precise and constant measurements over time. The start and the stopping of monitoring activity, downloading, and exportation of the data in Excel are carried out with a dedicated software Deltalog 13. The data acquisition takes place every 5 min, the maximum setting.

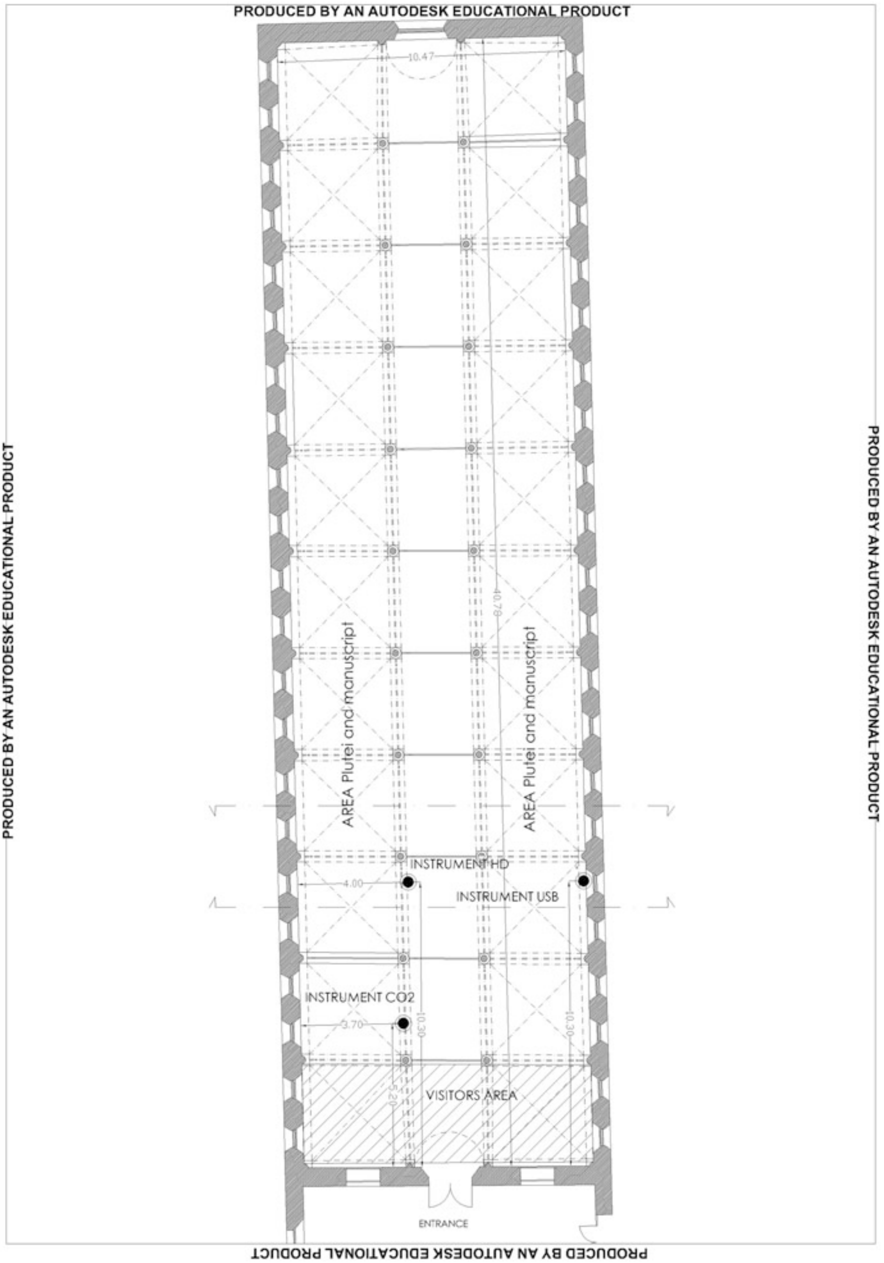

Fig. 8.6 Planimetry of the Malatestiana Library. The area where the visitors are allowed is highlighted and the places the proves are situated

(C) USB datalogger, humidity and temperature USB Datalogger LOG 32, with battery functioning, measuring range, temperature −40°C + 70°C, RH 0–99% with accuracy: ±1.0°C (−20..50°C)/±3% and memory: 32,000 measuring, with software for downloading of data and the exportation in Excel format. We had to resort to the use of a USB probe, because it was not possible to connect the two fixed probes with the one near the wall. The data acquirement happens every 5 min. The datalogger worked correctly during most of the monitoring period, apart from some gaps in the data collected by the USB probe, due to accidental factors such as the fall of the support of the probe itself.

(D) Lastly the outdoor climatic data has been collected by the DEXTER system of ARPA (the Regional Agency for Environmental Protection) of the Emilia Romagna region. The Dexter System is the interface with which it is possible to download data from weather-climatic stations in the territory, from which air temperature data, relative humidity, and solar radiation at various times have been downloaded.

The three probes are positioned as in Figs. 8.4 and 8.5; the *HD instrument* is positioned near the central part at about 30 cm from the ground on a special tripod; the *CO_2 Instrument* is seated on the first pluteo near the visitors zone; and the *USB Datalogger* was fixed to a plank at a height of 1.00 m, near the outside wall on the courtyard side (south-east).

8.4 Results of the In Situ Monitoring Campaign

The monitoring results have been downloaded from the three datalogger with relative software and elaborated with Excel.

The data have been registered at regular time intervals from each probe, one per hour, and then they have been elaborated with Excel, one data for each hour, so that the data from the probes can be compared to the climatic data from the Dexter system which collects data for each hour.

Figure 8.7 refers the data of the indoor air temperature (T_a in C°) of the three Datalogers and the average radiant temperature of the walls (T_g in °C) measured by the HD instrument. The three temperatures have the same increase tendency. The peak temperatures correspond to the opening of the windows. The temperature of the USB probe, located near the outside wall, is around 0.5–1°C lower than other probes of air temperature. The median radiant temperature (T_g) measured with the globe thermometer allows the measurement of the thermal exchanges due to radiance. This value is slightly lower (0.2–0.3) compared to the indoor temperature, the one measured with the USB probe near the wall.

The results shows that there are convective heat exchanges, not revealed by the globe thermometer whose temperatures are lower because of the vicinity of the wall.

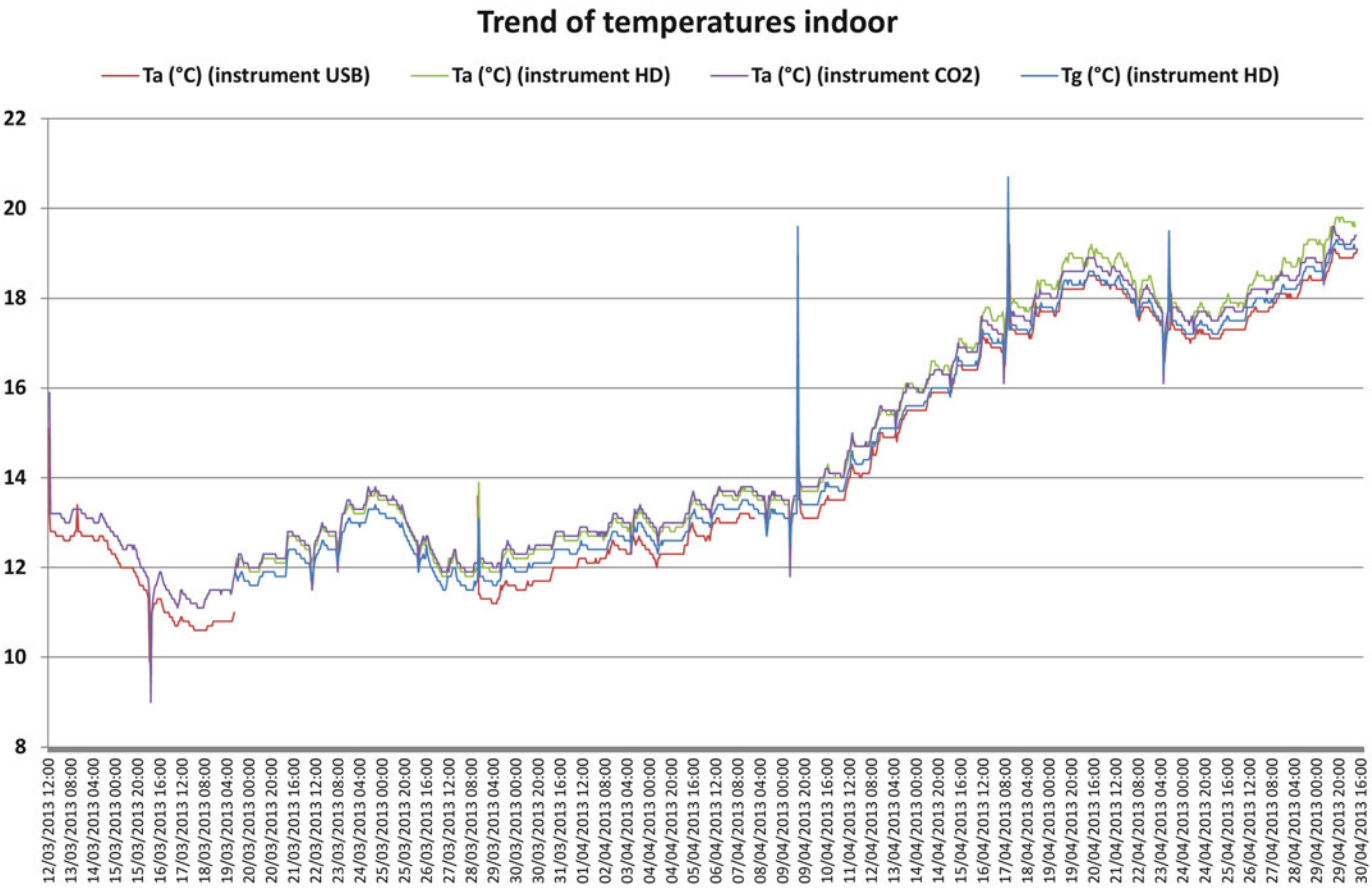

Fig. 8.7 Indoor air temperature trend

Figure 8.8 refers to relative humidity data (RH in %) of the three dataloggers. The peaks are produced by the window openings. The trend shows a variation between 55 and 65%, with the exception of the USB probe near the wall, which has a trend between 65 and 75%, about 10% higher. This difference is produced by the air temperature near the wall and by the vicinity with the windows. This particular difference isn't important for the preservation of manuscripts because they are far from the wall.

Figure 8.9 shows the trend of the indoor air temperature and the air temperature outdoors (by DEXTER) measured with three dataloggers. The System DEXTER is the interface with which you can download data from the weather stations within the region, from which we downloaded the data of air temperature, relative humidity, and solar radiation on an hourly basis. The monitoring is ongoing and it will continue. We highlight that the trend is the same as the indoor temperature, but the range of values of the outdoor temperature is larger, due to day-and-night thermal excursions and solar radiation. This graphic shows that the indoor temperature trend follows the outdoor temperature trend, but it doesn't reveal weather-climatic outdoor variations. Furthermore temperature variation peaks, produced by the opening of the windows, are not due to outdoor temperature peaks and variations.

The relationship between daily solar irradiation (hourly irradiation measure in W/m^2), temperature trend, and RH indoor remains to be considered. Figures 8.10 and 8.11 show the temperature trend, RH indoor, and daily solar radiation in W/m^2. Graphics show that there isn't direct relationship in the short period, whereas there is a direct one in the long period (weekly and monthly).

In both cases the peaks and daily trend aren't influenced by solar radiation, because the solar radiation doesn't hit directly the roof of the Malatestiana Library. The temperature variations and RH happen over a long period and with no peaks or rapid variations, with a nearly seasonal adjustment evolution, and this doesn't involve a variation of the indoor RH range.

Malatestiana *Specific Microclimate* highlights that, in particularly low-temperature conditions, the RH value that manuscripts can stand is higher, whereas when the temperature increases the RH value decreases.

8.4.1 The Distribution of Temperature and RH in the Environment

Figures 8.8 and 8.9 show that the distribution of temperature and RH is not homogenous in the environment and there is some degree of variation, most importantly a variation of about 10% in RH. The data from the probes, despite the little number of probes used and of points obtained, permit us to confirm this opinion: the difference of RH and temperature is present but it isn't relevant in producing convective motion or localized decay phenomena.

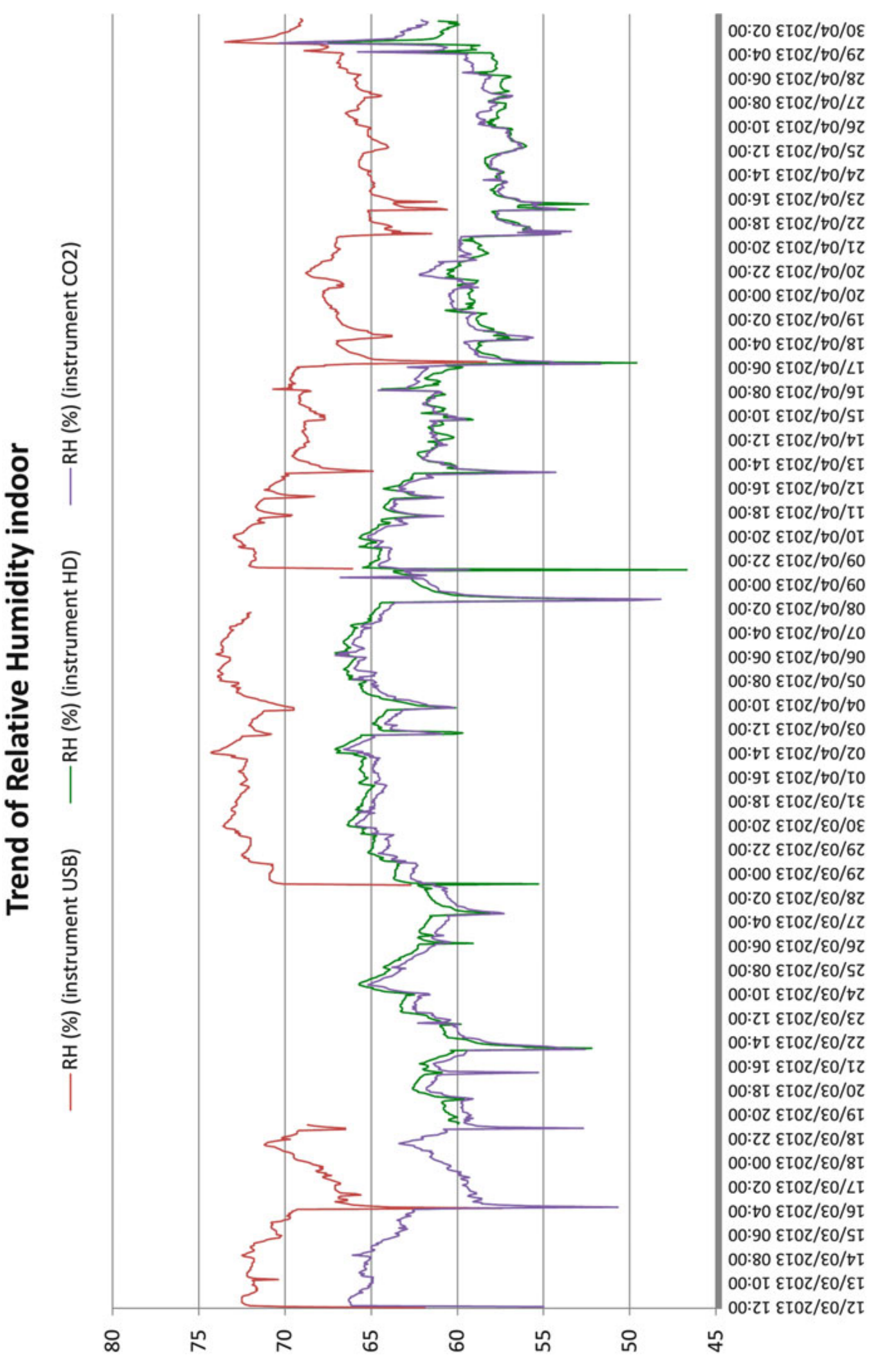

Fig. 8.8 Indoor relative humidity trend

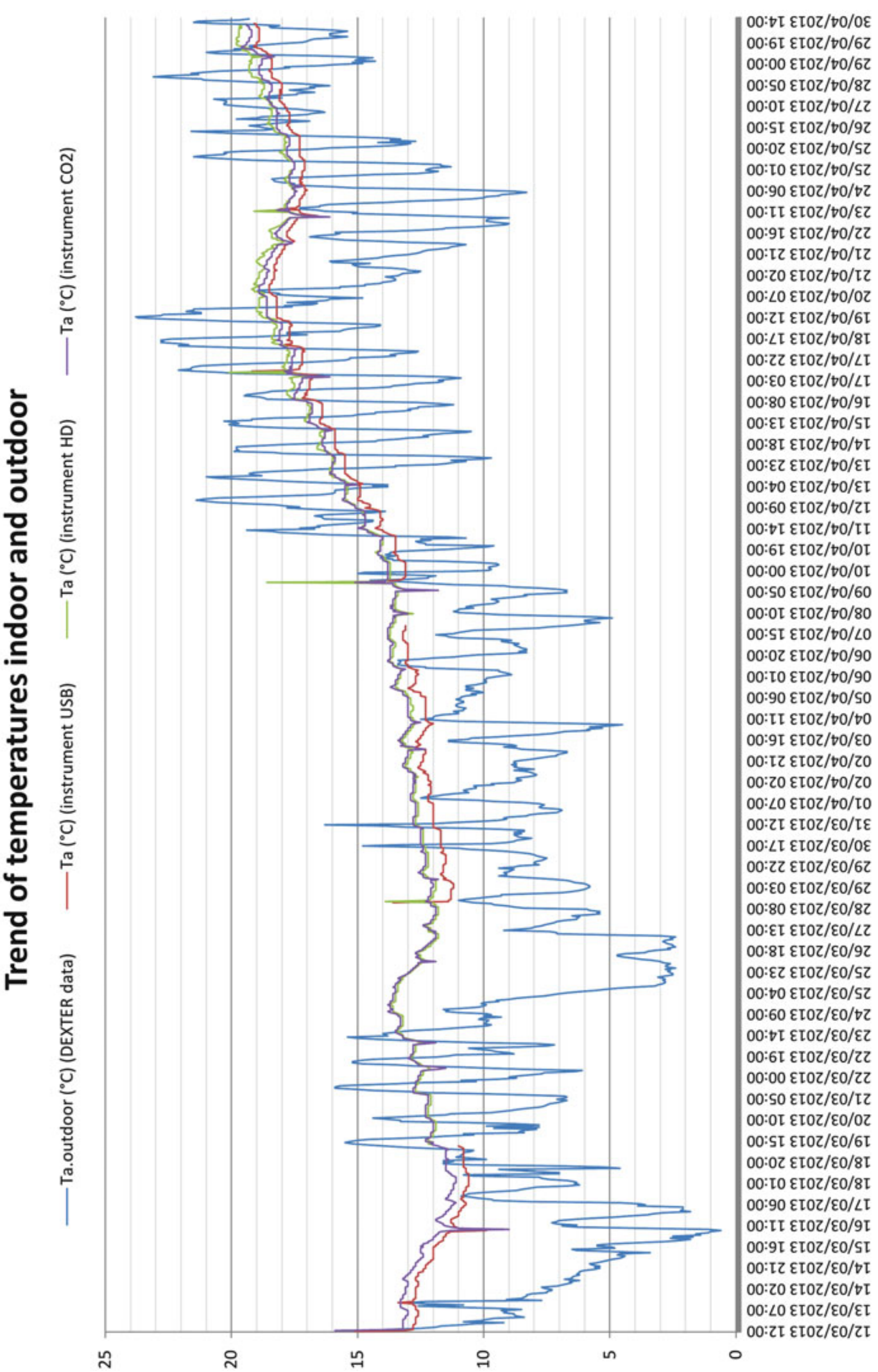

Fig. 8.9 Indoor and outdoor air temperature trend

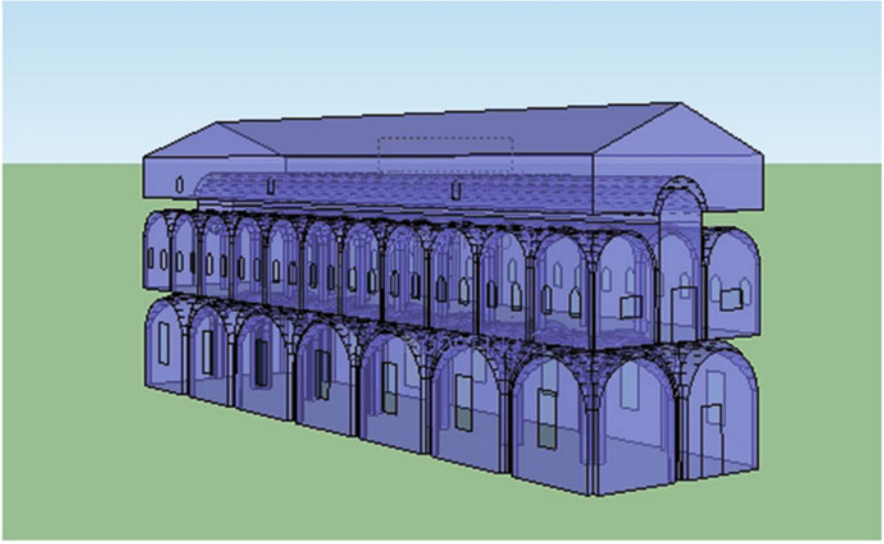

Fig. 8.10 SketchUp model of the Malatestian Library

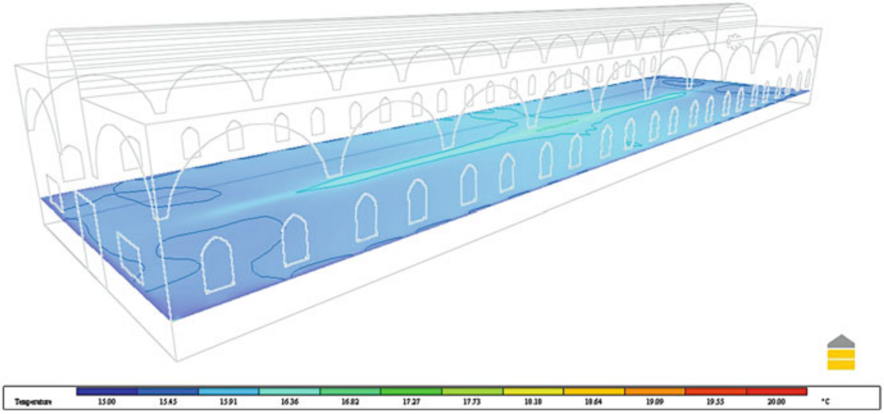

Fig. 8.11 BEP Simulation air temperature (°C) example of results

In order to understand the relationships between the distribution of microclimatic conditions, the maintenance conditions, and the decay of *plutea* and manuscripts, we suggest the planning and positioning of a continuous monitoring system in the library environment, with a higher number of probes, in order to elaborate "cartography" of indoor microclimatic conditions (spatial distribution of relative humidity RH, temperature, air velocity, etc.) like in the studies of Cataldo et al. (2005), Gysels et al. (2004), Litti et al. (2013), and Camuffo et al. (2004), with software of line and surface modeling (surface temperature). This kind of modeling could permit the monitoring of slow variations which take place inside the library, possible abnormalities, or decay phenomena distributions.

The study of the characteristic microclimate highlights that, above a certain value, the varying temperature is negatively correlated in the RH value that the manuscripts can stand. The graphic shows a polynomial tendency curve of 3rd degree and the related equations. On the contrary, from these data, it appears an inversion of tendency around 14–16°C, where the RH value adequate to the preservation of books is 65 and below which this value decreases again.

8.4.2 The Role of the Attic in Reducing Solar Radiation Effects

As explained before, the Malatestiana Library has been planned, since the initial project, as an environment enclosed between two air volumes: underneath there is the space currently used as an archaeological museum, which attenuates the heat exchange towards the ground; and above there is the large space under the roof which reduces the effect of direct solar radiation.

The presence of the attic is a highly relevant factor, which helps to reduce the entering flow of heat from solar radiations and constituting; in our opinion, the main one to reduce daily indoor temperature peaks. The heat flow caused by direct solar radiation, on the upper surface of the Malatestiana Library, is avoided thanks to the vast attic volume and natural air ventilation. The heat flow variations and outdoor temperature due to solar radiation do not modify the variations in indoor temperature.

Without the presence of the attic with its characteristics and dimensions, the incidence of solar radiations would certainly have a more relevant effect on the daily development of temperature, therefore maintaining the RH value in the range of microclimate characteristics. In this way peaks in the variations of daily indoor temperature are reduced. Solar radiation on vertical outdoor surfaces (heat flow of solar radiation) has little relevance because of the “thermal mass” and also because the vertical walls due to their orientation have a limited daily solar irradiation. The indoor microclimatic conditions are constantly maintained over time because heat flow by solar radiation reduces by attic volume.

The attic reduces solar radiation effect on Library ceiling, because there isn’t any continuity in heat transmission, by irradiation, which strikes the outside roofing going towards the environment inside the Library. The air-ventilated attic guarantees the convective exchange of air inside the room, in order to avoid all overheating and air stratification phenomena.

8.5 The Malatestiana Library Building Simulation

The research continued with the modeling of the Malatestiana Library with a software specifically built for building energy performance simulation (BEPS). The BEPS, by dynamic software, e.g., EnergyPlus, Trynsis, and ESPr, allows to calculate and study the indoor microclimate and how it is influenced by boundary conditions: outdoor climate, user and human behavior, HVAC systems, heating load, etc.

Scientific literature used different approaches on this subject. Balocco and Grazzini (2007) focus on the design of suitable air-conditioning systems, one of the aspects defining the building energy performance of historic building. The study refers to the Hall of the Five Hundred of Palazzo Vecchio in Florence and compares the technical system configurations with the simulation done using the CFD software. D'agostino and Congedo (2014) and Corgnati and Perino (2013) study a nonclimatized building, with a CFD simulation of the airflow. Other researches deal with specific problems such as the humidity effect and its transfer through the walls, as in the study of D'Agostino (2013) that happens with churches. Ecclesiastic buildings are the subject of the research of Bernardi et al. (2000) as well.

Google SketchUp is used in the current research for the 3D modeling and the IES.VE (IES.VE) software is used in current research to know heat exchange and indoor microclimate data. Furthermore IES.VE has been used in other studies such as the Technical guide to Historic Scotland (Historic Scotland). This analysis allowed to verify the internal conditions and characteristics in the different architectonical configurations. On the use of Google SketchUp in scientific research, refer to Ellis et al. (2008).

The Library has been modeled with IESVE with respect to the geometric thermophysical and climatic characteristics. The simulation gave data on:

- Indoor air temperature
- Outdoor air temperature (by DEXTER)
- Indoor relative humidity
- Indoor air velocity

In the simulations the building has been considered assuming different patterns of opening of the windows:

(a) All shut. As a first simulation, all of the 44 windows were considered constantly closed.
(b) 6 windows open 2 h/day. The dynamic simulation hypothesized that three windows per side were kept open 2 h per day from 7:00 am to 9:00 am. This causes airflow within the volume, with effects on temperature, air speed, and thermogravimetric characteristics.

The option of opening all of the windows with different times was not considered as this does not happen in reality, both because of the choice of the personnel responsible of the Library and because of the difficulty of opening the 44 windows at a time.

The IES.VE simulation[1] shows that in the (b) configuration the conditions in the Library are kept within the conservation range for longer periods during spring and autumn, compared to what happens in configuration (a).

The higher peak temperature is 27°C during a week in July. The CFD analysis (Fig. 8.11) has been conducted on the 8th of July at 12:00, and it is observed that the temperature is homogeneously of about 21°C. With the windows closed all the day long, air speed is null. The average temperature (Fig. 8.12) is of 17.05°C while relative humidity is of 69.26%. The results of the simulation show a difference of about 3°C compared to the air temperature measured in the monitoring campaign. The difference can be due to approximations of the model and of the outdoor climate data of DEXTER.

The analysis allowed to verify the characteristics and indoor conditions in the different configurations. The dynamic software gives a high number of information and repetitions on the studied building. It requires precise data to be adequately precise, mainly on the characteristics of the building, climatic data, materials, and surrounding conditions. The hardest part of dynamic simulations is to add the many input parameters in the simplifying structure of IESVE and Google Sketchup. The main advantage is that, once the model has been correctly developed, it is possible to compare different geometric and climatic configurations and to produce different outputs with different levels of precision.

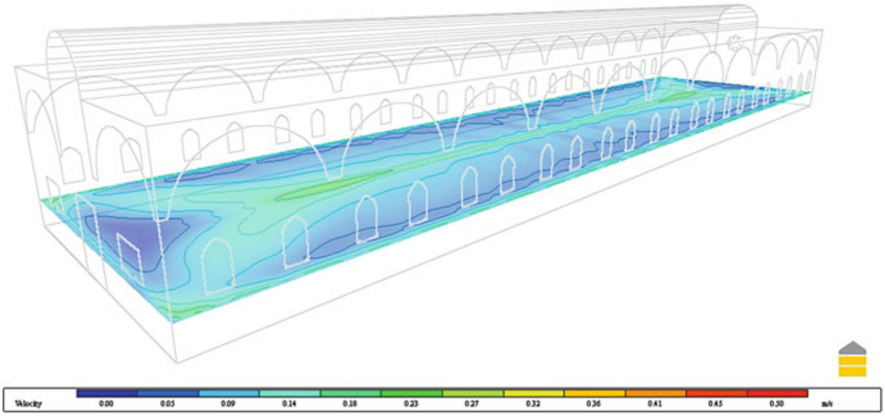

Fig. 8.12 BEP Simulation air velocity (m/s) example of results

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[1] Simulations have been part of the M.D. thesis of Angeli G, building energy performance simulation of the Malatestiana Library (Modellazione dinamica delle prestazioni energetiche della Biblioteca Malatestiana), AA 2012-13 Facoltà di Ingegneria Corso di Laurea in Ingegneria edile University of Bologna, Supervisor: Tronchin L Co-relators Fabbri K, Currà PN.

8.6 The Specific Indoor Environment Called *Malatestiana* Microclimate

The Italian Standard UNI 10829 (UNI 10829) defines measuring criteria and in Annex A establishes referent values recommended for constant weather conditions and the lack of different specific indications. In the case of archival objects like paper or parchment papyrus, manuscripts, print volumes, and philatelic collections the attachment considers a reference range from 13 to 18°C and a RH from 50 to 60% (MIBAC 1998). Other Italian Standards, UNI 10969 (UNI 10969) and EN 15757 (EN 15757), define that it is necessary to know the past history of microclimatic conditions in which the object has been conserved before modifying and they specify that these conservation conditions represent a microclimatic state to which the object adapted itself.

The rule requires that a multidisciplinary analysis is performed to individuate the previous history and values of microclimatic parameters in which the object was conserved. An object that was kept for many years in a constant ambient at the same microclimate conditions must not be changed so the object must be maintained in the environments in which it's adapted and by which is conditioned.

The Malatestiana Library confirm that fact: the past history shows a perfect conservation of the environment and of objects conserved in this place, due to the decision to not modify the conservation state through new HVAC system.

8.7 Conclusion

This research demonstrates that the Malatestiana Library has its own specific microclimate, which is the same historical microclimate that, since its construction, has permitted and is still permitting the conservation of the wooden *plutea* and the parchment manuscripts. The loaning of the manuscript in other buildings with different microclimatic conditions, with higher or lower humidity, involves many risks for the conservation of the manuscripts. Considering the necessity of the Library Institute to loan outside the manuscripts, the results of the research suggest to write and adopt a "*Manuscripts Loan Protocol*" prescribing the suitable transport modalities (microclimate boxes) and the criteria of exposition in museum spaces or in climate-controlled cases. This *Protocol* could also be prospected to pre-emptively verify the specific microclimate of the place where the manuscripts will be exposed, and to take useful measures in order to assure the microclimate keeping the same range of the Malatestiana Library.

The research results show that Malatestiana Library represents a unique instance: thanks to its typological, material, and architectural characteristics and also to the absence of a HVAC system, the building architectural pattern preserves its historical microclimate, probably the same that the building had at its construction time. For these reasons there is a recognizable "*specific microclimate*" in the Library, where the highest values and the thermal stresses are reduced because the building is lifted up and because of the empty space under the roof.

The BPS software allows verifying indoor microclimate parameters based on the different window and architectural configurations. Furthermore, the BEP software:

(a) Analyses indoor CO_2 (carbon dioxide) distribution, produced by visitors. We decided not to do this simulation because the measurement shows still air and the Library visits are strictly regulated, only a maximum of 20 persons, for 15–20 min, with a maximum of 80–100 visitors per day, with a peak of 300 visitors/day.
(b) Evaluates PMV and PPD of thermal comfort, also with CFD simulation. An interesting study concerns the simulation of PMV and PPD at the original Malatestiana Library during fifteenth–nineteenth century, when the neutral value of PMV was under $-1.5 \approx -2$ values.

The result allows us to understand the indoor environmental role of the architectural section, in order to know if the design has a role in choosing an environmental control strategy.

Following an archaeological study analysis criterion, we observed that several Libraries built in same century have the same architectural section; for example San Marco Library in Florence (fifteenth century), Santa Maria Incoronata Library in Milan (fifteenth century), and the Monte Oliveto Library in Asciano, Tuscany (fifteenth century), all have the same architectural section design. These libraries however have been modified over time.

So it’s easy to understand how Nuti’s project was, from the beginning, based on the protection of the library contents and on the manuscripts being consulted by researchers in the safest possible conditions. The outcome of the Renaissance culture is a space able to fulfil the planned goals, which maintains the highest efficiency level with very low overheads. *The machine for the conservation and consultation of the manuscripts*, built over five centuries ago, is still functioning and operative and its costs are still very low, because they need to be employed only for routine architecture maintenance and for the window opening management.

In conclusion, the conservation of the Malatestiana Library allows also the preservation of the—presumed—original microclimate: even though it is apparently an immaterial entity, it is as important as the roof, the walls, and the vaults in order to protect the building and all its contents. Obviously, to adopt this approach on the whole historical heritage is not possible, since to guarantee visitors’ minimal standards of comfort is sometimes inevitable and these conditions could partially conflict with those required for the perfect conservation of the artworks in a specific place, but the presence in here of such a delicate equilibrium is without any doubt to be protected.

Acknowledgments This is a welcome opportunity to thank the keepers and Vice-Director Paola Errani for their availability, courtesy, attention, and care demonstrated in the management and conservation of the Malatestiana Library. This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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UNI 10829 Works of art of historical importance – Ambient conditions or the conservation – Measurement and analysis

UNI 10969:2002, Cultural heritage – General principles for the choice and the control of the microclimate to preserve cultural heritage in indoor environments

Chapter 9
Villa La Petraia (Florence) UNESCO World Heritage

Kristian Fabbri, Leila Signorelli, Marco Pretelli, and Cinzia Magnani

Abstract This chapter focuses on Villa Medici La Petraia (UNESCO World Heritage), built in the fifteenth century in Florence, Italy. The relevance of this study case is due to a specific intervention that, during the nineteenth century, heavily influenced indoor microclimate: the addition of a glass and cast iron cover on the central courtyard. The change of status of this space, from outdoor to indoor, had an important effect on the whole microclimate of the Villa, as well as several other interventions including the addition of stoves and other systems of central heating. Finally, in the twentieth century, the Villa become a museum and no HVAC system has been added since then. On this specific case we done an extensive and complete analysis, including archival research for historic documents; survey of the building and of the HVAC systems; monitoring of indoor microclimate in three different spaces, including the covered courtyard; software modeling and calibration of the model; construction past configurations, with and without covering in the courtyard; and analysis of the associated microclimate, up to the suggestion of management solutions for microclimatic issues. Where the study case of the Malatestiana Library, presented in Chap. 8, has been the beginning of the research on HIM, the case of Villa La Petraia represents a fully developed analysis of indoor microclimate, giving some sort of standard on how to perform these kind of studies and increasing the knowledge on HIM in general and on simulations and the prediction of future microclimatic conditions in particular.

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9.1 History of Building

The current structure and shape of Villa La Petraia is the result of more than five centuries of transformations, during which the building abandoned the austere lines of the fourteenth-century design to acquire a more elegant and noble guise (Acidini Luchinat and Galletti 1992).

During the fifteenth century, the Villa belonged to Palla di Noferi di Palla Strozzi, whose coat of arms is still visible on the tower (1430), a rich merchant who started to improve the original construction. His interventions included part of the tower, the body directly touching its north side and the Villa's perimetral wall facing west, where appear a different original disposition of the openings, now closed. In 1544 the propriety became propriety of the Medici family (Vannucci 1994; Hibbert 1999), a relevant passage for the building because an extensive reconfiguration is carried on. Cosimo I de Medici follows closely the ongoing works, giving a mighty and austere appearance to the Villa, as he considered appropriate for his family. This idea was respected by his son, Ferdinando, who took his father's place in 1568 and was considered responsible for the terraces in the garden and the aqueduct (Butters 1991). Ferdinando was known for his interests in botany, herbal medicine, and its therapeutic applications, which appear in Villa La Petraia as well as in other of the family's proprieties.

Until the decadence of the Medici family, the Villa underwent several interventions aiming to increase its unity and regularity. In particular a two-story body adjacent to the tower was built, which includes service rooms in the ground floor and a new stair, and connects the north-east and north-west corners. This implies that the spaces previously facing north are now in contact with another internal space.

The internal courtyard changed as well, during this time. Two specular colonnades were added in the east and west sides, each of them with five aisles of tuscanic order, covered by loggias with architraves. The planimetric structure gives an axis of crossed penetrations, still distinguishable nowadays, with two sequences of openings in the south-north and east-west directions. In the late sixteenth century the raising of the tower was completed, in particular the arches over the mullioned windows.

These operations not only gave a more elegant conformation to the whole building, but symbolized the power and dominance of the family over the territory. Information on the state of the building and on the kinds of plants grown in the garden and terraces by the end of the sixteenth century come from a lunette painted by Giusto Utens (1599–1600), conserved in a room in the ground floor of the Villa (Bertocci et al. 2006).

After the Medici, Villa La Petraia became part of the proprieties of the family of the Lorena, who cared and managed the whole structure in accordance with the "Family Pact" they signed with Anna Maria Luisa de' Medici in 1737, when her brother Giangastone died and the Lorena acquired the propriety.

During the Napoleonic dominance (eighteenth century), some minor changes interested the outdoor area, as in the lower gardens or maintenances in the medicean aqueduct, while the building was barely touched, apart from the historic furniture which was taken and dispersed.

With the unification of Italy, in 1861, started a new period of interventions. The building came to belong to the reigning family, the Savoia, and King Vittorio Emanuele II made it a residence for his morganatic wife, Rosa Vercellana, countess of Mirafiore. This implied some sort of widespread reconfiguration, with changes in the floors and window fixtures, as well as in the furniture, which acquires the typical taste of the Savoys (Pretelli 2014). Alongside with these interventions, the central courtyard was covered with a ceiling of glass and cast iron. This has been one of the most relevant changes influencing the microclimate of the Villa, as the whole courtyard passed from being an outdoor space into an indoor one. The covering was done in occasion of the engagement of count Emanuele di Mirafiore, son of the king and of the countess, in order to create a reception room for the celebrations. The architects Fabio Nuti and Giuseppe Giardi designed a self-supporting structure, with four corner pillars. At the center of the cover there is a roof lantern with windows that can be opened, accessed through a suspended walk from the tower.

In 1919 the Villa was given to the Italian State and taken in charge by the all'Opera Nazionale Combattenti (National Opera fot the Fighters, ONC), which sold part of the lands associated, as well as furniture and art pieces that the Villa contained. During the II World War a grenade hit the covering in the central courtyard, causing some damages.

From the sixties, the whole structure belonged to the Italian Republic, which uptake a long and effort-taking restoration of the Villa. In 1984, the building became a National Museum and, afterwards, became part of the museum center of Florence.

Recognizing its artistic relevance, the Villa was included in the World Heritage List of UNESCO on the 23rd of June 2013, when Villa La Petraia was included alongside other 12 Villae and 2 Gardens in the 49th serial site for Italy (Ballerini and Scalini 2003; Zangheri 2015).

9.2 Indirect and Direct Investigation

The study of indoor microclimate includes, as described in the previous chapters, two different analyses: a first phase of indirect research on archival sources and a second, direct, one done through geometric survey and linked to HVAC systems. This analysis gives information on the different stages of construction of the building, which can be used in the building simulation and to define the places for the monitoring probes. Here follows the result of archival and survey researches on Villa La Petraia in Florence.

9.2.1 Archives and Catalogue Research

The archival research has been carried in collaboration with the Soprintendenza per i Beni Architettonici e Paesaggistici di Firenze (Ministero per i Beni e le Attività Culturali e del Turismo). Thanks to this institution it has been possible to have access to the historical archive and to the documents concerning medicean Villae, in particular to those linked to Villa La Petraia.

This material gives the opportunity to have an in-depth look on the events of the nineteenth and twentieth centuries: it included technical reports, correspondence, and reports of theft and of the restoration works concerning Villa La Petraia. It was then possible to have precise details on the changes of propriety, the main architectonical changes, the insertion of HVAC systems, and any other change that allowed the building to be up to date along time.

More data have been obtained from the Drawing Archive, a section of the archives conserved at the Sopraintendenza where several other representations of the Villa from the decades 1870 and 1880 were conserved. These drawings have been used as a basis for the surveys and for the modeling of the entire building (Fig. 9.1).

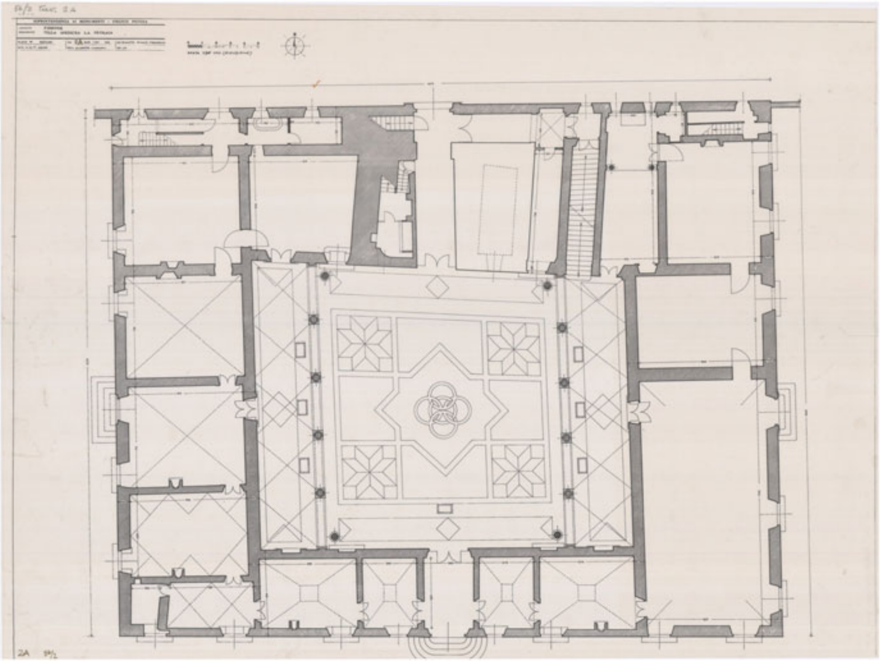


Fig. 9.1 Map of the ground floor of Villa La Petraia, Soprintendenza ai Monumenti, Firenze Pistoia (1977), Archivio Storico della Soprintendenza per i Beni Architettonici e Paesaggistici di Firenze

The documents found in the archives helped to determine the events concerning Villa La Petraia up to 1920; for previous times, other sources for the bibliographic research helped define the knowledge of the building.

9.2.2 Indirect Investigation Matches Direct Investigation

By cross-checking the data of the geometric survey (from direct investigation) with those coming from indirect investigation it was possible to infer several information on the changes which interested indoor microclimate. In particular the introduction of heating systems has been traced back and a stratification of technologies has been observed: from fireplaces to stoves and HVAC systems.

The three different phases have been divided as follows:

- Hearths and heating vents, from the eighteenth century
- Stoves, added in the nineteenth century
- HVAC systems installed in the internal court yard in 1992

In each room the historic heating systems have been listed (as is instructed in Chap. 5) and each item received a code where PT means ground floor (Piano Terra) and PP first floor (Primo Piano), plus a number (Fig. 9.2).

9.2.2.1 Fireplaces and Heating Vents

Fireplaces and heating vents (Fig. 9.3) are not documented clearly in the archives and an exact date for their first presence is lacking. Based on the history of the building, an approximate period can be inferred, probably at the end of the nineteenth century. To these years date some works to reinforce the building and to move the kitchens to the cellars. Earlier dates are to be excluded as in the oldest part of the building, the north wing and the tower, there are no heating systems. There are several fireplaces in the whole building, but, generally speaking, the systems to heat the spaces change from room to room.

Each of the fireplaces use a system that allows to extract heat not only from the hearth, but also from the raising smokes. This was usually obtained coupling the chimney with two spaced boxes. This way, the external air was warmed passing close to the chimney and introduced in the room through horizontal and vertical canalizations.

The smokes, instead of being directly taken outside, are used to warm incoming air. The channels to distribute this air are made of bricks and take the warm air directly to the rooms that need to be warmed, where a vent with a shutter allowed to regulate the flux of warm air.

A complicate system of canalization connects fireplaces and rooms in different parts of the building. In the cellars are the kitchens, where a big fireplace is used to cook food. United to other big hearths, they were probably warming the rooms in the upper floors thanks to this system of recycling of the smokes. Some rooms in the

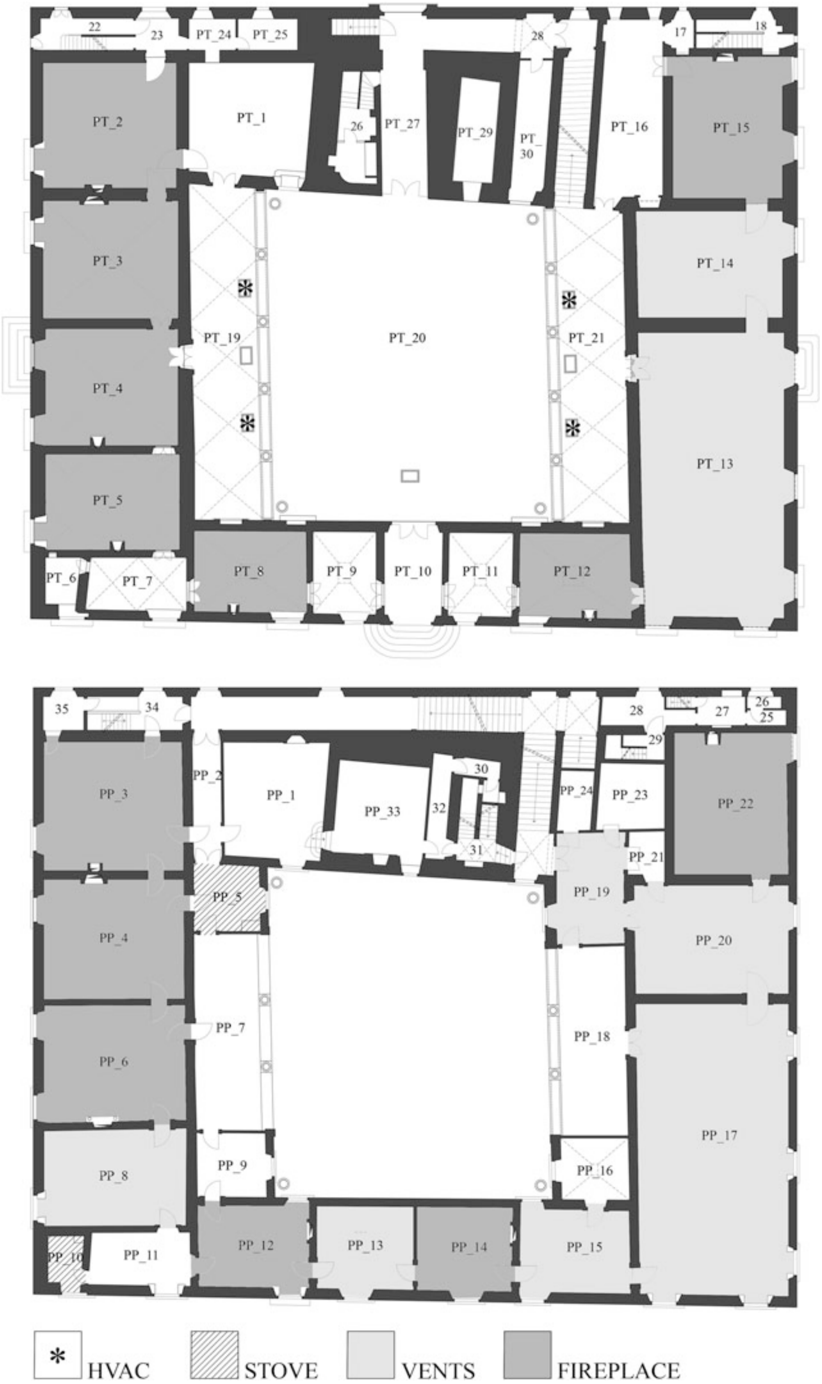


Fig. 9.2 Maps of the ground and first floor highlighting the type of technical system (fireplace, vents, stoves, and HVAC system)

Fig. 9.3 Fireplace surrounded by four heating vents

ground and first floor, such as the dining room, the games room, and the studio, have heating vents. Moreover, many ground-floor rooms are equipped with fireplaces warming them, which are as well connected to the heating system and warm the corresponding rooms in the first floor, the vents in these rooms being placed in correspondence to the position of the hearts in the lower floor. Some of the rooms in the first floor have their own fireplaces and, in the south wing, the hearths are connected with a canalization system to warm other rooms in the same floor.

9.2.2.2 Stoves

This second heating system, installed in the nineteenth century by the Savoy in several of the first-floor rooms, is constituted by several cast iron stoves with openings allowed to add the logs and remove the cinders. Some of the stoves were heating only the room they were placed in, while others contributed to the heating of other spaces.

Indeed, in a room in the north wing (Fig. 9.4), currently used only as a passage for the visiting tourists, a radiating stove was probably placed heating only this room. This is inferred by the presence of a single canalization leading up to the roof and from the position of the room itself, in the corner (one wall facing the internal courtyard and the other facing the west loggia), where it is not possible to connect the stove to contiguous rooms.

On the contrary, in the room PP_10 (Fig. 9.2) a convective stove was probably placed. This room was used as a storage closet and communicates with the toilette of the countess of Mirafiore. The stove was probably contributing to the heating of the bedroom of the countess (PP_8), directly contiguous, as heating vents facing the closet are present only in the bedroom and not in the toilette. The bedroom was

Fig. 9.4 Stove in a room of the first floor (PP_05)

heated as well by vents in the north wall, coming from a hearth placed in the Blue Empire Room (PP_6).

9.2.2.3 Heating System by Electric Fan Coil

The last HVAC system to be added in the Villa was eight fan coils placed in the central courtyard. Archival research informed that in 1992 a set of four electric fan coils has been placed in the courtyard, close to the openings in the floor (Fig. 9.5). The electric cables passed through these openings already present in the floor. After the intervention, these openings have been closed in order to reduce heat loss, with plastic shaped to fit the openings in the ceiling of the cellar.

Fig. 9.5 The fan coils installed in the court yard

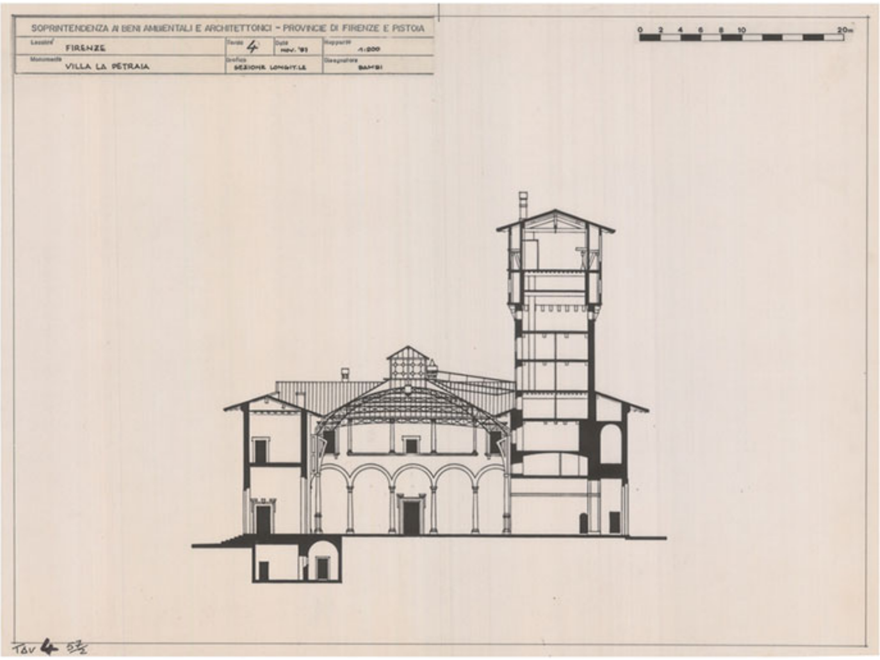


Fig. 9.6 Cross section of Villa La Petraia, with the suspended walk to access the lantern, Soprintendenza ai Monumenti Firenze Pistoia (1987), Archivio Storico della Soprintendenza per i Beni Architettonici e Paesaggistici di Firenze

This intervention further influenced indoor microclimate of the courtyard, as the connection between the underground corridor and the courtyard was allowing a constant natural ventilation and its obstruction favored the increase of temperatures in the courtyard.

The installation of the fan coils has been an unsuccessful attempt to regulate relative humidity in the courtyard during winter, when dew forms on the glass surface, but the eight fan coils are not adequate to solve the problem, given the size of the space. At the moment, this system is used only in occasion of special events, such as Gala Dinners (Fig. 9.6).

9.2.2.4 Daily Management of Villa La Petraia

As it has been highlighted with respect to other study cases, the daily management of windows can have significant effects on microclimate. It is hence worth to mention how this has been carried on in past times in Villa La Petraia and what changed since then. The covering of the internal courtyard is equipped with a set of windows in the lantern, which were regularly opened by the service personnel during the nineteenth century. This way an air flux was created, with hot humid air rising and cold air coming through the openings in the ground from the corridors underneath, creating a chimney effect. Since it is nowadays difficult to reach the windows through the suspended walk, the windows are currently always shut and this, coupled with the obstruction of the openings in the floor, has a very consistent effect on indoor microclimate.

9.2.2.5 Historical Change Effect on Natural Ventilation

The changes affecting the architectonical configuration of Villa La Petraia and the introduction of several different heating systems determined a substantial variation in the natural ventilation systems of indoor microclimate:

- In the fifteenth century, natural ventilation of the rooms occurred with a transversal motion, as they had outdoor openings in both sides, the external courtyard ones. This condition favors the forced draft of the chimneys.
- In the nineteenth century, the courtyard has been closed and the result was that the rooms have only one side facing outdoors. The natural ventilation with chimney effect is assured by the opening of the windows in the top lantern of the covering and by the connection with the underground spaces, which temperature is lower.
- By the end of the twentieth century, the openings in the floor of the courtyard were closed to install the electrical fan coils, reducing the effectiveness of the chimney effect.

- In the beginning of the nineteenth century, due to management costs and other difficulties, the windows in the lantern were not opened anymore and the natural ventilation was virtually completely absent.

This list of changes contributed to transform the central courtyard in some sort of greenhouse, with incredibly high values of air temperature during summertime, as recorded with in situ monitoring.

9.3 Monitoring Campaign

For this research, microclimate has been monitored in situ following the criteria presented in Chaps. 2 and 4. The goals of this activity were mainly two:

- Understand the actual indoor microclimate (AIM) of the Villa and define possible conditions posing problems for its conservation. Among these, the temperature increase in the internal courtyard, with possible effects on the frescoes decorating the courtyard and on the organic materials conserved in the building, and the effect on the comfort perceived by the visitors in summer times, usually moistly warm
- Calibrate the virtual model, in order to simulate different scenarios of Historic Indoor Microclimate.

Three probes have been placed to carry on this monitoring, in the courtyard and in a room per each of the two floors. In order to place the probes, two different operation have been necessary:

- First, the probes have been placed in the rooms following criteria based on the survey and on the usage of the rooms, in accord with the indications coming from the Sopraintendenza and in order to power the probes through the electric network.
- In a second time, because of a problem in the wireless transmission of signals, the probes have been moved and placed, thanks to the assistance of the producers of the monitoring system, in order to assure the communication between the peripheral and central nodes of the system.

Following the lesson that this problem gave, it is suggested to include in the research protocol a moment to interact with the producers of the monitoring system to acquire the technical requirements to assure the best functioning of the system itself.

Moreover, attention has been paid to reduce as much as possible the visual impact of the probes, when placing them in the rooms, and to avoid any permanent damage to the building.

A Genesis Wireless Sensor Network Beeper (Beeper-WSN) system has been used, which is constituted by the following:

- *Probes* measuring air temperature (°C), relative humidity (%), carbon dioxide CO_2 (ppm), and illuminance (lux): A single probe gave as well information on carbon monoxide CO and volatile organic compounds, VOC, both measured in ppm.
- *Wireless node*, connected to the probes in the room where the monitoring is going on: Powered by AA batteries, they collect the information registered by the probes and send them to the bridge.
- *Bridge*, the device collecting the data from the probes and sending them via GPS signal to the web and to the online platform through which it is possible to have access to the data.
- *Online platform*, which is a dedicated web app to access and download the data in.csv format, plus check the functionality of the monitoring systems, such as the battery level.

The probes were registering the values of the variables every 15 min, while the data were packaged and sent to the bridge through a wireless node every hour, to reduce energy consumption. For the same reason, the bridge was sending the data to the online platform every 8 h, after having collected them from the nodes.

The monitoring campaign in Villa La Petraia run from the 22nd of July 2015, h14:50, to the 23rd of March 2016, h14:50, for a total amount of 9 months (274 days, 6576 hours, and 23,604 collected data).

The probes have been placed in three rooms within Villa La Petraia (Fig. 9.7):

- In the central courtyard, ground floor (PT_20)
- In the Red Room, ground floor (PT_13)
- In the Games Room, first floor (PT_17)

The specifics of the monitoring campaign will not be analyzed further in here.

The variables used to calibrate the results of the monitoring on the virtual model are the trends of air temperature and relative humidity.

It is not possible to standardize CO_2 concentration in the model, as it has not been possible to have information on the entrance of people nor on the opening of the windows for the studied period. Similarly, illuminance has not been studied and not included in the virtual simulation, despite it being a useful information that can be used as a proxy for solar radiation, for the presence of people in periods when there is no natural light (such as early morning, late afternoon, or night), and as well to have information on the management of the systems to obscure the windows.

Fig. 9.7 The probes placed during the monitoring in the central courtyard (PT_20), in the Red Room (PT_13) and in the Games Room (PT_17)

9.4 Virtual Model Methodology Steps to Study Historic Indoor Microclimate

The research method to study Historic Indoor Microclimate and its correlates OIM, SIM, and AIM (see Chap. 3) includes the use of building performance simulation (BPS). The virtual model allows to perform simulations with different architectonic, technological, and climatic conformations, and compare them to the current ones to which the AIM refers.

The following steps must be followed:

First step: building the virtual model.

- Survey the current geometry and technological characteristics of the building, starting from planimetries or in situ survey.
- Construct the virtual model with a 3D simulation software, e.g., SketchUp, able to interface with the BEP software.
- Import the 3D geometry in the simulation software BPS or computer fluid dynamics (CFD).
- Attribute the technological characteristics to the vertical and horizontal walls and ceilings.

Second step: insert variables in the virtual model

- Definition of the usage of the thermal zones
- Definition of the climatic data on the basis of the locality and of the closest microclimatic station
- Calculation of the energetic performance and interpretation of the results

Third step: definition of levels of errors and approximation to calibrate the results.

The results can then be used to address future restorations and designs, or the management of the building or the museum, or for the choices concerning the conservation and lending protocols for preserved heritage.

9.4.1 Step 1: Construction of the Virtual Model

The virtual model has been built on the basis of data collected through archival research, such as historic planimetries, and of direct survey.

The building has been first modeled in 2D in AutoCAD and then transformed in 3D in SketchUp (SketchUp), georeferencing it in GoogleMaps. The level of detail includes the windows per each room, but the arched shapes of windows and loggiato have been simplified into rectangles to be imported in the software.

IES.VE (IES.VE) has been used for the building performance simulation and, thanks to a SketchUp plug-in, the 3D model has been imported with the relative thermal zones. The Virtual Environment by Integrated Environmental Solutions (IES.VE) is an environment to evaluate building energy performance, calculating with Energyplus (see Chap. 4).

9.4.2 Step 2: Variables to Simulate the Virtual Model (Boundary Conditions)

The virtual 3D model of Villa La Petraia represents the current architectonical and geometric configuration, as well as the technical and constructive characteristics, such as transmittance, obtained through documentation and visual in situ survey.

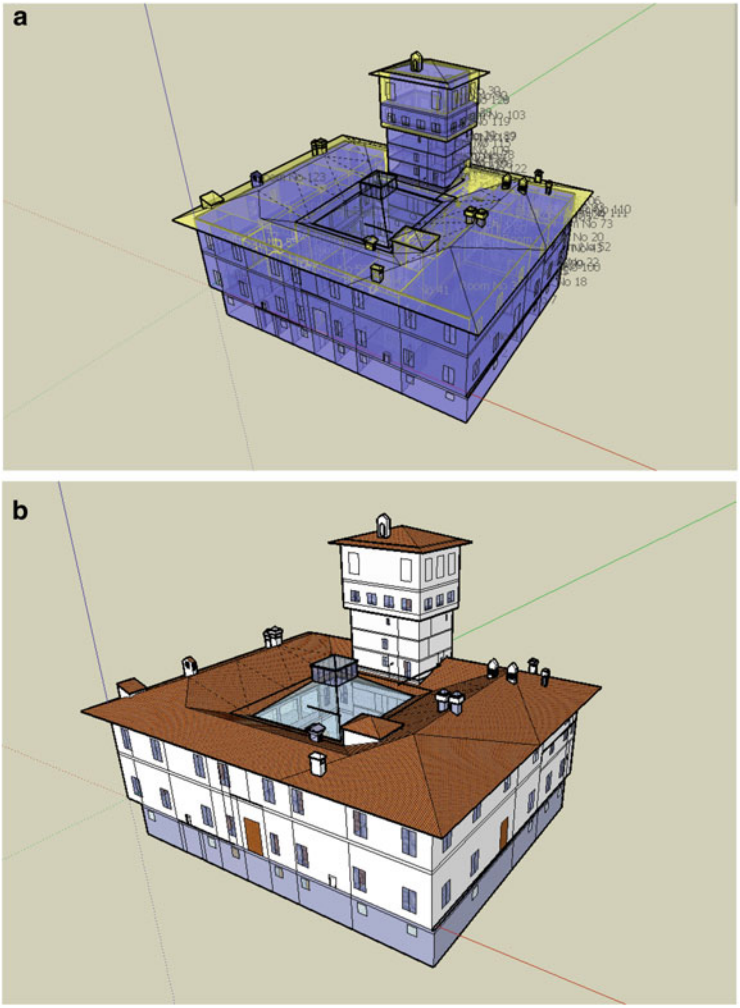


Fig. 9.8 (**a**) and (**b**) SketchUp model and thermal zones imported

The virtual model allows to test different architectonic configurations, change in building techniques, modalities of usage of the spaces by visitors or others, ventilation of the rooms, outside climatic conditions, etc., each variable influencing indoor microclimate. Given these different conditions, each combination of them is called scenario and to a single scenario refer the simulation (see Chap. 4) (Fig. 9.8).

The variables of each scenario concern:

(a) *Architectonic configuration,* with or without the covering in the central courtyard, i.e., in the current conditions or as the Villa was in 1650.

(b) *Weather data*, for which the data relative to 2015 and to 1650 have been used. The first were obtained from meteorological stations in situ and used to calibrate the results of the monitoring campaign; the seconds have been extracted from the reports of the meteorological stations founded by the Medici in the seventeenth century.

All the simulations did not consider the HVAC systems and only the natural ventilation of the rooms has been assumed.

9.4.2.1 Calibration of Virtual Model by Weather Data 2015

The first step in the research is to calibrate the virtual model, comparing the results of the physical variables in the simulation with air temperature and relative humidity as measured in the campaign.

The weather data of the current year must be inserted in the model in order to compare the results of the simulation with the real climatic data obtained with the in situ monitoring.

In the case of heritage buildings, the indoor microclimate of the simulated current conditions must be comparable to the real building, in order to study Historic Indoor Microclimate. The procedure to calibrate the model consists in the comparison of the real measured values of the studied variables with the same trends referred to the virtual environment for the same thermal zone. Maximizing the similarity between these two values allows to calibrate the model.

In the study case of Villa Medici La Petraia, the results of the virtual simulation with IES.VE have been calibrated on the basis of indoor air temperature obtained through monitoring in three specific rooms (central courtyard, Red Room in the ground floor, and Games Room in the first floor).

Indoor Air Temperature Trend Calibration (Monitoring Campaign Versus Virtual Simulation Results)

The calibration consists of the comparison of the trends obtained through the monitoring campaign and those from the virtual simulation with IES.VE for air temperature and relative humidity in relation to the entire monitored period. From the analysis of the obtained values it is possible to evaluate the level of similarity in each monitored room (Fig. 9.9).

In the virtual model, the thermal daily excursion is slightly higher than in reality (±3°C), probably because of the constantly clear sky assumed by the meteorological conditions of the model, which does not reflect the variability in the natural conditions. This does not imply significant differences in the average trend of hourly or daily values for the whole monitored time, so that the air temperature trend can be considered calibrated.

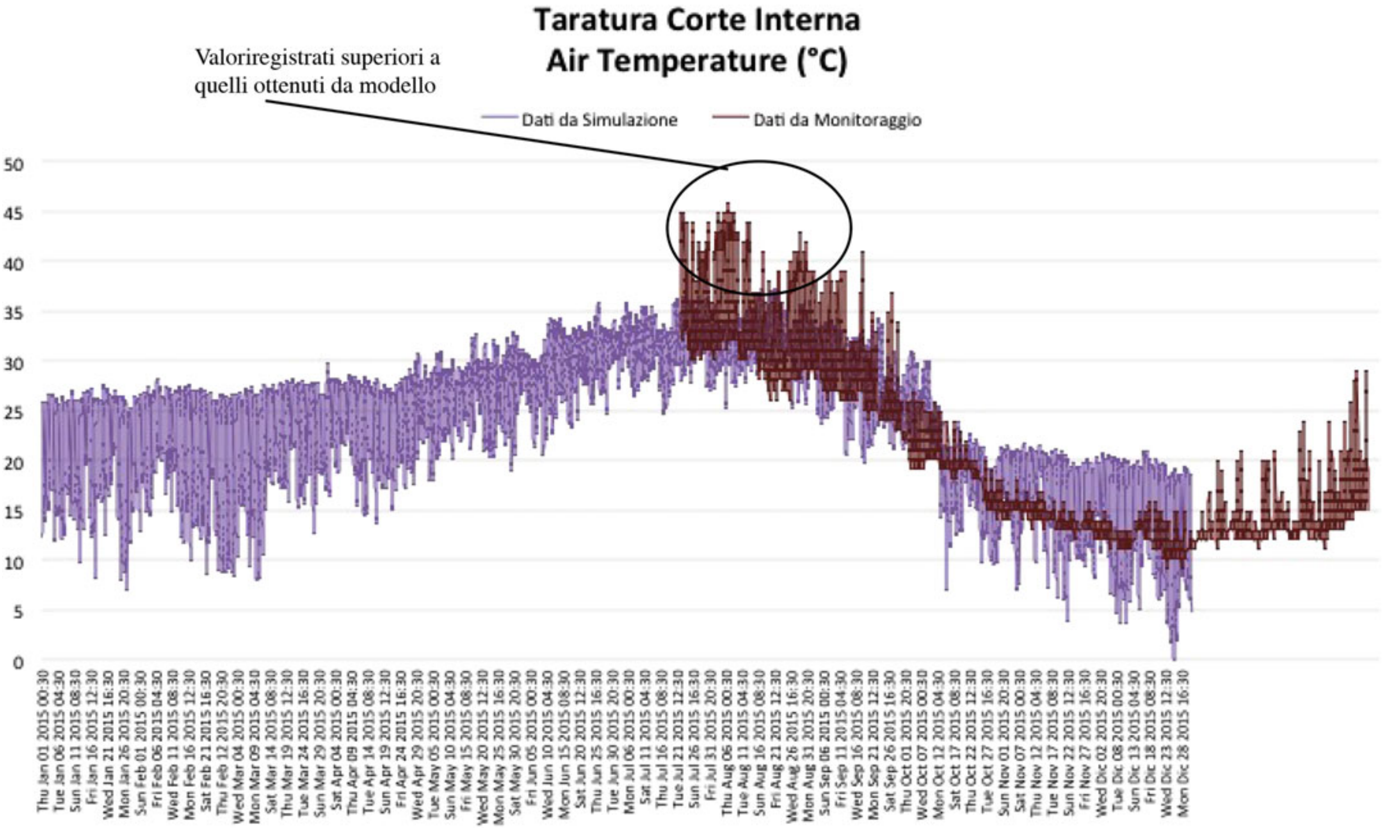


Fig. 9.9 Air temperature calibrated for the internal courtyard

If the virtual model in the three monitored rooms results calibrated, then it is possible to infer indoor air temperature in the other rooms, given that the whole model is calibrated.

9.5 Scenarios and Results

In this paragraph are reported the results from the building simulation concerning the scenarios with and without the covering in the internal courtyard with both the current and historic climatic data. The virtual models per each scenario are described and the results of the simulations follow.

9.5.1 Scenario Without Covering of the Internal Courtyard with Weather Data from 2015

Once the virtual model is calibrated, it is possible to build the scenarios used in the research. In this specific case the most interesting aspect to evaluate is the differences in the current indoor microclimate compared to the original one due to the addition of the covering in the courtyard and based on historic climatic data.

A further level of analysis, requested by the Director of the Sovraintendenza, has been to evaluate microclimate in other rooms to inform the decision to change place to furniture or paintings.

The first scenario concerns the configuration with no covering in the courtyard, so as to confront AIM with OIM, excluding the climatic variations. This way it has been possible to verify the effects of the covering in the courtyard on indoor microclimate in all the indoor spaces of the building, in particular in the Red Room and in the Games Room.

The elimination of the cover in the central courtyard implies changes in the convective motions in the rooms towards the court, as well as the effects of solar radiation and external temperature on the loggiato, again towards the court. The architectonical configuration towards the courtyard allows to evaluate the original indoor microclimate (OIM) of the Villa as it has been planned and wanted by the Medici family (Fig. 9.10).

In the virtual model, it has been sufficient to eliminate the thermal zone of the courtyard, giving it the characteristics of an outdoor space. The values used for this model are, as in the previous one, those of 2015.

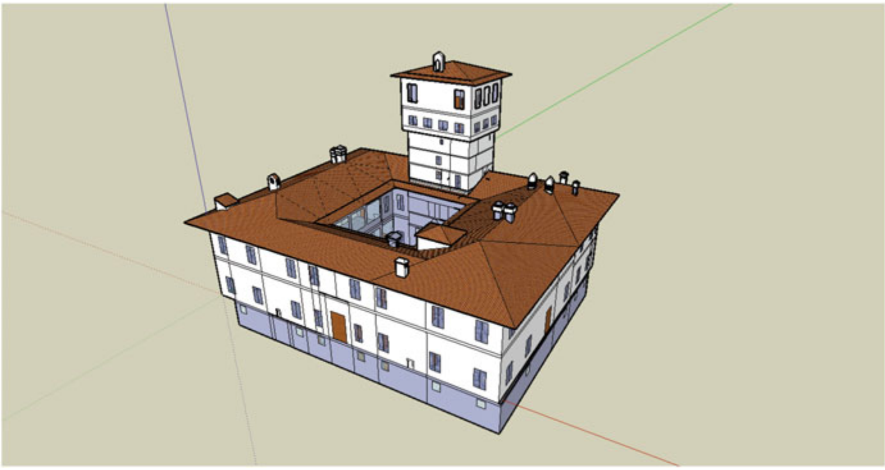


Fig. 9.10 Virtual model without courtyard

9.5.2 Scenario Without Covering of the Internal Courtyard with Weather Data from 1650

Indoor microclimatic conditions are determined both by the architectonical and technological configuration of the building and by the macroclimatic outdoor conditions of the times. The choice for 1650 is due to the presence of detailed historic climatic data for this year. It is indeed possible to insert these information in the virtual model.

9.5.2.1 Configuration of the Building in 1650

The probable conformation of Villa La Petraia in 1650 has been defined on the basis of archival and bibliographic research. The main differences from the current configurations are the following:

- The iron and glass covering in the central courtyard was absent in 1650 (it has been built after the union of Italy in 1861).
- Changes in the distribution of the underground spaces.
- Some of the capitals of the ground-floor loggiato have been substituted.
- Changes have been made in the external part, concerning the terraces and the park behind the Villa.

Of these, only the first has an influence on indoor microclimate, as only the removal of the covering in the courtyard had an effect on the simulations of indoor microclimate, i.e., only removing the virtual room “courtyard,” the model resulted different.

9.5.2.2 Climatic Data Collected in Florence in 1650

Climatic data from the seventeenth century have been obtained through Camuffo and Bertolin (2012a, b), who carried on some researches on climatic data and documents related corresponding to the time period between 1654 and 1670. These were based on the information given by the Medicean Net, the first international net for meteorological observations, formed by 11 climatic stations, 7 of which were in Italy, the main ones in Florence and Vallombrosa.

Results

The building simulation follows the construction of the virtual model. The main results from this study that are considered and commented here are the following:

- The current architectonic configuration which allows to calibrate the virtual model, as described in the previous paragraph, and to evaluate the trends of the variables in the rooms not included in the monitoring.
- The historic architectonic configuration and the climatic data form 2015, to verify the influence of the covering in the central courtyard on indoor microclimate and of possible design solutions that allow the opening of the central courtyard covering.
- The historic architectonic configuration and the climatic data from 1650, to evaluate the microclimatic conditions in the past and the comfort that the Medici were experiencing when living in Villa La Petraia. Consideration on comfort in past times, clothing, and other habits can be done starting from these analyses.

To illustrate the efficiency of this methodology, here follows a list of the most significant results obtained from the research, with graphics and relative observations. Other levels of analysis could be developed, but are not relevant here.

The results are on their own a support to evaluate the strategies of conservation of Villa La Petraia and the artifacts and furniture conserved in it, to manage the access of visitors and to evaluate further projects, such as to automate the openings in the covering, and finally to study life conditions in the past.

Here, for each configuration are reported the results of the simulated trend of air temperature and relative humidity, the cumulated curve of frequency, and the air temperature/relative humidity graph. This is for each of the three rooms where the probes have been placed: internal courtyard, Red Room, and Games Room.

9.5.2.3 State of Art (Actual as It Is)

The result refers to the model representing the current conditions and to the actual indoor microclimate—AIM.

Relative humidity in the *internal courtyard* ranges mainly between 30 and 70%, with some daily peaks, mainly during spring and autumn (April–May and October–November), up to 80%. During summer the values are usually particularly low because of the increase in indoor air temperature—which reduces relative humidity even if the total amount of vapor is the same or higher. Summer air temperature can reach and exceed 35°C, which has big negative effects on the thermal comfort of visitors. During winter, the temperature usually is around 20°C, with low peaks down to −10°C.

In the *Red Room*, the simulations show higher values of relative humidity during spring and autumn, with peaks of 90%. Despite this, most of the daily ranges are within 30–40%, with 10% variation, because of the higher stability of the mass exchanges due to ventilation in the standard values of the simulation. Summer values are usually a bit lower, with some peaks up to 70% and most daily variations within 10%. Temperatures can reach 30–35°C during summer time, and 5°C during winter. Hence, indoor microclimate of the Red Room results to be more stable than that of the central courtyard, but still shows level of relative humidity higher than those that would avoid thermal discomfort of the visitors and decay of the art pieces conserved in the room.

The results for the *Games Room* are similar to those of the Red Room, with a slightly higher daily variation of temperature during summer (Fig. 9.11).

The comparison of air temperature values in the three spaces shows something interesting:

- The highest daily variations happen during winter times.
- The two rooms share similar trends, except lower values of the Red Room during spring.
- The values in the internal courtyard are always higher than in the rooms, with a difference of about +5°C during summer and of about +15°C during winter and spring. This confirms the greenhouse effect in the central courtyard due to the covering, even if this doesn't appear having direct influences on the natural ventilation among rooms and from the rooms to the courtyard.

In the same way, comparing the trends of relative humidity, it appears that the three room have ranges and trends very similar in all the seasons, between 10–15% and 85% during winter and spring and between 25 and 65% in summer (Figs. 9.12 and 9.13).

The T/RH air temperature and relative humidity graphic (Fig. 9.14) defines characteristic indoor microclimate for each of the three simulated spaces. On the right side are evident the peaks of heat and relative humidity in the internal courtyard, with values, respectively, above 35°C and 40%, which is a situation of thermal discomfort. The internal courtyard has a different point distribution, compared to the other two rooms, which distributions describing indoor microclimate are mostly overlapping. In all the rooms there are several days in which temperature reaches 30°C and humidity 30–60%, and days with lower temperatures, of 10–15%, but higher values of relative humidity (50–80%).

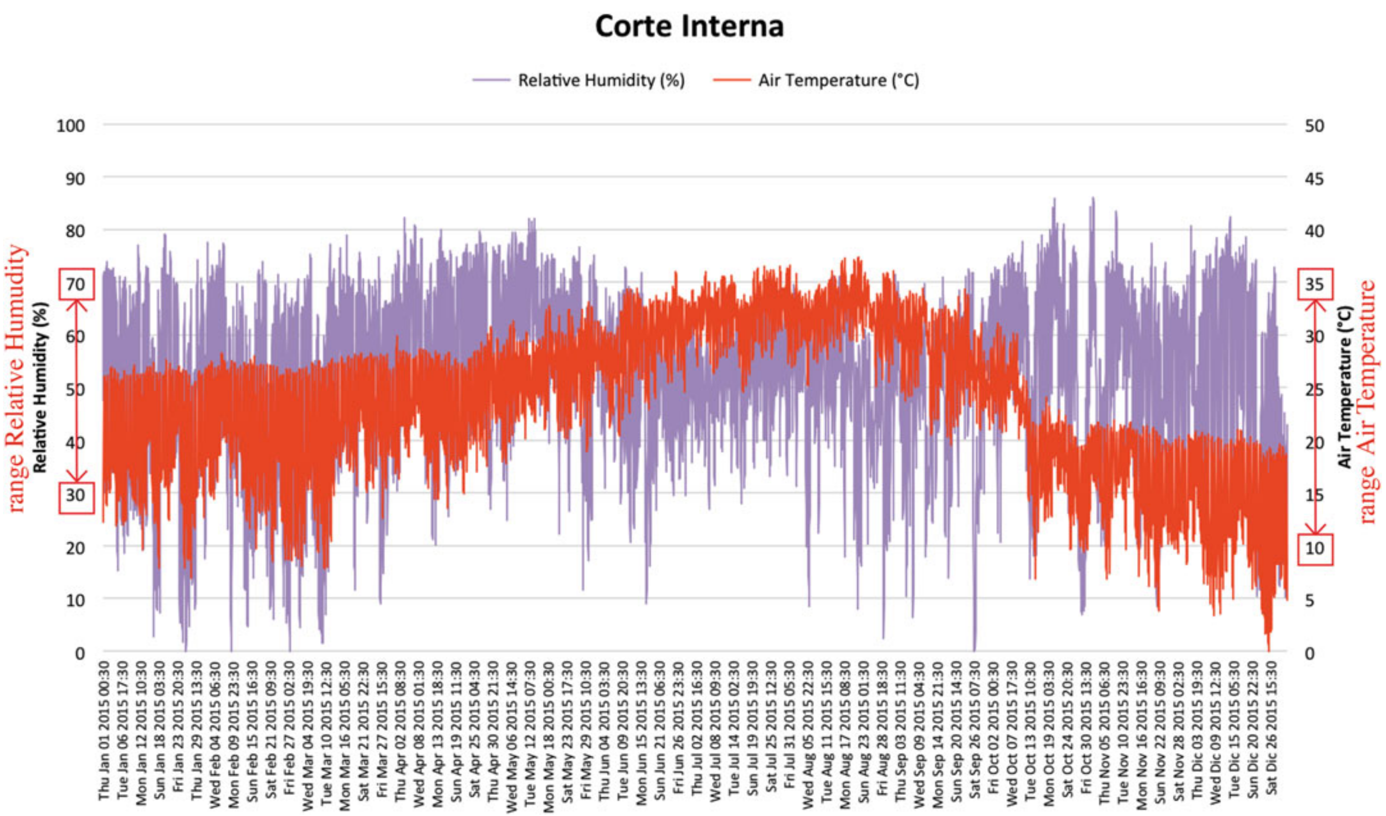


Fig. 9.11 Current conditions: results of air temperature and relative humidity trends: (**a**) internal courtyard, (**b**) *Red Room*, (**c**) Games Room

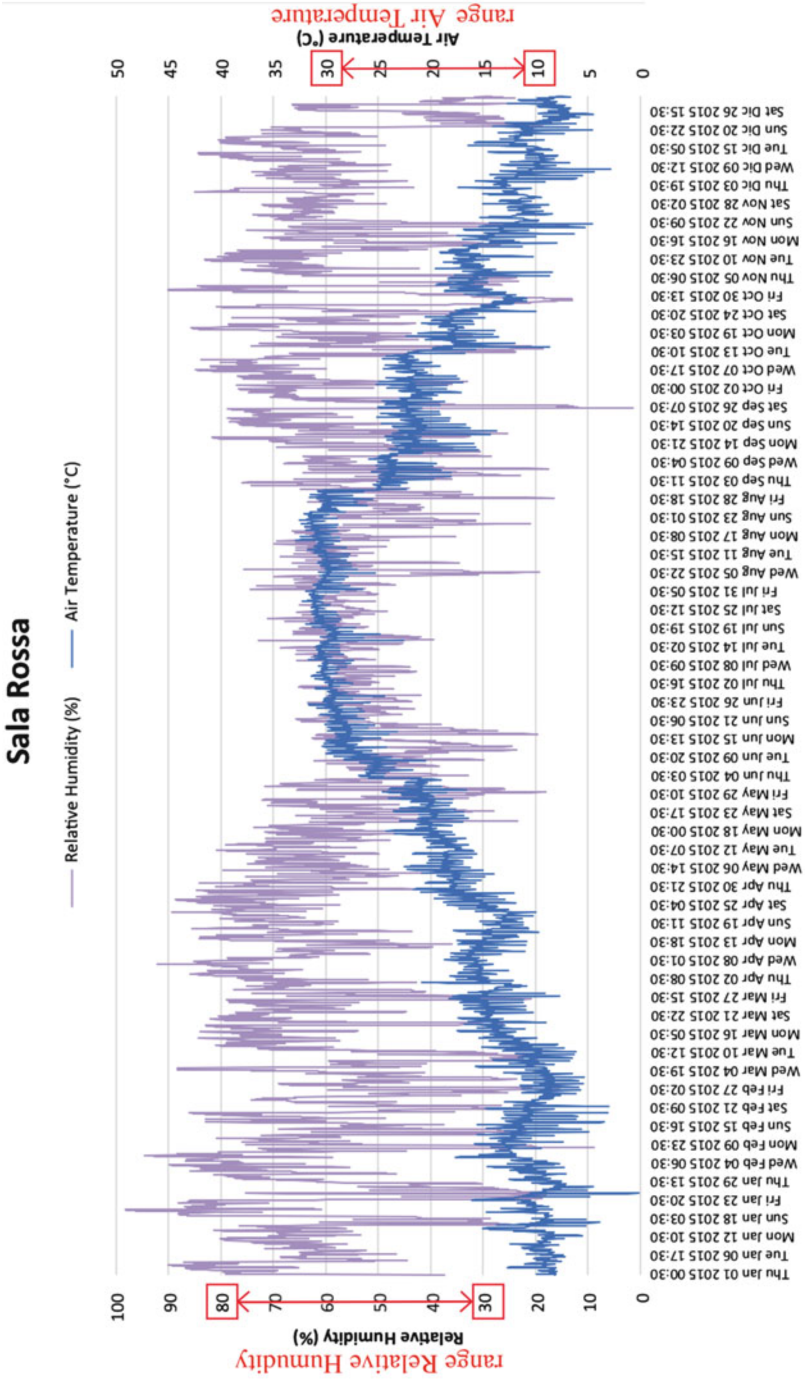
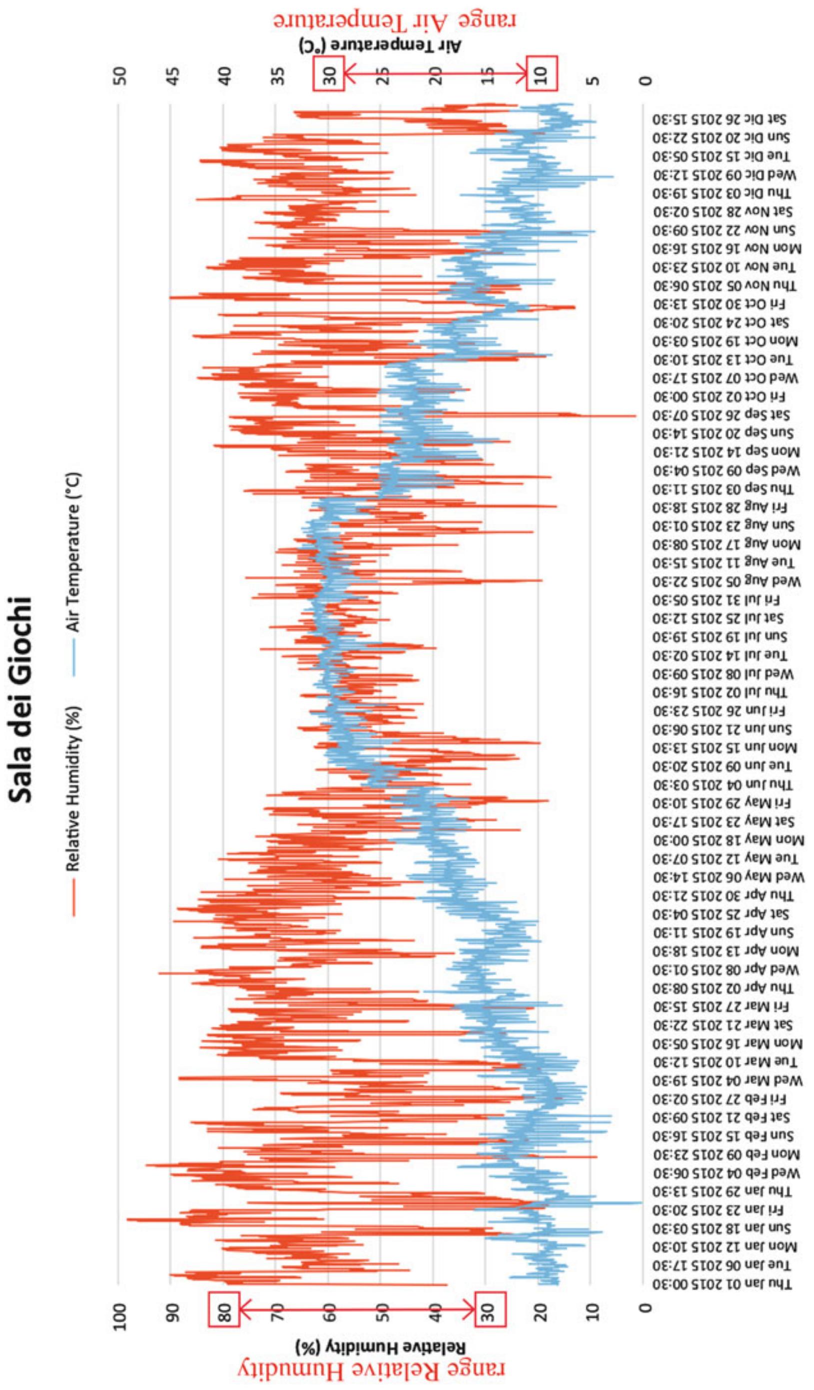


Fig. 9.11 (continued)


Sala dei Giochi
Relative Humidity (%)
Air Temperature (°C)
range Air Temperature
Air Temperature (°C)
0
5
10
15
20
25
30
35
40
45
50
range Relative Humidity
Relative Humidity (%)
0
10
20
30
40
50
60
70
80
90
100
Thu Jan 01 2015 00:30
Tue Jan 06 2015 17:30
Mon Jan 12 2015 10:30
Sun Jan 18 2015 03:30
Fri Jan 23 2015 20:30
Thu Jan 29 2015 13:30
Wed Feb 04 2015 06:30
Mon Feb 09 2015 23:30
Sun Feb 15 2015 16:30
Sat Feb 21 2015 09:30
Fri Feb 27 2015 02:30
Wed Mar 04 2015 19:30
Tue Mar 10 2015 12:30
Mon Mar 16 2015 05:30
Sat Mar 21 2015 22:30
Fri Mar 27 2015 15:30
Thu Apr 02 2015 08:30
Wed Apr 08 2015 01:30
Mon Apr 13 2015 18:30
Sun Apr 19 2015 11:30
Sat Apr 25 2015 04:30
Thu Apr 30 2015 21:30
Wed May 06 2015 14:30
Tue May 12 2015 07:30
Mon May 18 2015 00:30
Sat May 23 2015 17:30
Fri May 29 2015 10:30
Thu Jun 04 2015 03:30
Tue Jun 09 2015 20:30
Mon Jun 15 2015 13:30
Sun Jun 21 2015 06:30
Fri Jun 26 2015 23:30
Thu Jul 02 2015 16:30
Wed Jul 08 2015 09:30
Tue Jul 14 2015 02:30
Sun Jul 19 2015 19:30
Sat Jul 25 2015 12:30
Fri Jul 31 2015 05:30
Wed Aug 05 2015 22:30
Tue Aug 11 2015 15:30
Mon Aug 17 2015 08:30
Sun Aug 23 2015 01:30
Fri Aug 28 2015 18:30
Thu Sep 03 2015 11:30
Wed Sep 09 2015 04:30
Mon Sep 14 2015 21:30
Sun Sep 20 2015 14:30
Sat Sep 26 2015 07:30
Fri Oct 02 2015 00:30
Wed Oct 07 2015 17:30
Tue Oct 13 2015 10:30
Mon Oct 19 2015 03:30
Sat Oct 24 2015 20:30
Fri Oct 30 2015 13:30
Thu Nov 05 2015 06:30
Tue Nov 10 2015 23:30
Mon Nov 16 2015 16:30
Sun Nov 22 2015 09:30
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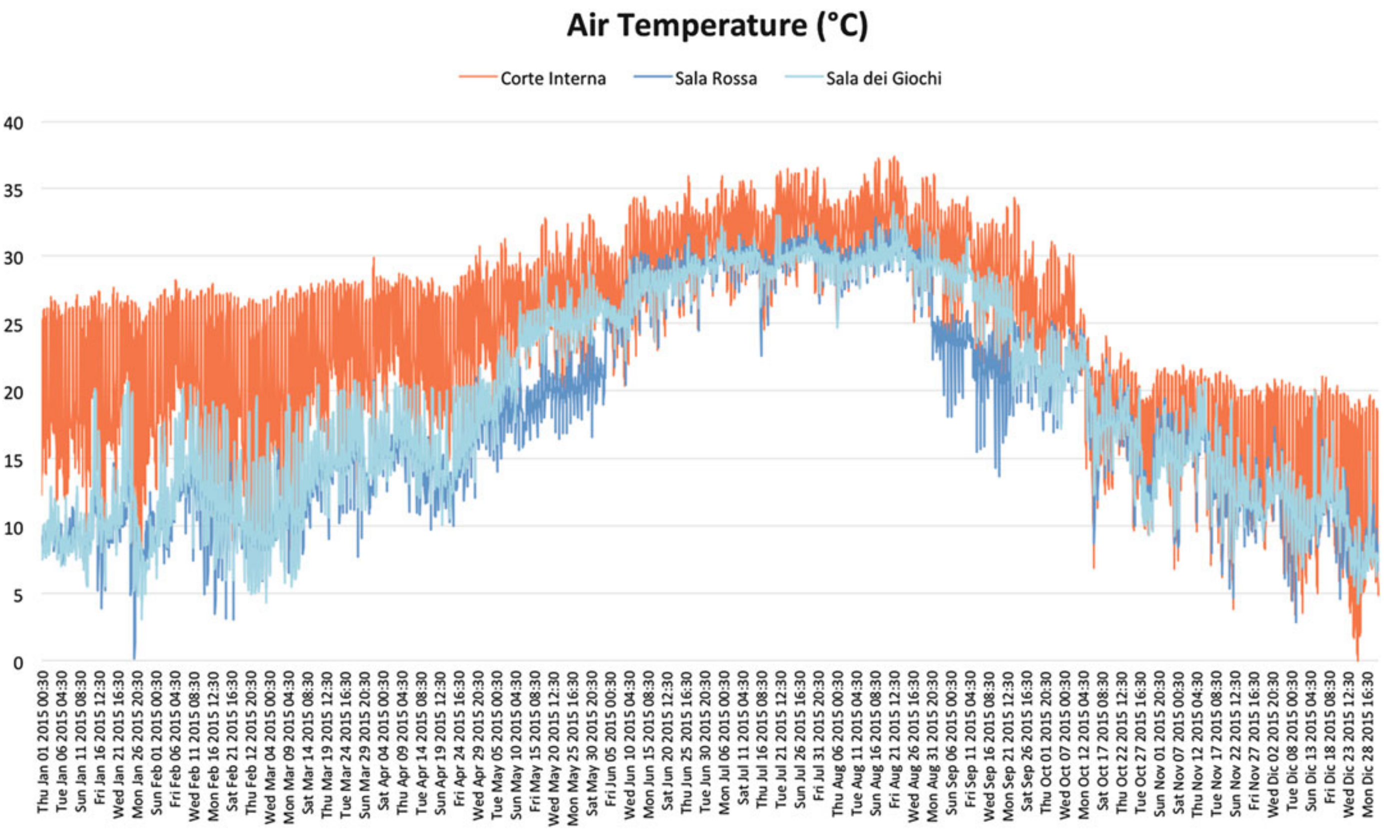

Fig. 9.12 Current conditions: results of air temperature trends in the three rooms

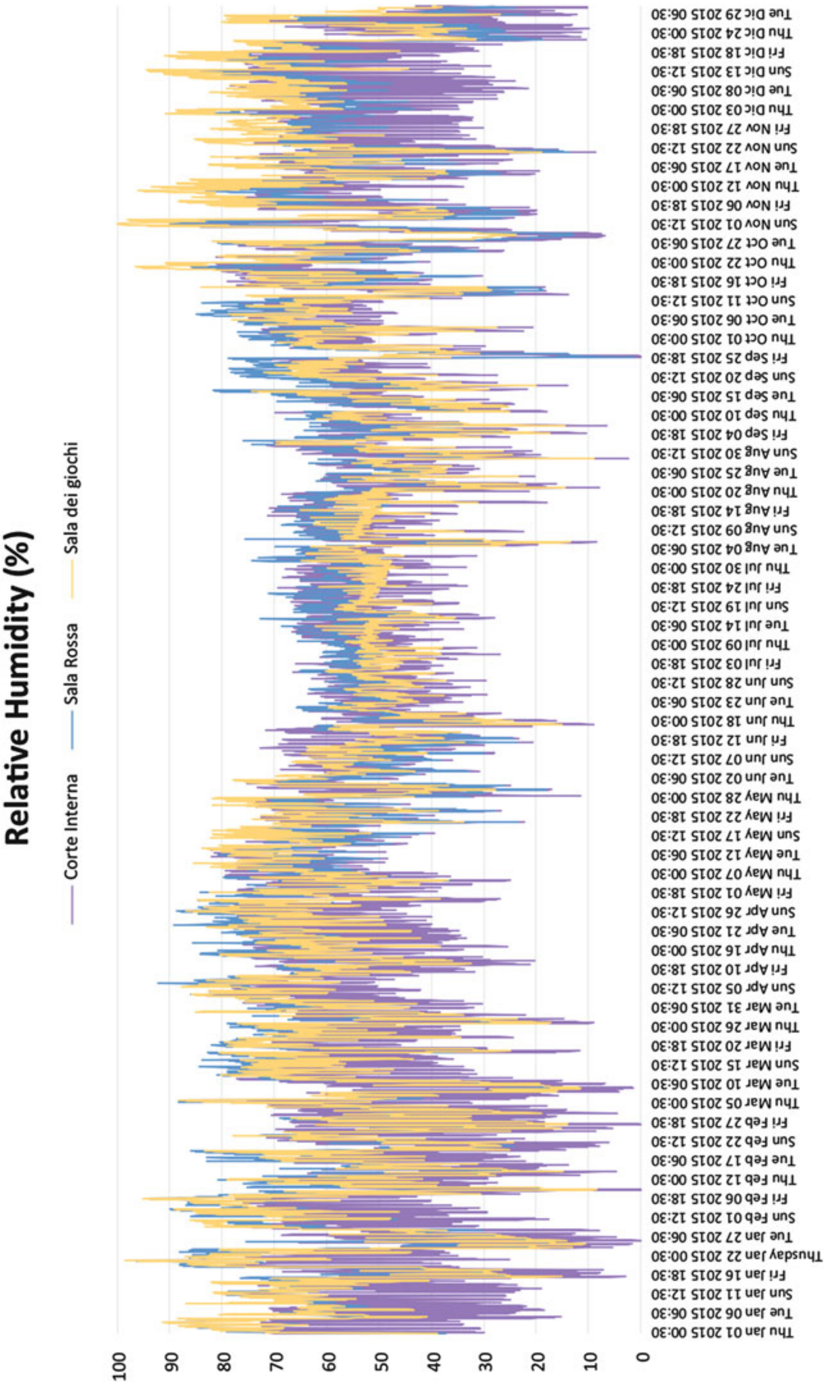

Fig. 9.13 Current conditions: results of relative humidity trends in the three rooms

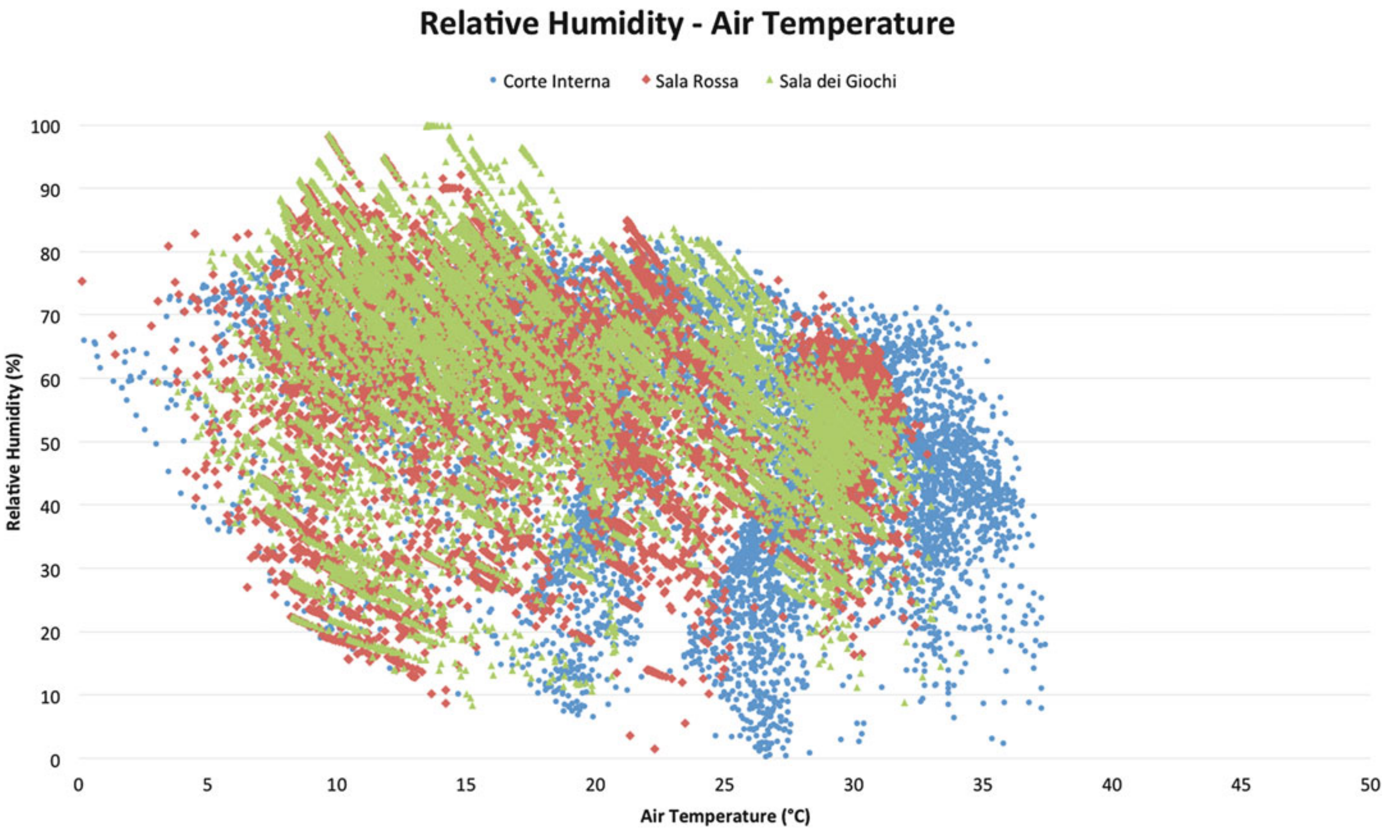

Fig. 9.14 Current conditions: graphic of T/RH, air temperature, and relative humidity in the three rooms

9.5.2.4 Results of Historic Conformation and Climatic Data from 2015

The following data have been obtained with the virtual building simulation using the architectonical configuration of 1650, without the glass cover in the internal courtyard, and the climatic data from 2015.

The data concerning indoor microclimate in the *Red Room* show an overall homogeneous trend, if compared to the simulation of the current condition. Temperature, in particular, doesn't show the steep increases that happen during summer with the covering. Moreover, average temperature during summer is lower, 25°C, compared to 30°C with the covering. Evident effects of the covering are hence to keep higher indoor temperatures in the rooms during summer. The influence of the covering on relative humidity is less evident, as consistent daily variations are still present, abundant during summer time, but their frequency is slightly reduced (Fig. 9.15).

The same differences appear in the *Games Room*: without the covering, summer temperature values are about 5°C lower than in the simulation with the covering, with small daily variation. On the contrary, relative humidity results to be slightly higher, but the difference is not relevant.

The comparison between the trends of air temperature and its cumulative frequencies, for both rooms, as well as with relative humidity and its cumulative frequencies, with the temperature/relative humidity graph shows that indoor microclimate characteristics of the two spaces are almost coincident, with a small difference of maximum and minimum temperatures.

The comparison of air temperature between Red Room and Games Room show, in the simulations with and without the covering, a decrease of about 3–5°C (Figs. 9.16 and 9.17).

9.5.2.5 Results of Historic Conformation and Climatic Data from 1650

Here are presented the results of the simulation of virtual building with the climatic data and architectonic configuration, i.e., with no covering in the courtyard, from 1650.

Indoor microclimate in the *Red Room* shows a more homogeneous trend, compared to the current situation. In particular, air temperature doesn't show the steep increase that appears in the simulation with the covering during summer, as it happens in the previous simulation. Moreover, temperature during summer is generally lower, and in the current conditions can easily reach 30°C, while in the scenario with no covering and with climatic data from 1650 average air temperature is usually about 22–25°C. The influence that the covering has on maintaining higher temperatures in the courtyard is evident and that external climate during the seventeenth century was on average less hot than today. Several peaks below 10°C indeed are registered in summer and a higher daily variation during winter.

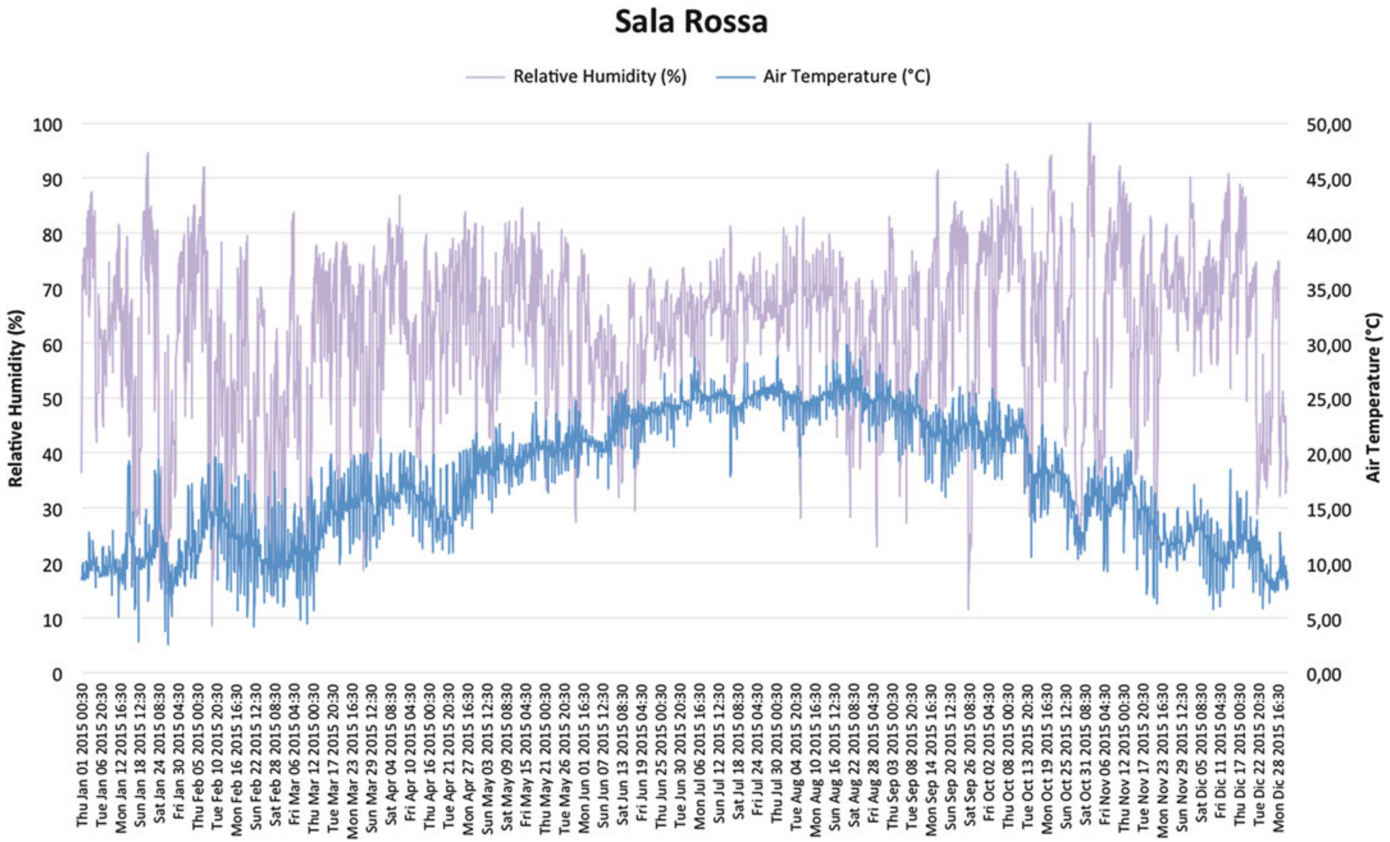

Fig. 9.15 Scenario with no covering 2015: results of the air temperature and relative humidity trends: (**a**) *Red Room*, (**b**) Games Room

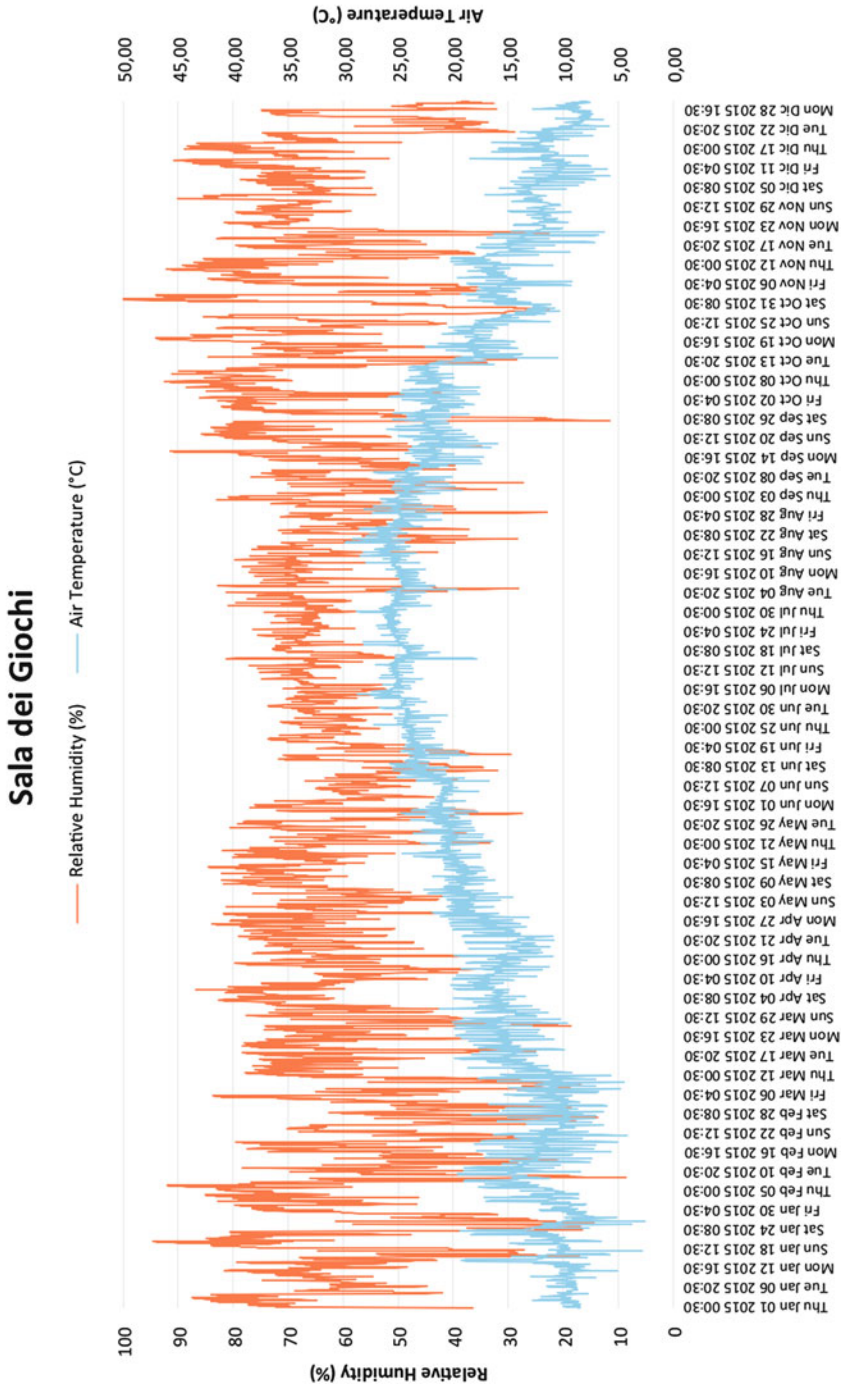

Fig. 9.15 (continued)

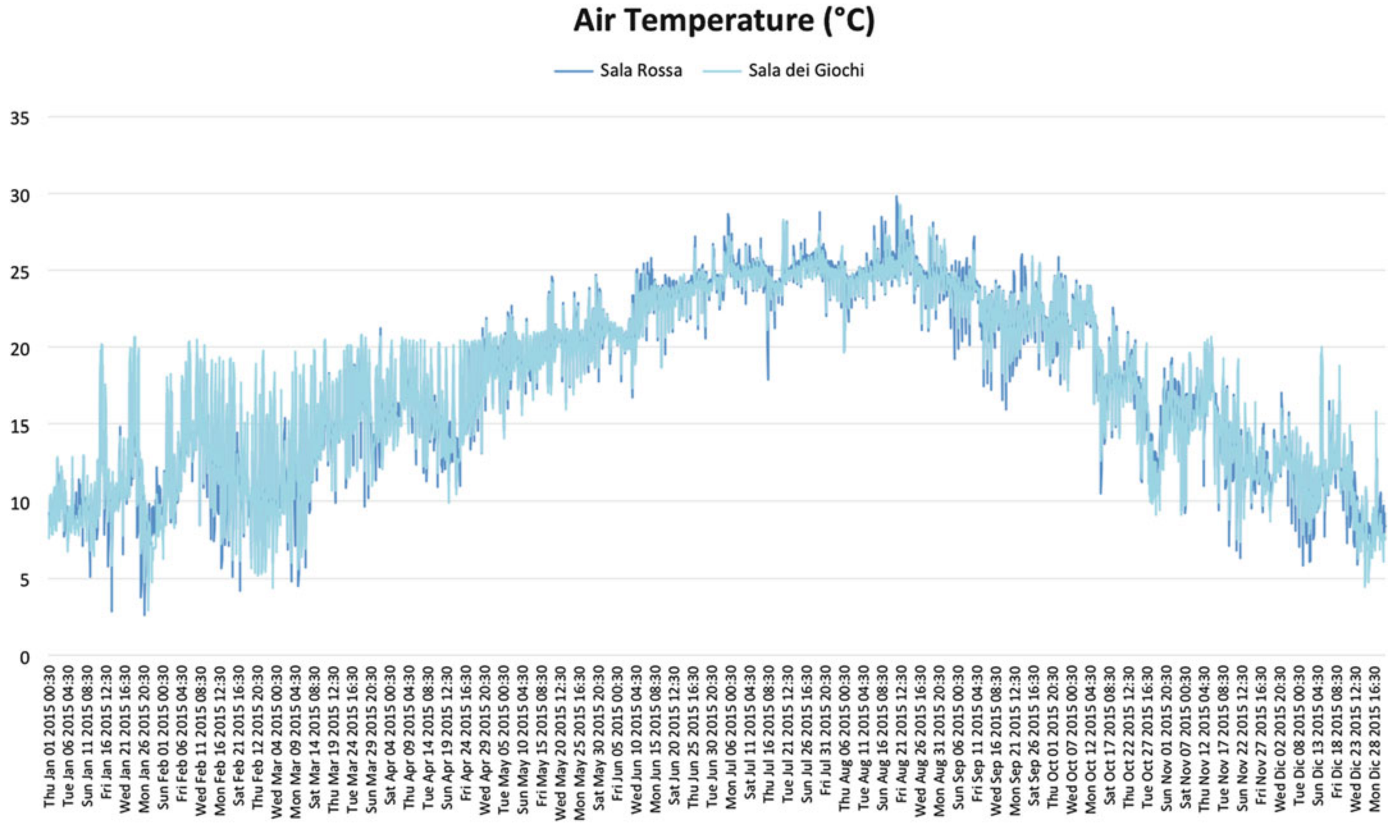

Fig. 9.16 Scenario with no covering 2015: air temperature trends (**a**) and cumulative frequency (**b**) in the *Red Room* and in the Games Room. It can be noted that, with no covering, the two trends are comparable, with a slightly higher value in the Games Room during summer times

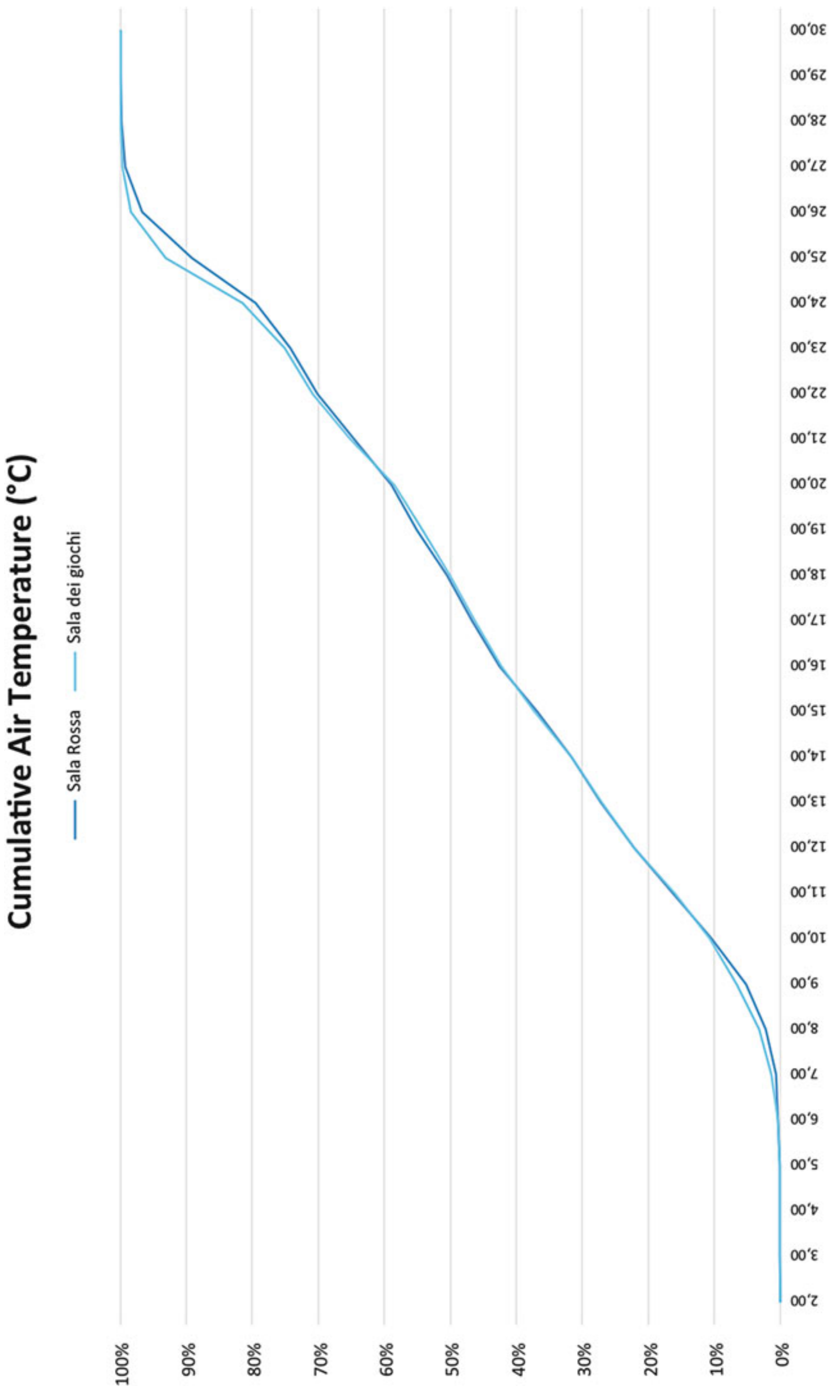

Fig. 9.16 (continued)

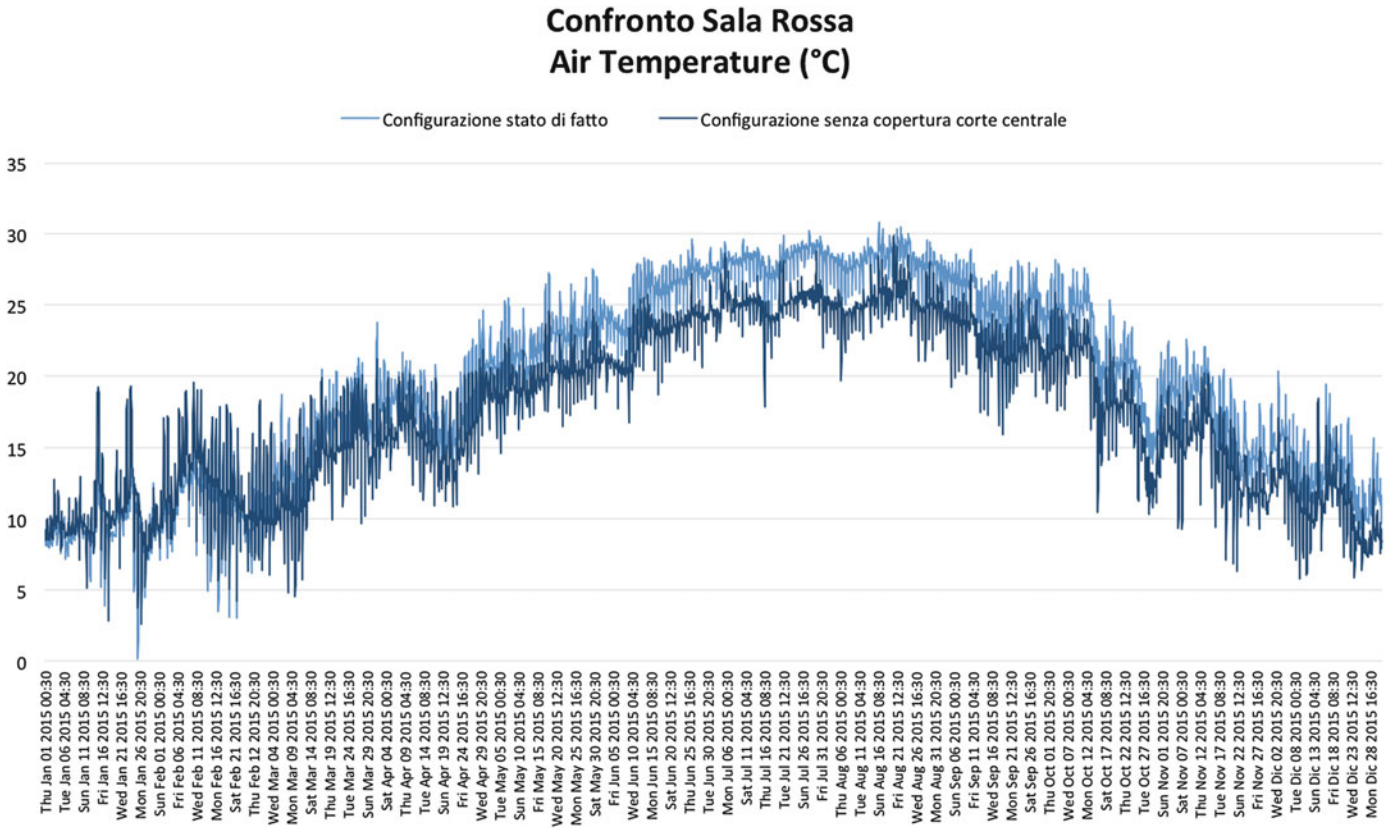

Fig. 9.17 Comparison between the results of air temperature trends of the real conditions and of the simulation with no covering 2015, (**a**) *Red Room*, (**b**) Games Room. In both graphics it is clear that air temperature is significantly higher during summer time in the configuration with no covering. This corresponds to the expectations, given that the covering on the courtyard determines in it a greenhouse effect, and reinforces the importance of the benefits of the convective motions that are created if the courtyard was to be opened. A difference amounting to 4–5°C, as this one, should not be underestimated with respect to the conservation of the building and the artifacts

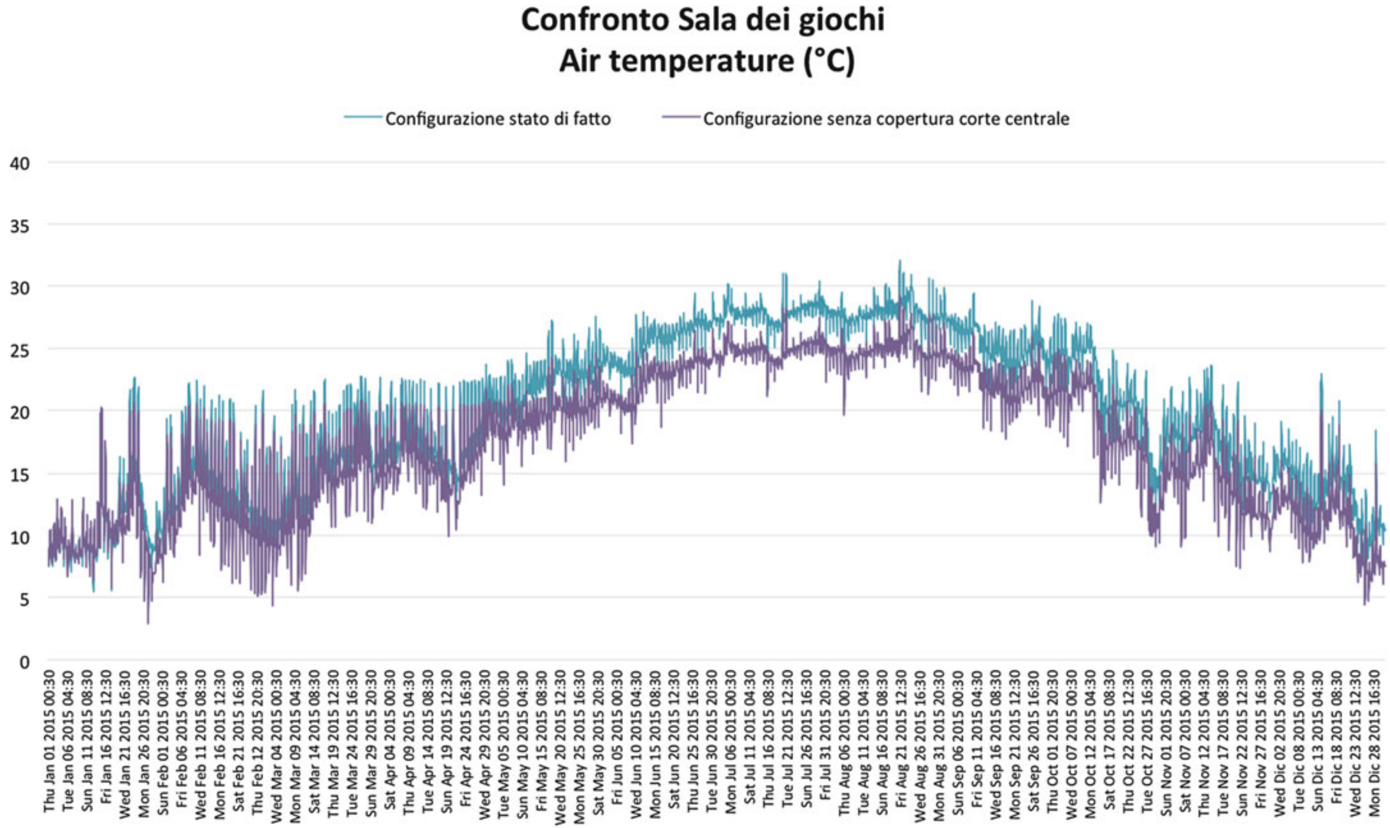

Fig. 9.17 (continued)

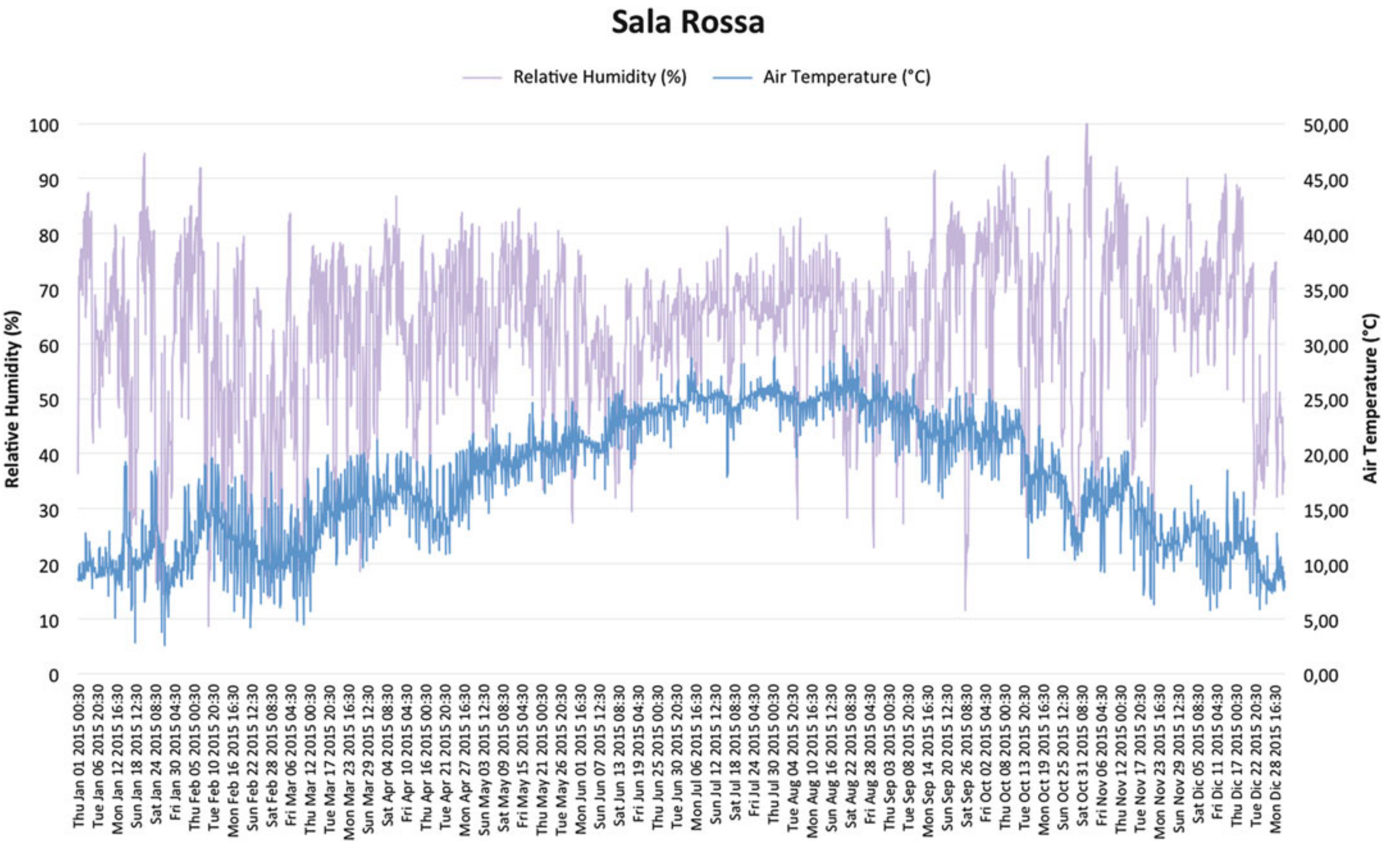

Fig. 9.18 Scenario with no covering 1650: results of the air temperature and relative humidity trends: (**a**) *Red Room*, (**b**) Games Room

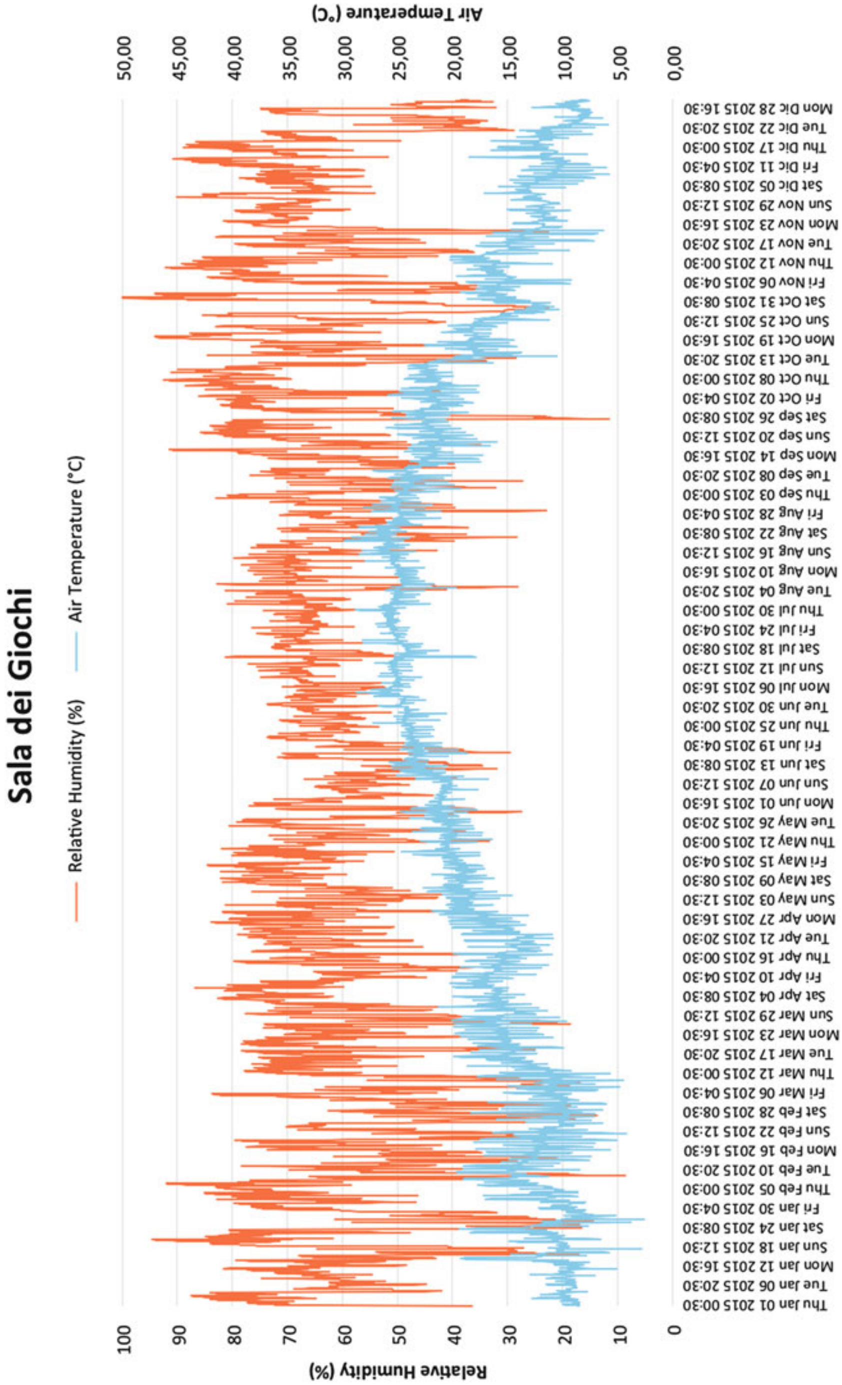

Fig. 9.18 (continued)

The influence of the covering in the courtyard and of 1650 climate in trends of relative humidity is less evident, and daily oscillations are still present if reduced in number.

Similar differences are registered in the *Games Room*: with no covering and with data from 1650, indoor temperature values are about 5°C lower, with small daily variations. On the contrary, relative humidity trends show slightly higher values during summer time, despite these not being significant (Fig. 9.18).

9.6 Restoration Strategies Based on Indoor Microclimate Simulations

The study of *Historic Indoor Microclimate* in Villa La Petraia allows to review the microclimatic conditions starting from the original ones (OIM) from medicean times.

The experience carried on in Villa La Petraia, applying the methodologies exposed in the first part of the book, makes it clear how the study of indoor microclimate allows to study the consequences of actions and interventions, to understand whether these can have positive effects on the conservation of the architecture and of its content, basing the research on virtual models coherent with reality.

This is one of the most efficient applications of the preventive conservation, carried on through researches and simulations on models specifically created (Fiorani 2009). It is a direction of research already traced more than a century ago by Aloïs Riegl, in order to save the historic value that each building intrinsically has, without affecting the physical matter that forms it.

It is then possible to define a project based on the specific knowledge acquired and on the modeling simulation. It is then evident that, in Villa La Petraia, historic research coupled with reconstruction of HIM can suggest some solutions to intervene on the building, gradually giving more and more concrete answers to the currently inadequate microclimatic situation, which endangers the building as well as are uncomfortable to the visitors.

The historic approach suggests several interventions. Adopting them in a sequence, it would be possible to specifically evaluate their effect:

- Recreate the top opening in the lantern with a mechanized system of windows, which would solve the problem of the difficult access to the lantern itself.
- Open the big ground grates, currently closed, to verify how the air current coming from the underground, with its difference in temperature and relative humidity, would help the microclimatic conditions of the courtyard and of the whole Villa.
- Define a protocol to manage the opening of crossed axial doors, which are a peculiarity of the plan of the villa, in order to achieve the same result.
- As a last, almost challenging, suggestion, the complete removal of the covering in the courtyard and recovery of the microclimatic conditions of 1650 at least as the configuration of the Villa is involved.

Observe that, with the exclusion of the last one, none of the suggested solutions affect the physical structure of the Villa. This moves the focus of the intervention from the direct restoration of matter, typical of restoration, to the conditions surrounding this matter, as is suggested in the whole school of programmed prevention (see Urbani 2000). In other terms, the study of HIM allows this passage that only few researchers in the restoration field had foreseen and hoped for.

It is as well clear that these studies should be preparatory to the introduction of sophisticate interventions, correlated to their results, as shown above. It is an example system of microclimatic monitoring, not temporarily placed but constant part of the monitoring of the building, which could, in the Villa, be connected to the system to open the windows in the lantern. This way, the programmed conservation would become some sort of automatic intervention, independent from the personnel of the Villa, and a much more efficient one, with the result of delaying in time and reducing in effort the real restoration of the building and of its content. These would be easy solutions, with relatively low costs of installation and management, that would assure greater savings as reducing the need of invasive and expensive interventions, as restoration of heritage buildings usually is.

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Chapter 10
The Santuario della Visitazione del Valinotto, Turin, Italy

Marco Pretelli and Kristian Fabbri

Abstract This chapter reports the study case of Santuario della visitazione del Valinotto in Carignano, close to Turin. In contrast to the previously reported cases, in this building the research has been carried on alongside restoration works and part of the collected information has been used to tune the works on the church and the frescoes. Some results have been already published. The building is characterized by a vertical development of spaces, and the consequences of it, mainly on air stratification and of relative humidity, have been observed through the monitoring and the analysis of the resulting graphics of variables and cumulative curves.

10.1 The Building

The Santuario del Valinotto is a Church in the countryside close to Turin North-West of Italy. The research has been developed within an agreement aiming at acquiring information for the restoration of the building and of the frescoes in it. The Santuario has a particular actual indoor microclimate, determined by its peculiar architectonic structure, with the accentuated vertical development, and the countryside location, far from any other building and influenced by the sole weather conditions. Within this book, this exemplum shows how to use the result of monitoring activities to evaluate trends and cumulative curves of air-temperature and relative humidity.

10.1.1 History of Santuario del Valinotto

The Santuario del Valinotto, in via Virle in Carignano (TO), is one of the main works of Bernardo Antonio Vittone (Torino, 1702–1770). The building is still

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Fig. 10.1 The Santuario della Visitazione al Valinotto complex, north side. The main entrance is on the other side. Note, on the right, the sacristy (picture of the authors)

surrounded by countryside and represents one of the most interesting examples of piemontese baroque (Fig. 10.1).

Built in 1738, it is a mature production of the architect, pupil to Juvarra and Guarini. Over the central hexagonal plan, the architect planned "volte l'una sovra l'altra (. . .) tutte traforate e aperte" (vaults each over the other (. . .) all pierced and open," from Vittone BA (Vittore, 1760).

The result is a complex geometry, with multiple levels, interlaced arches, windows covered with membranes, and a significant vertical development that allows the light to fall from above.

The main entrance of the church faces via Virle, a road with high frequency of cars and trucks, while the private drive on the southeast side takes to a working farm. The secondary entrance, which is today the way into the central body of the building, lays south of the sacristy, in the southwest side. The church counts a single space, covered by a ribbed dome completely decorated. Externally, it shows three shelving layers and the walking floor is aligned with the surrounding grounds, with the main entrance on the side facing via Virle.

The maximum height, that of the intrados, is about 23 m, while the diameter of the internal area is about 9 m. The walls are 60–70 cm thick, made of solid bricks and lime, plastered both internally and externally. Every wall is internally decorated by paintings at any level and the floor is covered in cotto tiles. The deep recesses of the bottom level open below a wooden-framed window.

The chapel is currently undergoing a restoration of the parietal paintings, a project started in January 2015, when the scaffoldings have been installed, while the monitoring started in February of the same year. The scaffoldings, with their several working floors, cover the whole internal surface of the walls and allow reaching the dome (at about 20 m high). The position of the scaffolding itself does not allow to open the main door, so that the entrance to the chapel is possible only through the sacristy. Visitors and observants coming to the church for the mass of Saturday (from about 16:00 to 19:00) use at the moment this latter entrance.

10.1.2 Indoor Microclimate of Valinotto as the Object of the Study

The indoor microclimate of Santuario del Valinotto constitutes the focus of the study, in particular the convective motions and the mass and energy transfer that happen close to the plastered walls. These are related to the internal and external climatic conditions, in addition to the physical and geometric characteristics of the building.

The content of steam in the indoor microclimate depends on the temperature and relative humidity. In general, a higher value of relative humidity corresponds to a higher risk of condensation close to the walls at the dew point. Condensation, in turn, causes secondary degradation phenomena, linked to freezing/defrosting cycles, to microbiological aggressions that become possible, to absorption of water in the plaster, to the dissolution in water of polluting powders, etc.

Temperature and relative humidity were monitored with probes and the data used to discuss about indoor microclimate and stratification of temperature and vapor. The availability of two probes only in the lower part of the church, though, reduces the accuracy of the information of the stratification in the upper levels.

The technicians responsible for the photographic surveys visited the church in February and March 2015, while in April few people visited the building, apart from the architect A. Mannina and the nun responsible for the mass.

The wiring frame is placed on the right of the entrance from the internal courtyard of the sacristy, behind the apse. People in charge of both the works of restoration and of the religious function can access the wiring frame so that electricity is disconnected when not needed.

10.1.3 Convective Thermal Exchange

The monitoring activity has focused on air temperature and humidity, and on contact temperature. The sensor used has a section of about 30 mm, while the contact probe is inserted in the wall for a length of about 15 mm. This results in the data being collected between the surface temperature and the 30 mm of the temperature sensor. In this layer, the exchanges are only convective, since:

- Thermal exchanges due to conduction between different materials are absent, since the contact probe is only inserted in the plaster layer.
- Thermal exchanges due to passage of heat from the outdoor space to the indoor one, due to solar radiation, can be considered null, because of the thickness of the wall, over 1 m. Hence the thermal shift due to irradiation can be considered noninfluent.
- Thermal exchanges due to irradiation from the wall surface and other surfaces can be considered null or not influent, since the walls face other walls with the same temperature, and inside the space there are no heat sources or other bodies at a different temperature, such as people.

Hence in this specific case, it is possible to study the sole thermal exchanges due to convective motions.

Convective motions within the building can concern:

- (a) The air volume, i.e., the movements of the indoor air volume, due to the localized differences in temperature or air pressure, originated by different phenomena: opening of door and windows, upward currents, presence of people, etc
- (b) Laminar and turbulent motions happening in the limit layer, dynamic and thermal, close to the walls

Convective motions of type a influence air speed and water vapor, hence relative humidity within the building. Convective motions of type b depend on the motions happening close to the wall.

This way two physical phenomena appear:

a. *Thermal exchange due to convention*, depending on the difference in temperature between one wall and the other, and on the geometry of the thermal exchange, which in turn determines a-dimensional numbers
b. *Psychrometric transformations* of the air close to the limit layer, with respect to the processes of condensation and vaporization of water vapor contained in the air between the limit layer and the wall

The higher risk for plastered walls in particular in heritage buildings when frescoes or paintings are present is due to the formation of superficial condensation. This, in turn, depends on the superficial temperature of the wall (T_p), which must be higher than the dew point (T_d) and of the content in water vapor close to that wall itself: the higher the RH value, the higher the risk of condensation formation.

10.2 The Monitoring Campaign on Site

The geometry of the building is complexly articulated, an elliptical basis with several chapels built on the profile, vertically developed with arches and vaults, up to the lantern as shown in Fig. 10.2.

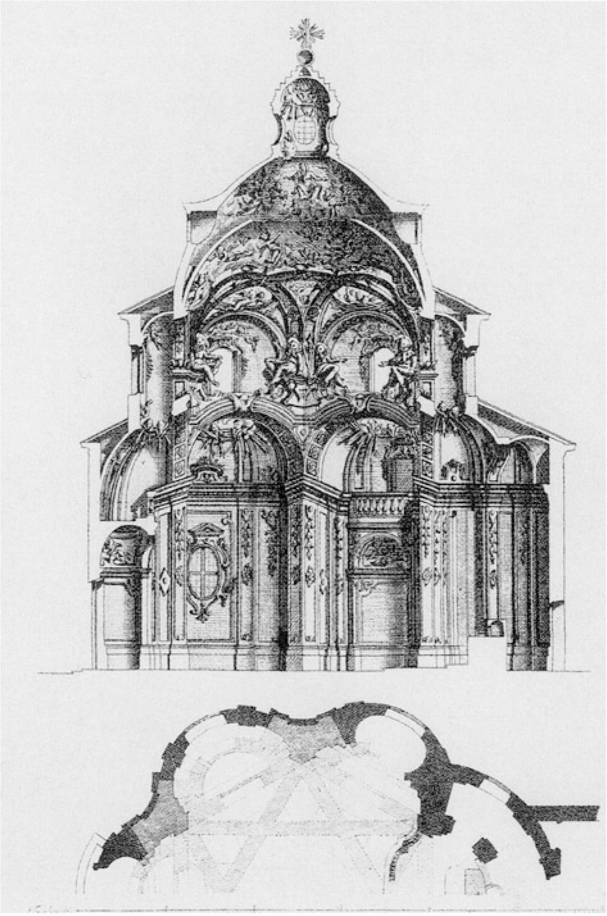

Fig. 10.2 Vittone BA, map and section of Santuario del Valinotto in Carignano (from Vittone 1766 II, tav. LXXVIII)

The monitoring campaign included the placement of probes to measure air temperature and relative humidity in two points of the building, one above the other, along a flat and homogeneous part of the building, so to evaluate the stratification of air in two points.

During the monitoring activities, several difficulties have been met, listed here in order to help with the data interpretation and to help with future researches with monitoring systems, such as that installed in the Santuario del Valinotto, with wireless sensors and remote control.

On the 26th of March 2015, following an inspection, a new probe, sensitive to gas concentrations, has been installed. This has sensors to check temperature, relative humidity, luminosity, as well as concentrations of CO2, CO, and NO2, with a lithium battery that can be charged straight from the plug. Since the electric current was not continuous (the operators of both the restoration works and religious activities kept switching off the wiring frame despite adequate signals), the probe, depending on electric current to work, couldn't be kept working continuously. As a consequence the data collected with it couldn't be considered significant to the research.

This has been a useful experience, if a negative one, because we learnt that, to activate a correct monitoring alongside ongoing works, it is very relevant to inform all of the people working in the buildings and to take into account the phases of the work itself.

The chosen system, developed by Genesis, allows placing several probes with different sensors. Each of them sends information to the bridge, which, in turn, sends the data to the server through GPRS. The data are downloadable from an online console which access requires a password. The possibility to check the data online simplifies the maintenance.

Figure 10.3 shows the positioning of the probes.

10.2.1 The Monitoring System

The devices used in the monitoring are:

- Hardware:
- 1 Bridge (Beeper-Bridge) to collect and transmit the data remotely through GPRS system
- 2 Probes (Beeper-Node), constituted by transponders and "onboard" sensors used to detect and monitor the physical characteristics of the environment as well as to transmit the data to the Bridge
- Website, to visualize the data remotely

The devices are tied to the walls with plugs and are fed by electronic batteries. Their placement was decided so to reduce the impact on the building (two holes per probe) and to collect significant data, considering the geometry of the architecture (software: EnergyPlus through graphic applications IES.VE o SImergy).

The net of wireless sensors (BEESPER di Henesis srl) represents a complete solution for remote monitoring. The system is formed by a hardware part that monitors and collects data, and by a software suite to save the data, elaborate the signals, and generate the data, plus the portal WEB WISnP that can recall data, configure some parameters of the net, and generate reports.

The Beeper-NodeA Genesis is a wireless MICROCOMTROLLED module, with high performances and low cost. The module can host the ZigBee® as well as the builder h-Pro, or other protocols defined by the user.

BeeperNode Base (No. 2) ID_060B, ID_BE48 → basic configuration, with temperature, relative humidity, and light sensors, plus probes of contact temperature. It needs #3 AA batteries. The contact temperature sensors are inserted within the walls in a 15 mm deep hole. Each of the probes has the following sensors:

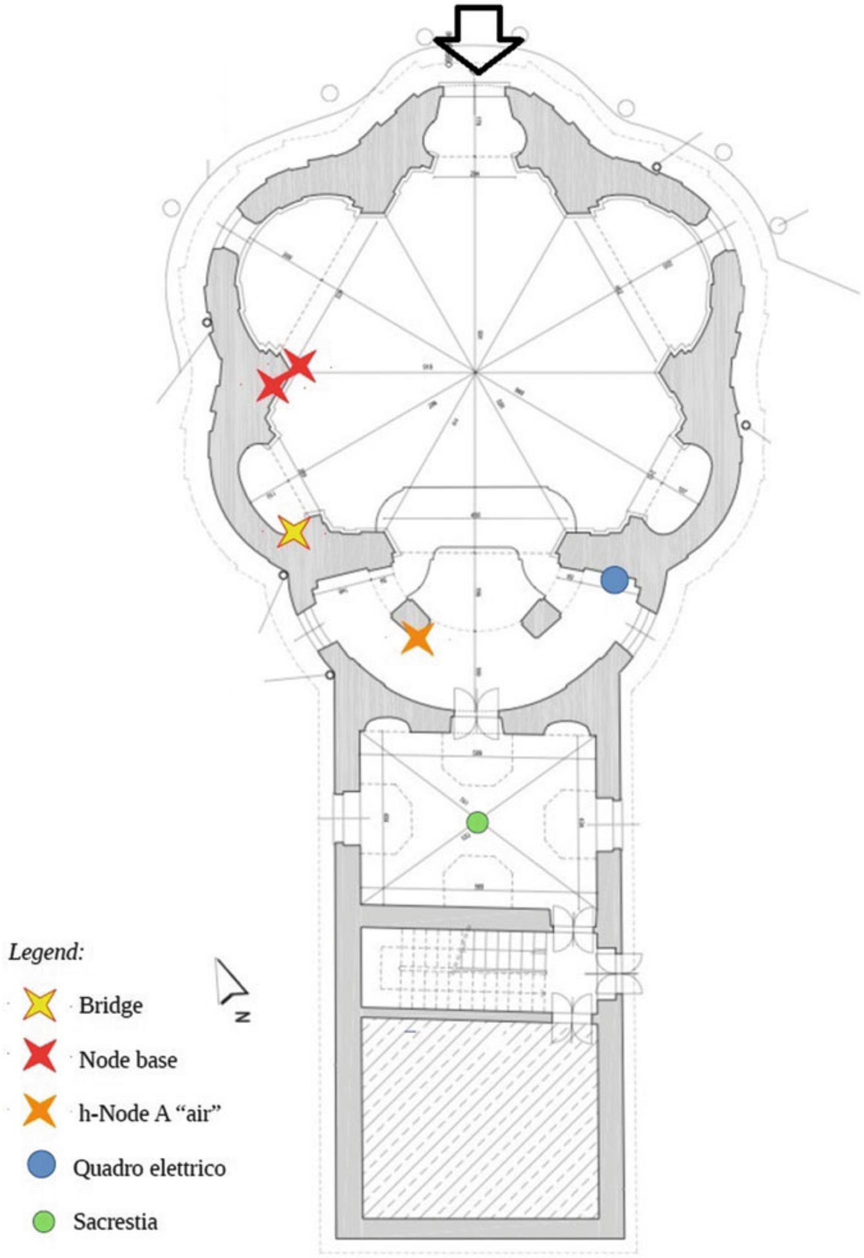

Fig. 10.3 Scheme of the building and positions of the probes, from the HENESIS report. Legend: "quadro elettrico" = wiring frame, "sacrestia" = sacristy

- Temperature (T) accuracy ±0.5 °C resolution 0.01 °C
- Humidity (H) as relative humidity (%), accuracy ±3% within the range (20–80%) resolution 0.03%
- Luminosity (L) based on phototypic curve (Vλ)
- Contact temperature (TC) accuracy ±0.5 °C resolution 0.01 °C

The phase of data transfer in the net and from the bridge to the server requires a constant and stable connection between the systems. This, practically speaking, implies the need to preliminarily evaluate the positioning of the instruments. A high amount of obstacles between the nodes or the bridge increases energy consumption and thus shortens the life duration of sensors. In the present project, the short life of the system was a consequence of the presence of metal scaffolding and thick brick walls screening the signal. The Beeper WSN net in this specific shape was designed for this particular project and is to be considered a prototype.

10.2.2 Probe Placement

The two probes have been placed adherent to the wall of a part of the building which geometry would allow studying the natural convective motions, since Santuario del Valinotto presents a complex geometry (Figs. 10.4, 10.5, 10.6, and 10.7). The two probes #60 and #48 were placed on the same vertical line, respectively:

- Node #60 at 1.65 m from the ground
- Node 48# at 5.65 m from the ground
- The distance between them being 4.00 m

The sensor recording the contact temperature, which diameter measures 6–8 mm, was inserted in a hole 15 mm deep, within the first layer of the wall. The sensor recording air temperature (AT) is 50 mm distant from the contact temperature (CT). The thermocouple data from below the surfaces of the walls and those from the onboard sensors had average difference of 0.3 degrees in the lower probe (0#60B) and of 0.5 C in the upper (BE#48).

10.2.3 Monitoring Data

The monitoring system was activated at 11:00 of the 30th of January 2015 and calibrated with default monitoring periods. These timings have been adapted during the same day to reduce battery energy consumption of the Bridge and Nodes that depends on the frequency of data transmission. The final setting was as follows:

Fig. 10.4 "Node 60" at 1.65 m from the ground

- Refresh time 32,000 s, data transmission time from the Bridge to the remote system for 8 h 53 min
- Sampling time 900 s, data transmission time from the probe and sensors to the Bridge of 15 min

This way the monitoring system records data every 15 min, four per hour. The period of time considered for the analysis goes from the 31st of January 2015, 0:00, to the 12th of June of the same year, for a total amount of 133 days.

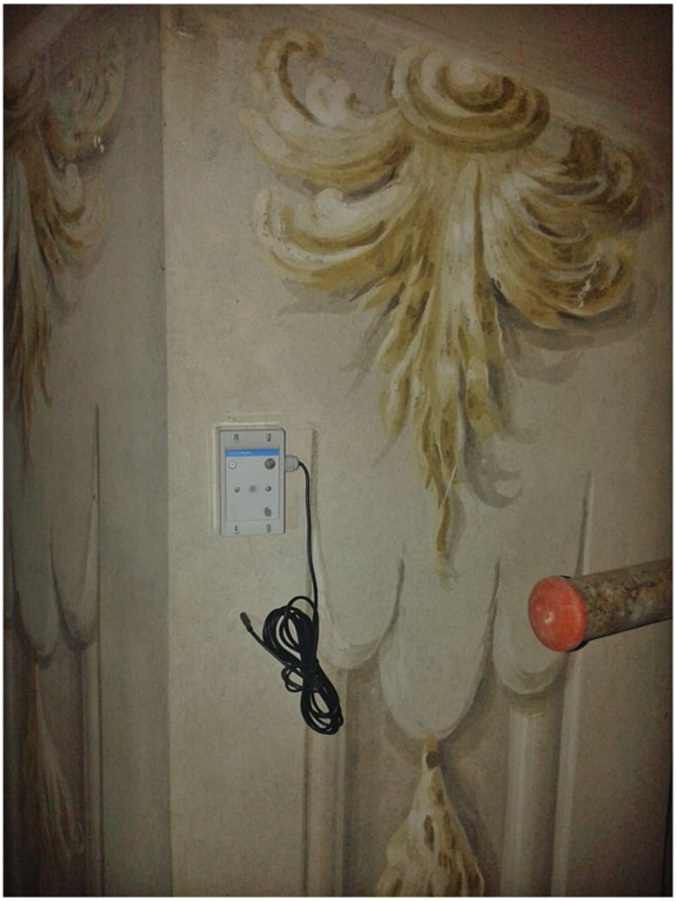

Fig. 10.5 “Node 48” at 5.65 m from the ground

10.3 Results of Indoor Microclimate Monitoring

Here follow the graphics describing the results of the monitoring activity. Two different levels have been evaluated:

- As a first level, the results have been interpreted with graphics relative to the variable trends or *x*/*y* graphics
- The second level concerns the construction of the frequency cumulative curves

The data recorded during the monitoring period starting on the 31st of January and the 12th of June 2015.

So Fig. 10.8 shows the trend of internal air temperature for both probes. The graph highlights that the range of temperatures is between 4 and 25 °C. The upper probe shows higher variation in the temperature of the air, with spikes probably due

Fig. 10.6 Profile picture of a node with the sensor and, in the lower part, the contact sensor inserted in the wall

to convective motions and irradiation phenomena. The difference between the two probes increases with internal temperature. Figure 10.9 shows the trend of air relative humidity close to the probes, where it is influenced by convective motions. The values are really high, between 60 and 95%, and in particular the lower probe ranges are 61.22–93.24% while the upper has ranges of 69.02–90.70%. The maximum difference between the two probes is 23.27, with a variation range of 32.02% in the lower node and 21.05% in the upper.

Fig. 10.7 Bridge location: 3 m high, in the first level of the scaffolding

Figure 10.10 shows the difference between the upper and lower values of relative humidity. Several daily peaks appear, demonstrating that, besides the temperature difference, other convective phenomena act during the day. The graph shows an increasing difference in the relative humidity values, which appears in contrast with the phenomena linked to humidity within the building such as the presence of saline efflorescence in the lower part of the building, for about one meter from the floor and saline efflorescences in the higher areas of the dome, close to trabeations and architraves, probably caused by rain coming in from the top windows.

10.3.1 Risk Phenomena

True phenomenon does not depend only on the external temperature, because this would cause an equivalent increase in both probes. Hence other causes can be searched, such as the following:

- The conformation of the building, developing mostly vertically, favors air convective movements and rising currents of warm air.
- The consequent stratification in the upper levels of the building, because of lack of continuously open windows that could contribute to removing the heat brought by convective motions.
- The impact of the solar radiation component in the upper part of the building and on the covering causes heating both because of direct entrance of the sunbeams

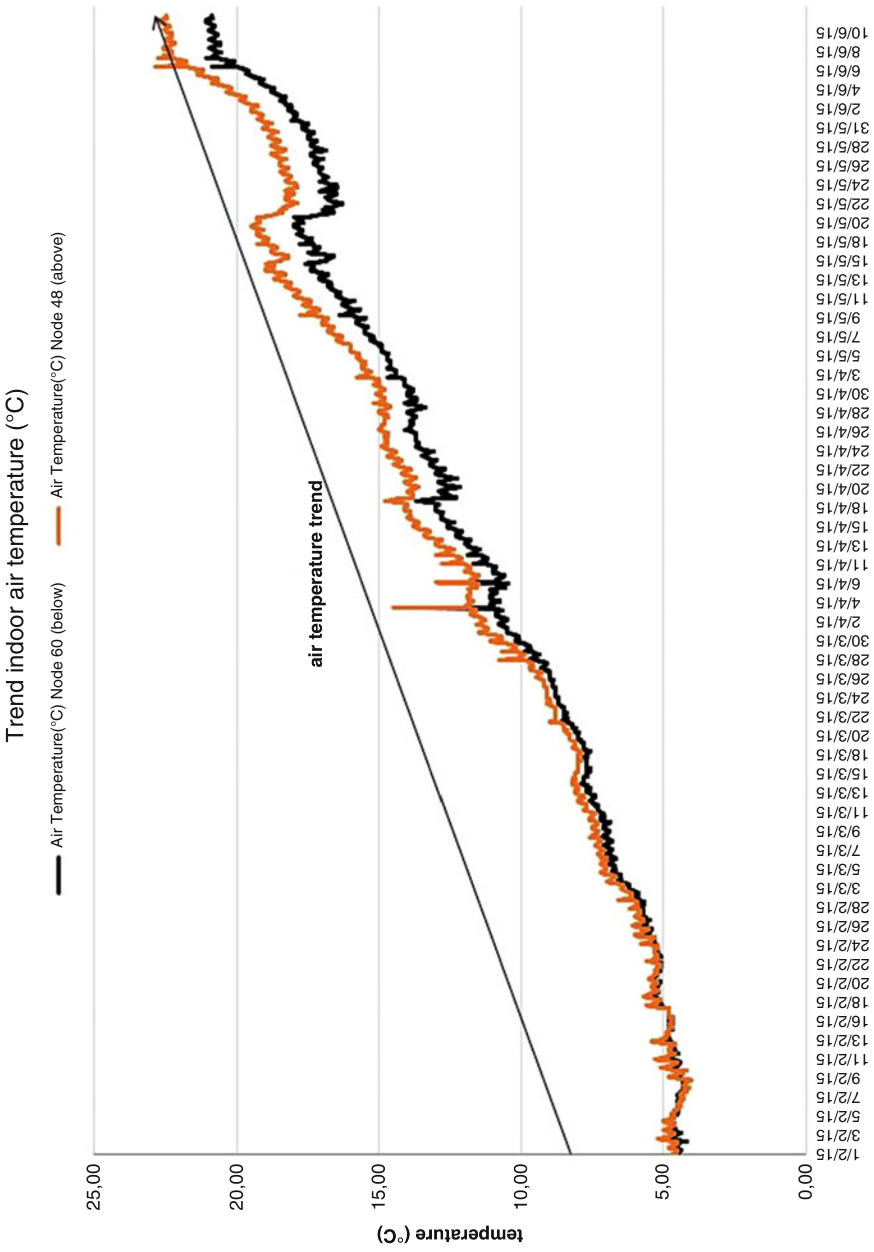

Fig. 10.8 Graphic 1: trend of internal air temperature (°C)

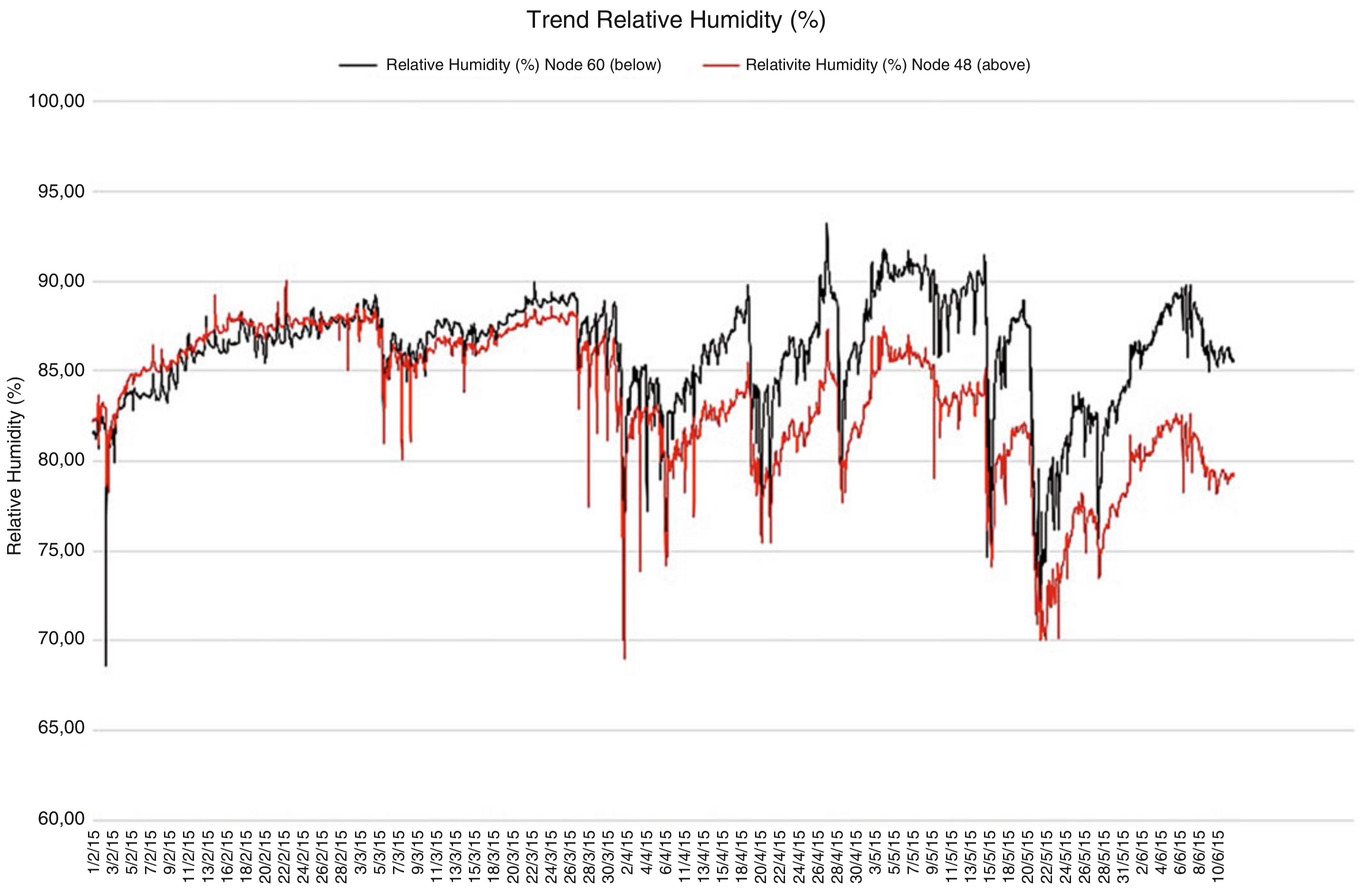

Fig. 10.9 Graphic 2: trend relative humidity (%)

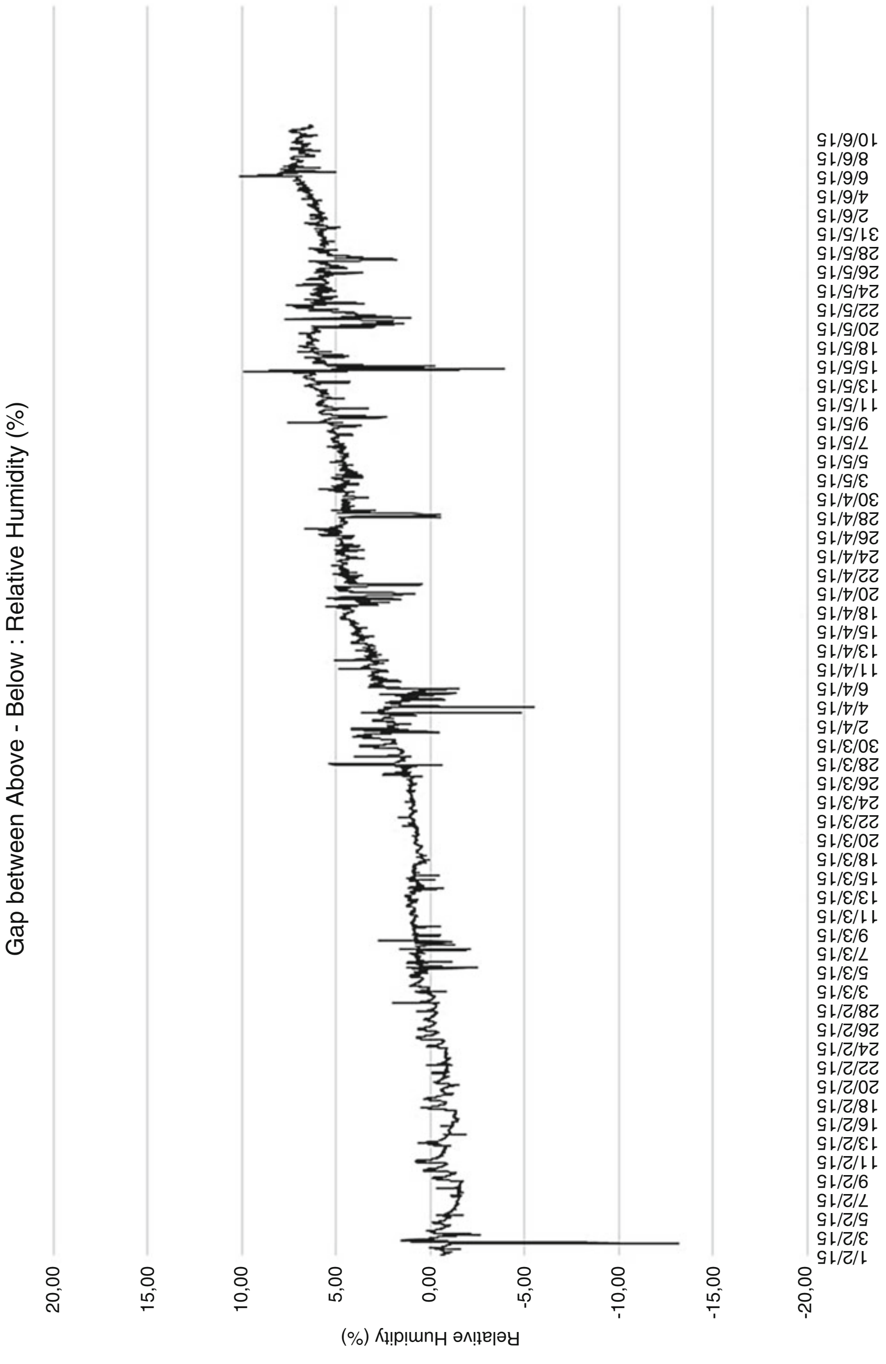

Fig. 10.10 Graph 3: trend of the upper-lower probe gap relative humidity (%)

through the windows and because of the heat transmission through the covering and the walls sustaining the dome.

With respect to the water vapor content and relative humidity, the first notable aspect is that this never goes below 60% and is often over 85%. This could be due to external meteorological phenomena, such as fog or rain, but the apparent difficult dispersion of vapor, even with high temperatures, implies that these values are specific of the indoor microclimate of the building.

To prevent these risks it would be important to manage the opening of doors and windows at the basis and at the top and avoid the building from remaining closed for a long period of time. It was verified in situ that *actually* there are no sources of humidity from rising damp within the building; hence the presence of vapor indoor can be due to:

(a) Movement of vapor from and outside to the inside of the building linked to climatic conditions, following seasonal changes, reaching maximum levels during foggy days
(b) Creation of vapor due to human presence, works, condensation phenomena, etc., i.e., due to a discontinuous use of the building

Table 10.1 Maximum and minimum values from the two nodes

	Contact temperature (°C) Node 60 (lower)	Contact temperature (°C) 48 (upper)	Air temperature (°C) Node 60 (lower)	Air temperature (°C) Node 48 (upper)
Value min.	3.90	3.60	4.10	4.00
Value max.	20.70	22.30	21.10	22.90
Interval	24.60	25.90	25.20	26.90
	Gap between air and contact temperature (°C) – Node 60 (lower)	Gap between air and contact temperature (°C) – Node 48 (upper)	Gap between upper and lower : air temperature (°C)	Gap between upper and lower : contact temperature (°C)
Value min.	0.10	0.10	−1.80	−0.30
Value max.	2.80	3.70	2.20	1.90
Interval	2.90	3.80	4.00	2.20
	Relative humidity (%) Node 60 (lower)	Relative humidity (%) Node 48 (upper)	Gap between upper and lower relative humidity (%)	
Value min.	61.22	69.02	−13.16	
Value max.	93.24	90.07	10.11	
Interval	32.02	21.05	−23.27	

Table 10.1 shows maximum and minimum values, as were recorded.

The negative effects of these sources of problems can be reduced with the ongoing restoration and with a management that would guarantee vertical ventilation. The windows of the top levels must allow continuous slow ventilation and there must be a coupled opening of windows at the top and the door at the basis to increase the natural ventilation due to ascendant convective motions.

10.4 Microclimate of the Santuario del Valinotto

Here follows the analysis of the specific microclimate of the Santuario del Valinotto, defined through the XY graphic of air temperature and relative humidity, and with cumulative curves.

10.4.1 The Graphic of Air Temperature/Relative Humidity

The graph in Fig. 10.11 shows the amount of variability in relative humidity per each value of temperature. It results in a correlation between relative humidity and temperature; in particular as long as the temperature is lower than 10 °C, relative humidity ranges from 65% (lower probe) to 90%: hence, if the air temperature is lower, the range of variability in relative humidity is higher (left area of the graph). Since the lower temperatures are recorded during the winter period, it could be deduced that relative humidity values are linked to meteorological phenomena such as rain or fog.

The graph shows on the contrary that most of the values are between 75 and 85%, but many values, mainly from the lower probe, are below 75%. It can be supposed that these values are due to particular temporary situations of rarefaction of vapor, as a consequence of convective movements of air following the opening of windows and doors (the convective movements increase because of the difference in temperature between indoor and outdoor air).

With temperatures between 10 and 15 °C (in the central part of the graph) the values of relative humidity do not differ much between the two probes.

A bigger difference can be observed with temperatures over 15 °C (right part of the graph), when it is clear that the variability range of the relative humidity registered by the lower node is higher than that of the upper node. The most significant phenomena of air convection appear with increasing temperature, because of air stratification, and, partially, because of solar radiation. Both, indeed, cause the air to evaporate.

From a first evaluation it is possible to assume that in the lower part of the building the convective motions favor the dilution of the vapor content close to the wall (as long as no capillarity is observed), while in the upper part the convective

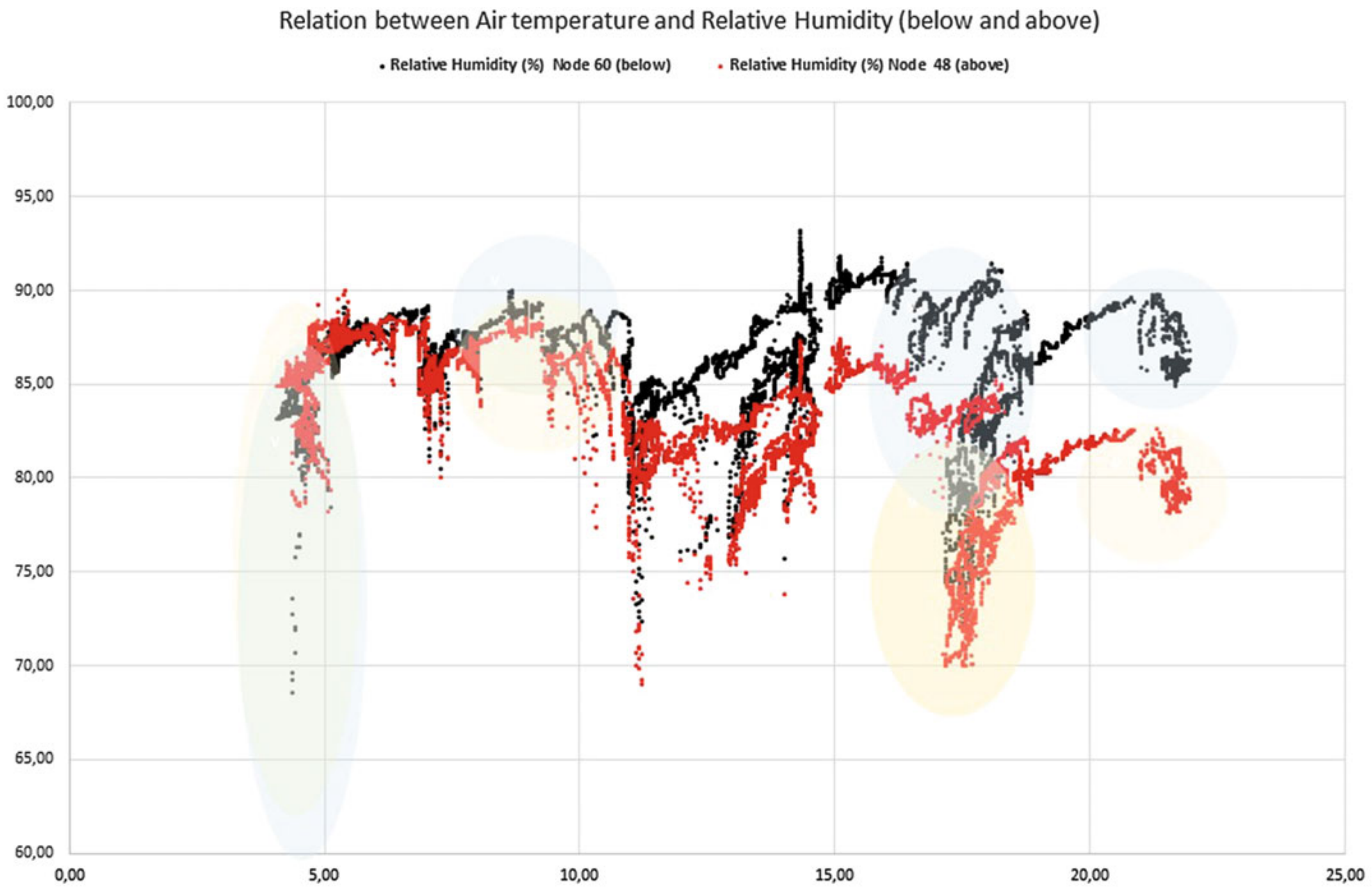

Fig. 10.11 Graphic 3: comparison of the upper-lower probe gap trends of air temperature, contact one, and relative humidity

motions appear to be mainly laminar, parallel to the wall, so that the water content is not modified.

With the end of this monitoring campaign, it can be deduced that:

- The monitoring system allows to obtain reliable information on indoor microclimate of study cases.
- Small differences in the distribution of temperatures and relative humidity reveal stratification of air currents and vapor.
- In the upper part of the building there are a higher humidity concentration and absence of convective motions that are not the air curtain of the laminar flow.

10.4.2 Cumulative Curves

The study of cumulative percentage frequency of physical variables in indoor microclimates allows to define the characteristics of indoor microclimate with every probe.

The cumulated frequency of air temperature shows that the values recorded by the lower probe are below 15 °C in 74.85% of cases, while the percentage decreases to 71.56% in the upper probe, which means that it is slightly, but not relevantly, hotter. Indeed, comparing the two cumulative curves, the lower probe has a value which is lower than the upper probe in 98% of cases, of at least -1 °C in 42% of cases and of -2 °C in only 0.7% of cases.

The cumulated percentage frequency of contact temperature shows that temperature in the wall stays below 15 °C in 76.15% of cases in the lower node (#60) and on 73.33% in the upper one (#48). There is hence a difference of 2 percentage points among the probes. The phenomena of energetic exchange are due only to thermal convective exchanges.

Cumulative curves allow to know the most frequent condition of a physical variable, such as temperature or humidity. The comparison among the curves from the upper and lower node allows to visualize stratification problems and to plan the consequent action.

Form the comparison between Figs. 10.11 and 10.12, we can observe that contact temperature of the lower node is below the equivalent values in the upper nodes. This can be due to convective motions close to the main door, to the reduced quantity of direct solar radiation, and to the fact that air stratifies increasing temperature.

The comparative Fig. 10.13 confirms that the highest difference is registered for temperatures between 15 and 20 °C, i.e., in the intermediate seasons, spring and autumns. The difference is recorded between the temperatures of air and that of contact as well (wall temperature).

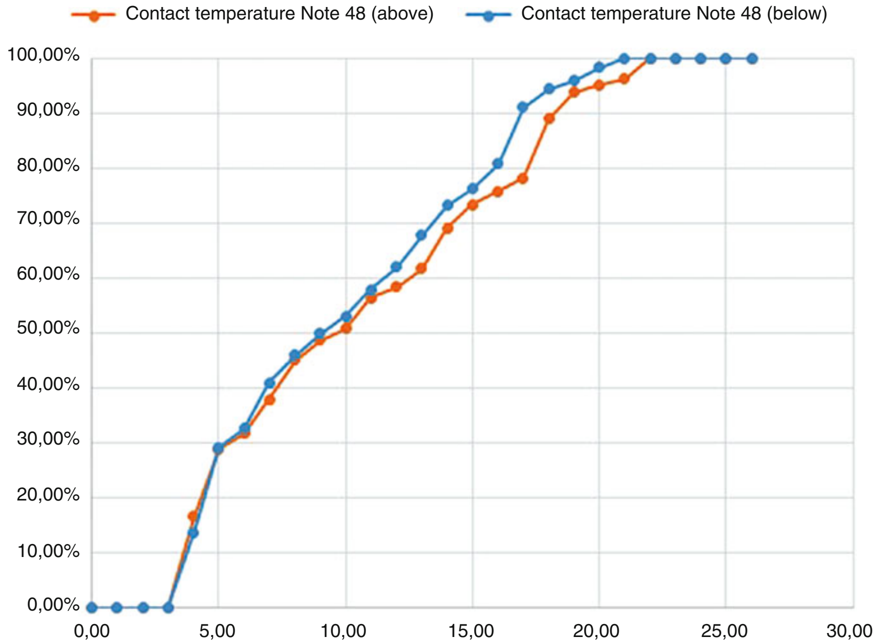

Fig. 10.12 Graphic 4: comparison between percentage of cumulated frequency of indoor air temperature for the two probes, upper and lower

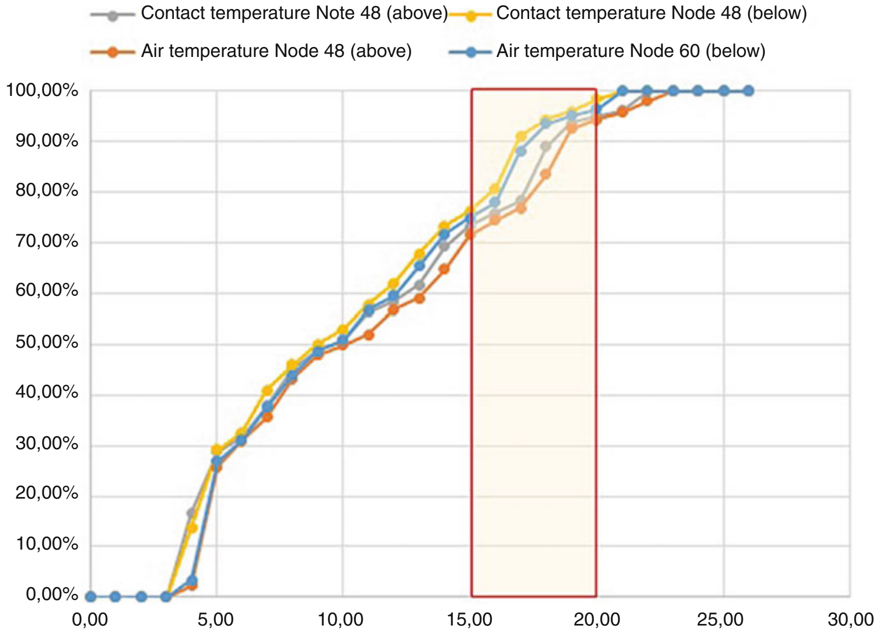

Fig. 10.13 Graphic 5: cumulated frequencies for the 4 contact and air temperatures from the two probes

10.5 The Software Model: Why It Has Not Been Done

A model of the building is currently being developed to evaluate its microclimatic behavior, if the opportunity of opening windows was to be recreated, in the presence of opportune patterns (first upper ones, then lower, or east-west, or with the sun close to the zenith or further, or taking into account the prevalent winds).

Another factor to be considered is the differential thermal inertia of the walls at different levels, since the lower ones, more than 60 cm thick, have completely different performances compared to the much thinner upper ones and to the coverings at different levels. The covering themselves have an intrinsic tendency to condensate water vapor, but it is to be noted that, since they do not present significant historical artistic value, they are expected to be replaced cyclically in accordance with maintenance needs.

The development of a building model with CFD evaluation would be a possible future of this research. This would allow simulating the alternate opening of windows taking into consideration prevalent winds and solar radiation. Such a model would allow as well analyzing the specific role of the peculiar structure of walls and fake domes of the building in the maintenance of the present microclimate.

As it has been explained, building simulation and CFD modeling have not been requested.

In this study case, the results of the research concerned only the data on monitoring, since it has not been possible to develop the virtual modeling and building simulation. The reasons why this has not been possible are mainly two:

- A computerized model was not included in the agreement and requests of the clients, who thought the information from the monitoring to be sufficient for the restoration of the building.
- The geometric complexity of the building would have required the use of Laser Scan instrumentations or similar ones to obtain the geometric input for the simulation software.

10.6 Conclusions

The results of the monitoring activity and the suggestions for the restoration that have been deduced from them have been given to the clients. In particular, it appeared evident that the higher risk for condensation is close to cold surfaces, along the day/night cycle, since the water condensed close to walls during nighttime evaporates with more difficulty because of the air within the building saturated with water vapor.

The monitoring demonstrates that, in the absence of intense phenomena of rising damp, migration of water vapor in a building is due to two main factors:

1. Interference of external climatic conditions, due to seasonal cycles, with the effect that the higher values of humidity happen mainly in foggy days
2. Presence of people in the church, with the consequent generation of water vapor and correlated generation of water vapor and condensation, related to discontinuous usage of the building

The problems mentioned above can be reduced with a careful management, in order to guarantee the vertical ventilation, hence vertical convective and laminar close to the wall motions, increasing thermal exchanges and reducing the risk of condensation. Upward convective motions and natural ventilation can be induced by opening the windows in the sommity. These should be opened in order to guarantee continuous slow ventilation and/or air leakage between the basal and the top part of the building.

The management of the opening of the windows would impact positively the behavior of microclimate of the whole church, and long periods in which the windows stay closed have negative consequences.

In conclusion, the monitoring campaign and the analysis of data, including the cumulative curves of values, gave information useful for the restoration of the building and to plan its management at the end of the ongoing works.

At last, as a suggestion to the restorers, waiting for further comments and requests of information, it is highlighted that, as far as the first portion of the building is concerned, the upper part has a higher risk of decay than the rest of the building, domes excluded, a decay acting mainly on plasters and that is dependent on the indoor microclimate and on the geometric conformation of the building itself.

Acknowledgments The authors thank the Faccio-Fracchieri Foundation for the financial support to the monitoring and research in the Santuario del Valinotto in Carignano (TO) and the staff for the help during the installation of the system and during the first observations. A thanks to the architects Agostino Magnaghi, Antonio Mannina, and Andreina Milan for the operative support and the relevant information related to the historical past of the building and to its characteristics, and moreover for the details of the ongoing restoration project. Thanks to the HENESIS srl – CAMLIN GROUP and in particular Antea Franceschin and Christian Iasio, for the support, testing, and development of the monitoring system and remote control.

Reference

Vittone BA (1766) Le Istruzioni elementari, Lugano

Chapter 11
Vleeshuis Museum: Antwerp (Belgium)

Giovanni Litti and Amaryllis Audenaert

Abstract Understanding the indoor building microclimate means also verifying how the building interacts with the outdoor microclimate and how homogeneous this interaction is inside the building. As the hygrothermal dynamics influence both building users' thermal comfort and state of conservation of movable heritage, it is essential, especially in historic buildings and museums, to combine both indoor building microclimate diagnosis and certification in an iterative process.

This chapter reports on a microclimate monitoring of Vleeshuis museum in Antwerp (Belgium). The onsite monitoring activities are intended at acquiring data for indoor microclimate diagnosis and certification. The building diagnosis was performed by means of descriptive statistics analysis, while the building microclimate certification, limited to the thermal comfort, was implemented on the basis of a certification model introduced in Chap. 6 of this book.

11.1 History and Building Characteristics

The monitored building, *het Vleeshuis*, is the museum of musical instruments: "klank van de Stad" in Antwerp, Belgium. The building was built between 1501 and 1504 on the project of the Belgian architect Herman de Waghemakere (the old). The Vleeshuis originally functioned as slaughterhouse of the city (from which indeed it takes the name, Meat-house). Although the building use destination has changed across the centuries, it is still possible to identify the original building architectonic integrity both on the inside and outside (Figs. 11.1 and 11.2).

The Vleeshuis was built to host four functions in independent spaces: the slaughter space, the market space, the leaving space, and storage space. Each one

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Fig. 11.1 Vleeshuis museum, main façade

was typologically defined by independent architectonic features and indoor performance requirements (Herk 1939). The slaughter space was built in the cellar for facilitating blood and waste disposal while the prestigious market hall, built at ground floor, was designed for hosting around 60 meat seal counters.

The cellar and the ground floor as well as the upper floors with the only exception of the last two levels of the attic are longitudinally partitioned in two naves by a brick wall; the width of the two parts is almost identical (between 7.00

Fig. 11.2 Vleeshuis museum, monitored exhibition hall at the ground floor

and 7.50 m). This bipartition was a limit imposed by the span of oak timber beams used for the intermediate ceiling construction.

The ceiling of the basement and ground floor is built with brick vaults: respectively, two longitudinal barrel vaults at the basement and two lines of 7 cross vaults at the ground floor. The vaults at the ground floor are sustained by the boundary walls and in the middle by six sand-stone pillars which replace the central partition brick wall existing at the basement level and at the upper levels; see Figs. 11.2 and 11.3.

The volumetric proportions of the spaces at the basement and ground floor are different: 3.45 m is the maximum height of the basement and 8.50 m the one at the ground floor, and the total net volume is, respectively, ±1300 m^3 and ±5300 m^3 at the basement and ground floor. On the first floor there were spaces for reception, meetings, and forestry. Still now, original furniture, fire places, and finishing from the sixteenth century as well as replicas from the last restoration works (beginning of the twentieth century) are present. The upper four levels are part of the building

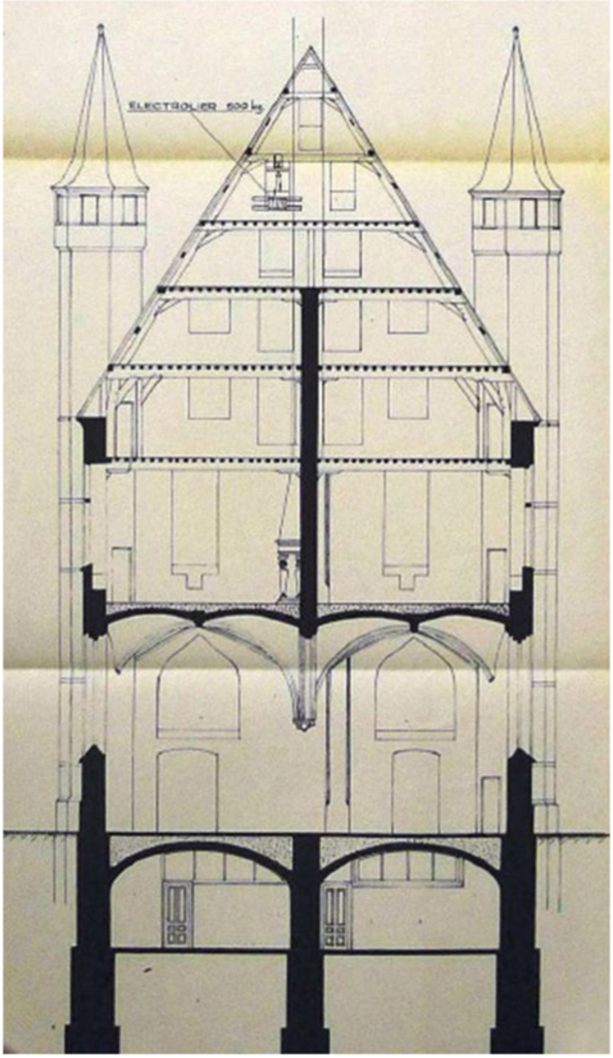

Fig. 11.3 Vleeshuis museum transversal section

attic. In this space, according to the original project, goods were stored. The internal vertical distribution through the levels is allowed by five towers with winding stone staircases located at each building corner. An extra tower on the south-oriented façade is the sole one allowing a vertical internal/external connection through all the levels including the cellar and the street.

Currently the building hosts the permanent collection of musical instruments at the basement and ground floor, while the upper levels are utilized as artifact stocking space and partially as offices. However, due to the poor conservation state of the building (influencing the indoor microclimate quality for artifact preservation) it was decided to transfer part of the collection elsewhere.

11.2 Onsite Building Monitoring for Indoor Microclimate Diagnosis and Certification

The monitored exhibition space is technologically characterized by uninsulated brick masonry and almost 218 m^2 of stained glasses across surface. Both brick masonry and windows are interested by severe deterioration issues responsible for constant heat, moisture, and air mass transfer from and towards the outer environment.

The windows allow air and water infiltration at the connections between the glazing panes and the stone frame. Also the brick masonries present visible humidity infiltrations. The presence of moisture in the masonries (from absorption and infiltration) was observed to be responsible for remarkable thermal performance decrease in the Southern-oriented facade (Litti et al. 2015a). Moisture in the masonries not only can bring to thermal performance reduction (see also Lucchi 2016), but it can also bring to variations of the indoor hygrothermal dynamics (see Camuffo et al. 2010).

During the cold period if the building is heated and if neither condensation nor evaporation occurs, the moisture flow (directly dependent on the vapor pressure gradient and inversely dependent on the moisture diffusivity of the parietal components) migrates from inside to outside. However, if superficial or interstitial condensation inside the building occurs as well as infiltration from capillary or driving rain, part of the condensed vapor tends to evaporate inside the heated space rising the vapor in the air volume; this was discussed with regard to the Vleeshuis museum in the study of Litti et al. (2015a). This evaporation occurs because the vapor pressure of the condensed vapor (water) is higher than the one of the moist air in the building. Moreover, the presence of radiators inside can raise the convective air motion increasing the rate of inward moisture evaporation. For further considerations on thermal convective exchange the interested reader may refer to Sect. 10.1 in Chap. 10 of this book.

During mild or warm periods, overcooling and overheating might occur. With overcooling the authors mean that the indoor temperature decreases under the outdoor one and with overheating the inverse. Depending on temperature and vapor pressure inside and outside and on the state of conservation of the building envelope, the moisture transport may be in or outwards or in both the directions.

In the monitored exhibition hall, the doors opening towards outside are not allowed; hence, also in summer the outdoor air enters the space when the sliding door at the entrance opens for visitors' entrance. It is therefore possible to consider the ventilation rate, invariable through the seasons. This hypothesis was tested and is later discussed. The environmental parameters continuously monitored in the exhibition space are listed in Table 11.1.

The external parameters, utilized for the hygrothermal analysis, were withdrawn from the weather data station in Antwerp–Deurne (6 km distant from the building). These are dry-bulb temperature (°C), dew-point temperature (°C), relative humidity (%), global horizontal solar radiation (W/m^2), wind speed (m/s), wind direction (°E of N), atmospheric pressure (Pa), and cloud covering (fraction).

The onsite monitoring was not only aimed at providing a hygrothermal building diagnosis, but it was also aimed at acquiring data for a simultaneous indoor microclimate quality (IMQ) certification for people and collection. Parameters measured for the evaluation of building users' thermal comfort were measured during three short time intervals throughout 2014, while parameters measured for IMQ assessment with regard to the artifacts were measured continuously for the whole year; see Table 11.2. However, due to logger failure, data from July the 20th to September the 8th are not taken into account in this analysis.

Table 11.1 Measured environmental parameters

Inside-position code	Physical parameter	Logger	Accuracy (of absolute reading)
0.1.2–0.1.4–0.1.5	Dry-bulb temperature (°C)	Hobo U12	(±0.35)
0.1.2–0.1.4–0.1.5	Dew temperature (°C)	Hobo U12	(±2.5%)
0.1.2–0.1.4–0.1.5	Relative humidity (%)	Hobo U12	(±2.5%)
0.1.2–0.1.4–0.1.5	Light intensity (lux)	Hobo U12	(±2.5%)
0.1.2	CO_2 (ppm)	Vaisala GM70	(±2%)
0.1.2	Radiant temperature asymmetry (°C, W/m^2)	MM 0036 Innova	(±1)[a]
0.1.2	Operative temperature (°C)	MM 0060 Innova	(±0.3)
0.1.2	Air velocity (m/s)	MM 0038 Innova	$(0.05\alpha + 0.05)$[b]

[a] Difference air temperature—plane radiant temperature < 20°K

[b] With air velocity < 1 m/s and 0.25α with air velocity up to 10 m/s

Table 11.2 Monitoring campaign characteristic

	Temporal representativeness		Temporal resolution	
	Start (date)	End (date)	Sampling (min)	Averaging (min)
Building users				
Heated period 1	04/03/2014	12/04/2014	120	120
Warm period	11/08/2014	30/09/2014	15	60
Heated period 2	01/10/2014	26/11/2014	120	120
Movable heritage				
	19/02/2014	31/01/2015	15	60

Parameters in Table 11.1 were sampled each 15 min with the exception of operative temperature, radiant temperature asymmetry, and air velocity sampled each 120 min. Because low temporal resolution might bring to biased results if outliers occur, an analysis for observing normality of distribution and outliers was performed.

In order to acquire data in vicinity of the certification targets (people and artifacts), the sensors were installed 1.30 m high from the floor. This height allowed to measure in simultaneous presence of people and collection.

For avoiding biased heat and moisture transfer due to contact between sensors and building (or other) surfaces, each logger was installed on an independent support, distant from any environmental disturbance. On the top of each support, a 1.5 mm thick highly conductive metal wire extension (0.15 m long) was installed for hanging the instruments. In such a way, the loggers measured the free air. Sensors MM 036, MM038, and MM060 were positioned on a dedicated support also distant from surfaces; see Figs. 11.4 and 11.5.

Fig. 11.4 Hobo U12 data logger during the installation on dedicated support

Fig. 11.5 Innova MM 0036, MM 0038, MM 0060, and Vaisala GM70 sensors during the installation on dedicated support

The position code for each logger is given in Table 11.1 and Fig. 11.6. The distance between sensors 014 (entrance) and 012 (center of the exhibition space) is ±10 m, the distance between sensors 012 and 015 (back of the exhibition space) is ±13 m and the distance between sensors 012 and 015 is ±22 m.

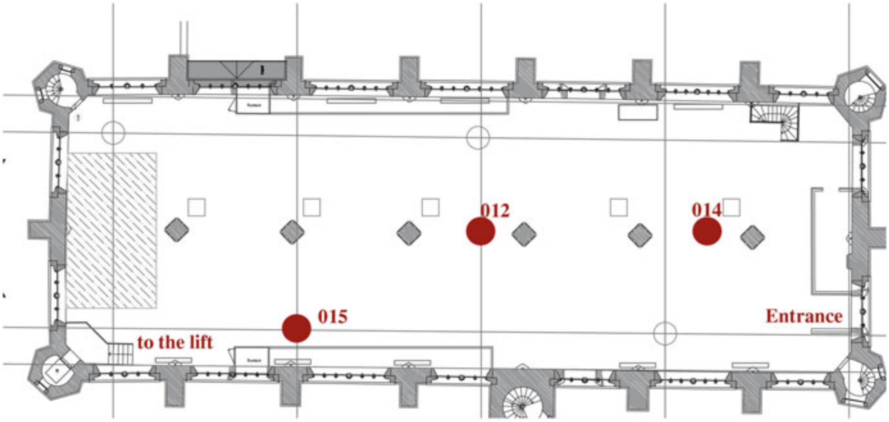

Fig. 11.6 Localization of sensors in the exhibition hall at the ground floor of Vleeshuis museum

11.3 Indoor Microclimate Diagnosis: Methodology

On the basis of the monitored parameters at Table 11.1, vapor pressure (hPa), absolute humidity (g/m^3) and mixing ratio (g/kg) were calculated each 15 min and hourly averaged. The evaluation of the vapor density of the moist air (absolute humidity) and the ratio between mass of water vapor and dry air (mixing ratio) allowed to identify the air mass interactions between the indoor and outdoor environment. Because mixing ratio (MR) is invariable to both isobaric and nonisobaric and adiabatic and nonadiabatic processes (because of its independency from pressure, volume and temperature), its analysis allowed to trace the vapor dynamics in the monitored exhibition space. In the text, the mixing ratio will also be referred with the general term, water vapor. The inside-outside hygrothermal parameters (temperature, mixing ratio and relative humidity) were observed throughout the entire monitored period under the conditions at points (a) and (b):

(a) $\text{Temp}_{\text{inside}}$ and $\text{Vapor Pressure}_{\text{inside}} > \text{Temp}_{\text{outside}}$ and $\text{Vapor Pressure}_{\text{outside}}$
(b) $\text{Temp}_{\text{inside}}$ and $\text{Vapor Pressure}_{\text{inside}} < \text{Temp}_{\text{outside}}$ and $\text{Vapor Pressure}_{\text{outside}}$

The possible sources of water vapor in the exhibition space are reported below together with the methodology for their identification.

11.3.1 Portable Humidifiers

The presence of portable humidifiers in the exhibition space, though continuous throughout the year, was inconstant. The humidifiers were observed often defected, moved or not in use. However, during onsite inspections regularly four humidifiers in use were observed. With this regard the maximum water vapor entered into the air volume was estimated from the use of these machines at their maximum speed.

11.3.2 Visitors and Staff

The influence of visitors and staff on vapor enrichment was tested by means of independent *t*-test statistic. The test was developed on two hierarchical steps: test 1 and test 2 for both cold (months 11-12-1-2) and warm (6-7-9) periods. Test 1 aimed at verifying the mean variation between nonvisiting and visiting days, excluding the concert events. In case of negativity of the first test, therefore in case the mean vapor concentration during museum visiting days was verified to be not significantly different from the one during closing museum days, a second test (test 2) was performed. The second test aimed at verifying the same as the first but including the concert events; see Table 11.3. More specifically, the second test allowed to verify if the variation of water vapor was insignificant also in case of short intervals of high occupation rate.

The museum is visitable from Thursday to Sunday from 10 am to 17 pm; the other days the exhibition space is closed to public. However, since in the cold period the contribution of visitors in terms of vapor concentration enrichment had a delay in comparison with the visiting hours, the independent *t*-tests were performed considering a time interval from 13 pm to 23 pm. It was considered a time interval until the end of the day, for taking into account the whole enrichment and successive dilution process of the vapor concentration caused by people during the visiting time.

From the hourly vapor concentration calculated on the basis of the current indoor environmental parameters and considering a per capita water vapor production of 50 g/h (see Dario Camuffo et al. 2007), the average vapor load produced by people during the museum visits was calculated.

11.3.3 Ventilation due to the Operating of the Entrance Sliding Door

The ventilation rate in the exhibition space is supposed to be invariable through the seasons because the openings towards outside are not differently operated during

Table 11.3 Independent *t*-test conditions for tests 1 and 2

Independent *t*-test	Continuous variable (in the model)	Dummy variable (in the model)		Time interval
Test 1	Mixing ratio_012	Closing hours	Visiting hours	13 pm to 23 pm
Test 2	Mixing ratio_012	Closing hours	Visiting + concert hours	13 pm to 23 pm

the year (because of obvious safety reasons). For understanding the effect of the door opening on the indoor air movement, an independent *t*-test was done. The modeled dummy conditions were museum closed and open within the time interval 10 am–17 pm. This test was performed for cold and warm periods considering as continuous variable the indoor air velocity (m/s) measured in point 012.

11.3.4 Moisture in the Masonries

The presence of moisture in the masonries is discussed in a previous contribution (see Litti et al. 2015a) and in this chapter it is only mentioned for the sake of clarity and completeness.

11.4 Indoor Microclimate Quality (IMQ) Certification: Methodology

Besides the analysis of the hygrothermal dynamics in the exhibition space, the study was intended at proposing an IMQ certification, limited to the thermal comfort, for people and collection. The certification methodology is described in Chap. 6 of this book and in the study of Litti et al. (2015b).

The certification model is developed on the principle of thermal comfort neutrality for people and artifacts (meaning nonharmful microclimate for the latter ones). Comfort neutrality is considered the optimal microclimate condition to be maintained and in the model is numerically represented by zero; any deviation from it is indicated with a (symmetrical) stepwise numerical and linguistic alteration, such as good conditions (±1), moderate conditions (±2), and unacceptable conditions (±3). The model is category dependent and is developed on the basis of European Standards or existing studies; see ISO 7730, EN 15251, EN 15757, and Silva and Henriques (2014).

In Tables 11.4 and 11.5 the category intervals with regard to people and collection are indicated. An explanation of the theoretical formulation for the

Table 11.4 Category ranges for people (P); source of category for heated period ISO 7730 and for free running period EN 15251

Deviation (β)	MCP (microclimate comfort people) winter	MCP (microclimate comfort people) free running
±3	PMV < -0.7; PMV $> +0.7$	$\theta_{i\max} > 0.33\theta_{rm} + 18.8 + 4\,;\, \theta_{i\min} < 0.33\theta_{rm} + 18.8 - 4$
±2	$-0.7 \leq$ PMV $\leq +0.7$	$0.33\theta_{rm} + 18.8 - 4 \leq \theta_i \leq 0.33\theta_{rm} + 18.8 + 4$
±1	$-0.5 \leq$ PMV $\leq +0.5$	$0.33\theta_{rm} + 18.8 - 3 \leq \theta_i \leq 0.33\theta_{rm} + 18.8 + 3$
0	$-0.2 \leq$ PMV $\leq +0.2$	$0.33\theta_{rm} + 18.8 - 2 \leq \theta_i \leq 0.33\theta_{rm} + 18.8 + 2$

Table 11.5 Category ranges for collection (H)

Deviation (β)	MCH (microclimate comfort heritage)	Daily fluctuations (Δ_{day}) Incremental factors to (β)	
±3	$\varphi_{(k)} > \overline{\varphi}_{30}(k) + \overline{\varphi}_{30}(k)10\%; \varphi_{(k)} < \overline{\varphi}_{30}(k) - \overline{\varphi}_{30}(k)10\%$	–	
±2	$\overline{\varphi}_{30}(k) - \overline{\varphi}_{30}(k)10\% \leq \varphi_{(k)} \leq \overline{\varphi}_{30}(k) + \overline{\varphi}_{30}(k)10\%$		Max 3% CV Temp-RH
		0	$\Delta_{\text{day}} \leq 3\%; \geq 80\%$ time
		0.5	$\Delta_{\text{day}} \leq 3\%; \geq 70\%$ time
		0.75	$\Delta_{\text{day}} \leq 3\%; < 70\%$ time
±1	$\overline{\varphi}_{30}(k) - \Delta_{\varphi\, L} \leq \varphi_{(k)} \leq \overline{\varphi}_{30}(k) + \Delta_{\varphi\, U}$ $\Delta_{\varphi\, L} = 5^{\text{th}}$ perc ; $\Delta_{\varphi\, U} = 95^{\text{th}}$ perc		Max 2.5% CV Temp-RH
		0	$\Delta_{\text{day}} \leq 2.5\%; \geq 80\%$ time
		0.5	$\Delta_{\text{day}} \leq 2.5\%; \geq 70\%$ time
		0.75	$\Delta_{\text{day}} \leq 2.5\%; < 70\%$ time
0	$\overline{\varphi}_{30}(k) - \Delta_{\varphi\, L} \leq \varphi_{(k)} \leq \overline{\varphi}_{30}(k) + \Delta_{\varphi\, U}$ $\Delta_{\varphi\, L} = 7^{\text{th}}$ perc ; $\Delta_{\varphi\, U} = 93^{\text{rd}}$ perc		Max 2% CV Temp-RH
		0	$\Delta_{\text{day}} \leq 2\%; \geq 80\%$ time
		0.5	$\Delta_{\text{day}} \leq 2\%; \geq 70\%$ time
		0.75	$\Delta_{\text{day}} \leq 2\%; < 70\%$ time

selected categories is given by Litti et al. (2015b) to which we refer the interested reader.

11.5 Indoor Microclimate Diagnosis: Results

The indoor building microclimate was observed significantly dependent on the outdoor climatic conditions for the entire monitoring period. In Figs. 11.7 and 11.8 is plotted the monthly mean outdoor and indoor temperature when conditions in (a) or (b) were, respectively, satisfied. The condition in (a) was met in all the months while the one in (b) was met mainly during the warm period (June–July and September) and exceptionally at the beginning of the heating season (October and November) for a total of 56 h. It is worth mentioning that the slight cooling of the space between October and November resulted in a negative skewness of the PMV, later discussed in this chapter.

A noteworthy cooling of the exhibition space occurred especially during the warm period. In June and July (no data for August are available), the indoor temperature was registered up to 3.5 °C lower than outside. The building is not equipped with cooling system; therefore the overcooling was caused by the thermal inertia of the masonries.

In order to observe the relation between indoor and outdoor microclimate, the correlations between hygrothermal parameters were analyzed. The correlation

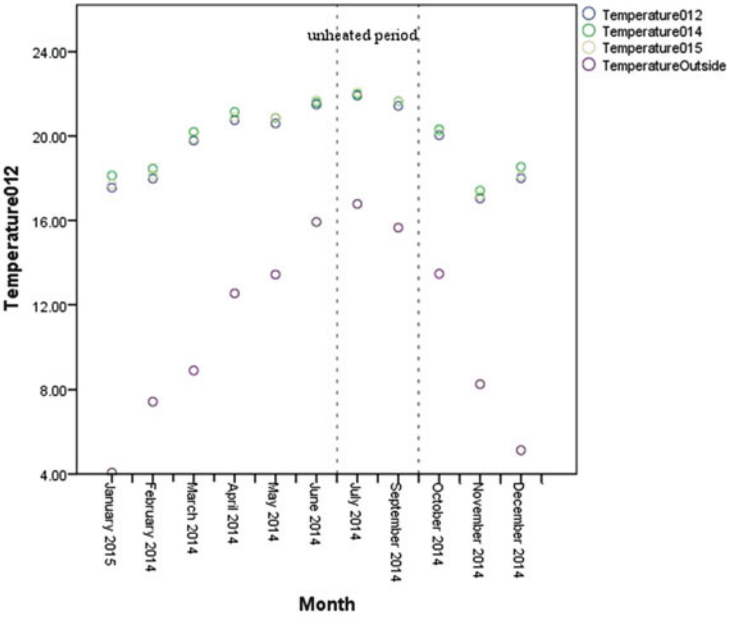

Fig. 11.7 Indoor temperature point 012, condition (a)

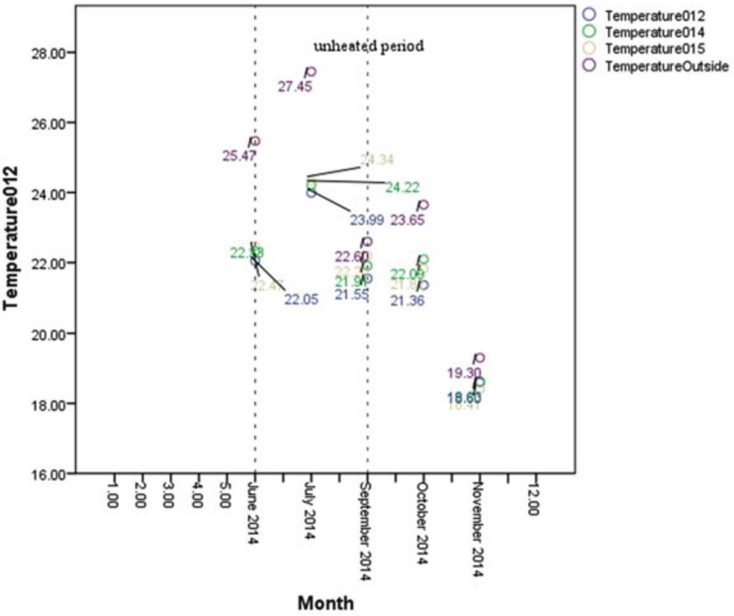

Fig. 11.8 Indoor temperature point 012, condition (b)

coefficients, for indoor–outdoor parameter relationship, are given in Tables 11.6, 11.7, and 11.8, respectively, for cold period (condition a), warm period (condition a), and warm period (condition b). The mentioned correlations refer to each time period; no distinction between opening or closing days of the museum is made.

The Pearson correlation coefficients in Table 11.6 illustrate the typical indoor–outdoor hygrothermal relations in the cold period, while Tables 11.7 and 11.8 show the same relationships in warm period, respectively, for the case of overheating and overcooling of the exhibition space.

During the cold period, a poor correlation between outdoor and indoor temperature is observable; this relationship is 0.365 in point 012 and it is never higher than 0.380 (point 015). The correlation, reasonably, rises during the warm period especially when the indoor temperature is lower than outside. The low significance of the relation between indoor and outdoor temperature during the cold period is attributable to the heating system effect.

The mentioned effect of the heating system, during the cold period, can also be identified by the inverse correlation between indoor temperature and relative humidity (Pearson −0.212); the same negative correlation is calculated for the other points, maximum −0.261 (014). However, the reduction of relative humidity does not stand for water vapor reduction. Indeed the correlation between indoor mixing ratio and temperature explains rather the contrary (Pearson 0.786). The RH decreases because the saturation vapor pressure increases as a consequence of the temperature increase. The positive significant correlation between indoor mixing ratio and temperature

Table 11.6 Pearson correlation of temperature (TEMP), relative humidity (RH) and mixing ratio (MR) between point 012 and outside; Sig. > 0.01; months 11-12-1-2; condition (a)

Correlations (Pearson)	Months 11-12-01-02_condition a					
	TEMP 012	TEMP out.	Rh 012	RH out.	MR 012	MR out.
Temperature 012	1.000	0.365	−0.212	−0.280	0.786	0.267
Temperature outside	0.365	1.000	0.556	−0.321	0.685	0.915
Relative humidity 012	−0.212	0.556	1.000	0.166	0.423	0.653
Relative humidity outside	−0.280	−0.321	0.166	1.000	−0.156	0.062
Mixing ratio 012	0.786	0.685	0.423	−0.156	1.000	0.659
Mixing ratio outside	0.267	0.915	0.653	0.062	0.659	1.000

Table 11.7 Pearson correlation of temperature (TEMP), relative humidity (RH) and mixing ratio (MR) between point 012 and outside; Sig. > 0.01; months 06-07-09; condition (a)

Correlations (Pearson)	Months 06-07-09_condition a					
	Temp 012	TEMP out.	Rh 012	RH out.	MR 012	MR out.
Temperature 012	1	0.592	0.093	−0.306	0.76	0.309
Temperature outside	0.592	1	0.018	−0.717	0.426	0.239
Relative humidity 012	0.093	0.018	1	0.511	0.711	0.723
Relative humidity outside	−0.306	−0.717	0.511	1	0.125	0.497
Mixing ratio 012	0.76	0.426	0.711	0.125	1	0.697
Mixing ratio outside	0.309	0.239	0.723	0.497	0.697	1

Table 11.8 Pearson correlation of temperature (TEMP), relative humidity (RH) and mixing ratio (MR) between point 012 and outside; Sig. > 0.01; months 06-07-09; condition (b)

Correlations (Pearson)	Months 06-07-09_condition b					
	Temp 012	TEMP out.	Rh 012	RH out.	MR 012	MR out.
Temperature 012	1	0.735	0.372	−0.425	0.97	0.702
Temperature outside	0.735	1	−0.147	−0.835	0.604	0.584
Relative humidity 012	0.372	−0.147	1	0.415	0.581	0.334
Relative humidity outside	−0.425	−0.835	0.415	1	−0.258	−0.045
Mixing ratio 012	0.97	0.604	0.581	−0.258	1	0.708
Mixing ratio outside	0.702	0.584	0.334	−0.045	0.708	1

and in less extent the positive correlation between indoor relative humidity and mixing ratio (Pearson 0.423) explains that the temperature triggers some addition of vapor to the air volume; this is also visible from Fig. 11.9 in which the hourly variation of temperature and mixing ratio is plotted for the cold period.

The enrichment caused by the temperature increase might be explained either by a process of evaporation of the masonries towards inside, discussed by Litti et al. (2015a), or by other source of vapor related to temperature increase such as latent gains from people or humidifiers, discussed later in this section.

During warm period (months 6-7-9), when temperature indoor is higher than the one outdoor (see Table 11.7), indoor mixing ratio correlates positively with indoor

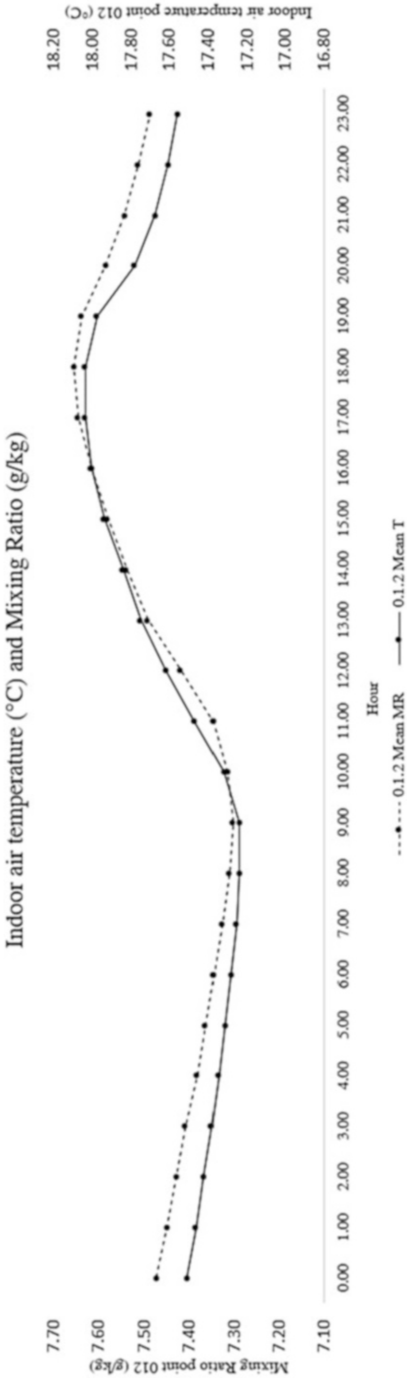

Fig. 11.9 Point 012, temperature (°C) and mixing ratio (g/kg) hourly average over the months: February, November and December 2014–January 2015; *R* 0.786

temperature (Pearson 0.76 in point 012); however this correlation is slightly lower than the cold period. This reduction can be explained by a smaller temperature gradient (DT is 17.44 °C and 9.80 °C in cold and warm period in condition (a) at the 95th percentile.

It can be supposed that also during the warm period part of the residual vapor from the moist masonries evaporates inside. When the indoor air temperature is higher than outside, condition a (Table 11.7), the correlation between indoor temperature and RH is zero for the reasons above mentioned (Pearson 0.09), but when the temperature drops, condition b (Table 11.8), the RH unavoidably increases (Person 0.37).

From thermal imaging of the walls, the risk of surface condensation was not evidenced; hence, the presence of moisture evaporating inwards might be caused by the natural drying of the masonry after the moisture accumulation in winter (see Litti et al. 2015a). During the warm period when the indoor temperature is lower inside than outside (Table 11.8), the correlation between indoor temperature and mixing ratio rises up to 0.97. In this case, as the temperature is lower, the correlation between indoor RH and temperature is positive and significant in all the points; it is 0.372 in point 012 and it increases up to 0.582 in point 015.

11.5.1 Influence of Humidifiers on Air Vapor Concentration

In order to assess the maximum contribution to the moisture enrichment given by the humidifiers present in the exhibition hall, it was hypothesized that all the four machines worked constantly at the maximum speed (level 4). The air recirculation rate at the given speed, according to the manufacturer, is 750 m^3/h, with a humidifying capacity of 2.7 l/h (45% and 23 °C) and maximum room volume (per machine) of 900 m^3, hence a volume coverage of 68%. With an approximation on the steadiness of the air temperature and considering isenthalpic air humidification from the water-based humidifiers (generally, water-based humidifiers work with isenthalpic transformation), it was estimated that the maximum moisture amount that entered the air volume per hour from the four humidifiers was 2.01 g/kg (68% of 2.96 g/kg). The calculated vapour enrichment caused by the humidifiers should be considered as a proxy representing the maximum vapour load attributable to the humidifiers. The equipment was found not constantly set at the maximum power.

11.5.2 Influence of People on Air Vapor Concentration

For testing the influence of people on the indoor vapor concentration variation, a test of mean independency was run considering both museum visiting and closing days within the time interval 13 pm–23 pm, during both cold and warm periods. The tested continuous variable was mixing ratio. The obtained results pointed out that

Table 11.9 Mixing ratio point 012; cold period (months 11-12-1-2) and warm period (months 6-7-9); time interval 13 pm–23 pm

Mean hourly mixing ratio 012 statistics						
	N	Mean	Std. deviation	Std. error mean	Period (months)	Interval (h)
Museum close	473	7.522	0.618	0.028	11-12-1-2	13–23
Museum open (visiting)	627	7.615	0.594	0.024	11-12-1-2	13–23
Museum open (visiting + concert)	649	7.609	0.586	0.023	11-12-1-2	13–23
Museum close	341	10.061	0.638	0.035	6-7-9	13–23
Museum open (visiting)	451	10.311	0.791	0.037	6-7-9	13–23
Museum open (visiting + concert)	462	10.295	0.788	0.037	6-7-9	13–23

the presence of people constantly contributed to the air vapor enrichment and this contribution increased consistently with the museum visiting rate.

In the cold period, the hourly mixing ratio (and also CO_2 concentration and indoor temperature) during opening days was higher than during closing days only from 13 pm. In the warm period, the mixing ratio during visiting days was constantly above the one of closing days. In order to compare the mean mixing ratio variation within the same time interval, the tests were run considering the time interval 13 pm to 23 pm.

During the cold period and in the considered time interval (13 pm–23 pm), the mean mixing ratio was 7.52 g/kg (SE 0.03) and 7.61 g/kg (SE 0.02), respectively, for closing and visiting days, without concert events (test 1). The difference was -0.093 g/kg (CI $= -0.166, -0.021$), and it was significant $t(994) = -2.524$, $p = 0.012$ (see Tables 11.9 and 11.10). The test significance (t) was calculated considering the weighted variance (pooled variance) from the two—differently sized—data population. In Table 11.10 is reported the unweighted variance; therefore the t values (compared to the one discussed in the text) might differ of few decimals.

It is worth noting that, after including in the statistic population the opening hours related to the concerts (in addition to the ones of museum visits), the mean mixing ratio slightly decreased (see Table 11.9). This occurred because of the low initial vapor concentration in the hours prior to the concert. Figure 11.10 shows this circumstance with regard to the last week of October 2014.

The concerts are performed once per month during the last of the three museum closing days, on Wednesday. In Fig. 11.10 is visible that immediately before the concert on October the 29th, the exhibition space has low mixing ratio (8.36 g/kg); this happened because no vapor was accumulated during the previous two closing days. Successively, during the concert hours, the mixing ratio increased up to 9.15 g/kg. The air mass was enriched of 5 kg of water vapor in less than 3 h (the number of people participating in the event was in average 100). After the concert, the vapor started being diluted. Nevertheless, before the entrance of visitors during the successive day (15 h later) the vapor concentration was still 0.19 g/kg higher

Table 11.10 Independent *t*-test for equality of the mean (mixing ratio); Test 1, readings without concert events (13 pm–23 pm)

	Levene's test for equality of variances			*t*-test for equality of means						
									95% Confidence interval of the difference	
		F	Sig.	*t*	df	Sig. (2-tailed)	Mean difference	Std. error difference	Low	Up
MR 012 (test 1) months 11-12-1-2	Equality of variance assumed	3.21	0.07	−2.54	1098	0.01	−0.09	0.04	−0.17	−0.02
				−2.52	994	0.01	−0.09	0.04	−0.17	−0.02
MR 012 (test 1) months 6-7-9	Equality of variance assumed	7.56	0.01	−4.78	790	0.00	−0.25	0.05	−0.35	−0.15
				−4.92	786	0.00	−0.25	0.05	−0.35	−0.15

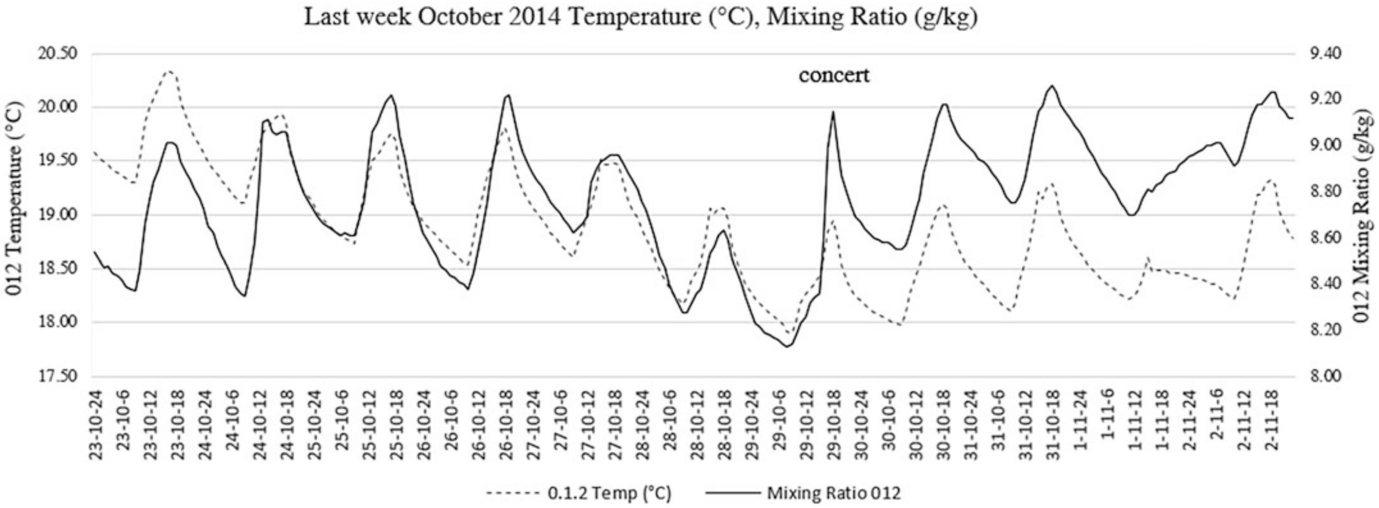

Fig. 11.10 Indoor air temperature (°C) and mixing ratio (g/kg) monitored from point 012; last week of October 2014

Table 11.11 Cold period (months 11-12-1-2) and warm period (months 6-7-9); indoor temperature, mixing ratio and CO_2 summary statistics for museum opening and closing days, time interval 00 am–23 pm

	Temperature (°C)			Mixing Ratio (g/kg)			CO_2 (ppm)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Opening days (cold period)	17.19	18.09	17.49	7.29	7.69	7.46	508.16	630.4	560.92
	9 am	18 pm		10 am	18 pm		10 am	18 pm	
Closing days (cold period)	17.31	17.98	17.60	7.32	7.59	7.47	494.47	541.32	521.89
	9 am	17 pm		10 am	17 pm		9 am	16 pm	
Opening days (warm period)	21.17	22.4	21.74	9.82	10.41	10.1	535.63	713.13	606.06
	6 am	15 pm		7 am	17 pm		10 am	17 pm	
Closing days (warm period)	21.08	22.12	21.58	9.7	10.13	9.93	500.91	600.91	548.16
	6 am	16 pm		7 am	17 pm		9 am	14 pm	

than the one previous to the concert. In other words, still 1.22 kg of water vapor emitted from concert attenders was not expelled.

The mean hourly mixing ratio and temperature in the exhibition space during the cold period, both in case of museum visiting and closing days (excluding concerts), are plotted in Fig. 11.11. Although negligible, the mean air temperature during closing days is 0.11 °C higher than the one during opening days (see Table 11.11).

Because of the strong relation between air temperature and mixing ratio already discussed in Sect. 11.5, the slight higher temperature during the closing days (in comparison to the opening days) results also in a higher mixing ratio. However, during the opening days, it is possible to distinguish the effect of the people presence from the speeding of temperature, mixing ratio and CO_2 variations between 10 am and 17 pm and from the more significant ranges of absolute variation as described below.

- During the museum closing days, the indoor air temperature maximum variation was 0.59 °C between 9 am and 17 pm, while it was 0.90 °C between 9 am and 18 pm during museum opening days.
- During museum closing days, the mixing ratio maximum variation was 0.27 g/kg between 10 am and 17 pm, while it was 0.40 g/kg between 10 am and 18 pm during museum opening days.
- During the museum closing days, the CO_2 maximum variation was 46.85 ppm between 9 am and 16 pm, while it was 122.24 ppm between 10 am and 18 pm during museum opening days.

Clearly, from the moment the museum is open (10 am), a significant increase of temperature, vapor concentration and CO_2 is registered in comparison with the closing days. However, the readings from each parameter are higher than the ones registered during the closing days from 13 pm; see Fig. 11.11.

The extra vapor produced by people is diluted between 18 pm and 20 pm; after this period, the residual moisture decreases similarly (with the same slope) as the closing days. Considering the interval from 13 to 18 (when the vapor starts being diluted) the daily extra water vapor added by people to the exhibition hall air mass

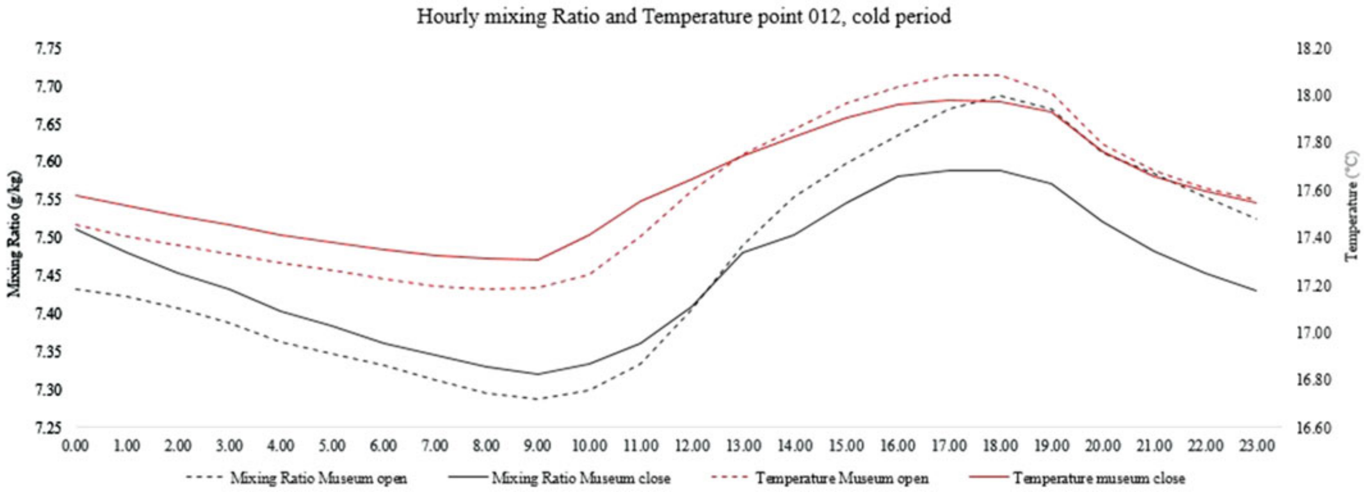

Fig. 11.11 Mean hourly indoor mixing ratio and temperature during closing and opening hours of the museum (open from 10 am to 17 pm); cold period (February, November, December 2014 and January 2015); point 012 (color figure online)

is 0.34 g/kg or 2.20 kg. If considering a vapor production of 50 g/h per person, in the exhibition space during the cold period, there were in average 8 people/h.

During the warm period, again result from the independent *t*-test confirmed that people presence influenced the mean vapor concentration variation in the exhibition space. The mean mixing ratio was 10.06 g/kg (SE 0.05) and 10.31 g/kg (SE 0.05), respectively, for closing and opening days, without concert events (test 1) and during the time interval 13 pm–23 pm; see Table 11.9. The mean difference was −0.250 g/kg (CI = −0.35, −0.15), significant $t(786) = -4.922$, $p = 2\text{E}{-}05$; see Table 11.10.

In Fig. 11.12 is reported the hourly mixing ratio and temperature of museum opening (dotted black and red lines) and closing (continuous black and red lines) days for the warm period. Differently from the cold period, the indoor mixing ratio during the opening hours was always higher than the closing hours, but similarly to the cold period the increase of temperature, mixing ratio and CO_2 was faster and more significant in the presence of people as reported below.

- During the museum closing days, the indoor air temperature maximum variation was 1.04 °C between 6 am and 16 pm, while it was 1.23 °C between 6 am and 15 pm during museum opening days.
- During the museum closing days, the mixing ratio maximum variation was 0.43 g/kg between 7 am and 17 pm, while it was 0.59 g/kg between 7 am and 17 pm during museum opening days.
- During the museum closing days, the CO_2 maximum variation was 100 ppm between 9 am and 14 pm, while it was 177.5 ppm between 10 am and 17 pm during museum opening days.

If considering the entire visiting time interval 10 am–17 pm (when the vapor starts being diluted), the added vapor from visitors from an average visiting day during the summer was 8.64 kg (or 1.87 g/kg), an average of 170 people per day or 30 person/h. The occupation rates for the cold and warm period, calculated from the indoor monitored hygrothermal parameters, were consistent with the ones provided by the museum administration.

11.5.3 Influence of Entrance Door Operation on Air Vapor Concentration

As described in Sect. 11.3, the influence on the vapor concentration produced by air ventilation was assessed by observing the relation between indoor and outdoor air velocity, air temperature, relative humidity and mixing ratio during museum opening and closing hours as well as by performing a test of mean independency of the indoor air velocity for museum opening and closing days during both cold and warm periods. The considered time interval was 10 am–17 pm (museum opening hours). According to this time interval museum opening and closing days for the cold and warm periods was compared.

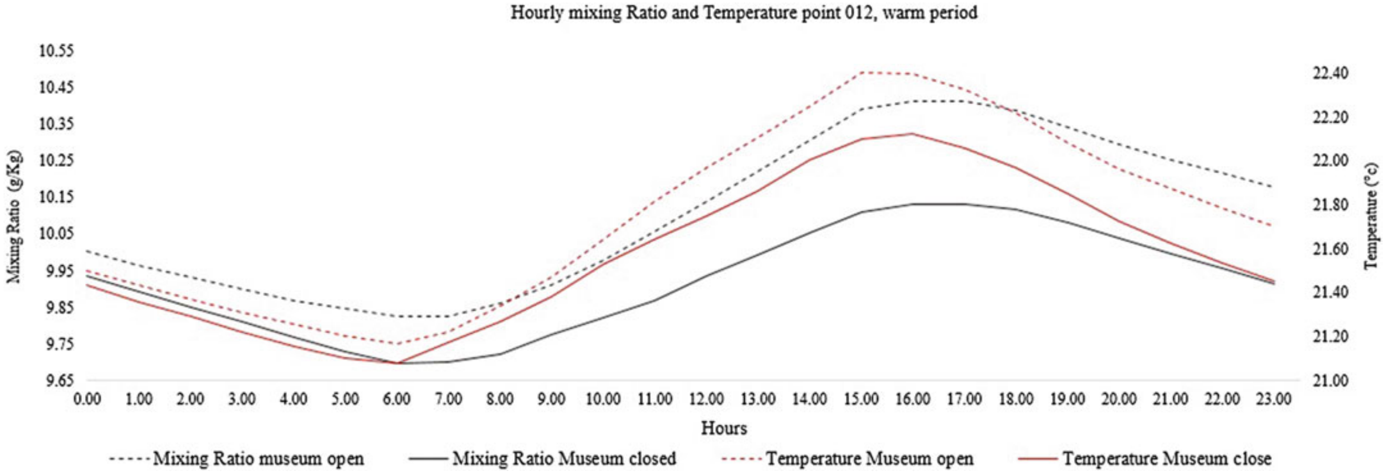

Fig. 11.12 Mean hourly indoor mixing ratio and temperature during closing and opening hours of the museum (open from 10 am to 17 pm); cold period (June, July, September 2014); point 012 (color figure online)

Table 11.12 Air velocity point 012; cold period (months 11-12-1-2) and warm period (6-7-9); time interval 10 am–17 pm

Mean hourly air velocity 012 statistics						
	N	Mean	Std. deviation	Std. error mean	Period (months)	Interval (h)
Museum close	30	0.063	0.034	0.006	11-12-1-2	10-17
Museum open (visiting)	51	0.058	0.037	0.005	11-12-1-2	10-17
Museum close	41	0.054	0.030	0.005	6-7-9	10-17
Museum open (visiting)	60	0.058	0.029	0.004	6-7-9	10-17

For the cold period, the results from the independent *t*-test confirmed that the opening of the door had no influence on the mean indoor air velocity variation in the exhibition space. The mean air velocity was 0.063 m/s (SE 0.006) and 0.058 (SE 0.005), respectively, for closing and opening days, without concert events and during the time interval 10 am–17 pm; see Table 11.12. The mean difference was 0.005 m/s (CI $= -0.012$, 0.021), not significant $t(79) = 0.56$, $p = 0.577$; see Table 11.13. Same results were observed also with regard to the warm period. The door opening was not significant for the mean air velocity variation. The mean air velocity was 0.054 m/s (SE 0.005) and 0.058 (SE 0.004), respectively, for closing and opening days, without concert events and during the time interval 10 am–17 pm; see Table 11.12. The mean difference was -0.004 m/s (CI $= -0.016$, 0.007), not significant $t(99) = -0.748$, $p = 0.456$; see Table 11.13.

The results from the test confirmed that the door opening had no effect on the variation of the indoor air velocity both in the cold and warm periods, confirming that the ventilation rate in the exhibition space stays invariant throughout the seasons. This is also confirmed by the invariability of the mean indoor air velocity during the opening days between cold and warm periods; see Table 11.12. It is worth noting that the indoor air velocity during the museum closing hours is slightly higher than the museum opening hours (difference of 0.005 m/s); this condition is attributable either to the increase of the air convection from the heating system or to the increase of air infiltration or exfiltration. These aspects will be the object of further study.

11.6 Indoor Microclimate Quality (IMQ) Certification: Results

As mentioned in Sect. 11.2, the cold period (heated period) considered in the certification was made up of two short intervals: March–April 2014 and October–November 2014. For these intervals, 2-hour-based PMV was calculated. Descriptive statistics for both the data samples are given in Table 11.14.

Table 11.13 Independent *t*-test for equality of the mean (air velocity); readings without concert events; cold period and warm period, time interval 10 am–17 pm

		Levene's test for equality of variances		*t*-test for equality of means						
									95% Confidence interval of the difference	
		F	Sig.	*t*	df	Sig. (2-tailed)	Mean difference	Std. error difference	Low	Up
Air velocity 012 months (11-12-1-2)	Equality of variance assumed	0.24	0.63	0.56	79	0.58	0.00	0.01	–0.01	0.02
				0.57	64	0.57	0.00	0.01	–0.01	0.02
Air velocity 012 months (6-7-9)	Equality of variance assumed	0.15	0.70	–0.75	99	0.46	0.00	0.01	–0.02	0.01
				–0.75	84	0.46	0.00	0.01	–0.02	0.01

Table 11.14 Statistics PMV period 1 (March–April 2014), period 2 (October–November 2014)

	PMV March–April 2014		PMV October–November 2014	
	Statistic	Std. error	Statistic	Std. error
Mean	0.067	0.01	−0.249	0.014
Std. deviation	0.22		0.353	
Minimum	−0.58		−1.02	
Maximum	0.6		0.49	
Skewness	0.07	0.115	−0.023	0.098
Kurtosis	−0.247	0.23	−1.032	0.196

Table 11.15 Microclimate—Simultaneous Performance Index (SPI)

	Thermal quality heritage (H)	Hygrometric quality heritage (H)	Hygrothermal quality people (P)	Simultaneous Performance Index (SPI)
	0.32	0.55	0.48	0.45
Incidence	23%	41%	36%	

The first heating period has a positive mean around zero, meaning a thermal sensation around the thermal neutrality, while the second one has a negative mean around −0.25, meaning a thermal sensation skewed towards cold. The PMV votes for both the periods were tested for observing normality of distribution; the test results evidenced that the data distribution from the first period (March–April) is normal (Shapiro–Wilk normality test Sig. 0.064) with no relevant outliers, while the one from the second period (October–November) slightly departs from the normality. This occurred due to indoor temperature readings measured below the one outdoor as reported in Fig. 11.8 (condition b). However, the deviating values were consistent with the indoor environmental variations in the specific period; therefore the data were retained in the certification model.

The warm period (free running in the specific case) from May 2014 to September 2014 was certified according to the interval categories from the EN 15251.

On the basis of the certification methodology presented in Chap. 6, the obtained Simultaneous Performance Index (SPI), representing the hygrothermal quality for both people and collection, is 0.45 (see Table 11.15). This value falls in category 1, good level of microclimate comfort, according to the considered scale (see Tables 11.4 and 11.5). Even if minor deviations from the optimal microclimate range occurred (such as the overcooling in October–November), these did not compromise neither the hygrothermal quality for people nor the safety for material preservation. Breaking down the microclimate indicators, it is possible to observe that the hygrometric comfort for artifacts was responsible for the 41% of the diminishing of the whole microclimate quality performance. During the monitoring period, relative humidity showed almost equal stability as temperature with regard to long- and short-term fluctuations, but 10% of RH observations (versus only 5%

Table 11.16 Frequency of deviations from thermal comfort optimality for three monitoring intervals and associated *P*(people) values

	Categories of deviation							$\overline{P_p}$
	−3	−2	−1	0	1	2	3	
Cold period (heating period 1)	0.00	0.00	0.11	0.62	0.24	0.02	0.00	0.41
Warm period (free running)	0.00	0.00	0.00	0.99	0.00	0.00	0.00	0.01
Cold period (heating period 2)	0.13	0.15	0.24	0.37	0.11	0.00	0.00	1.04

of temperature) fallen in the second class of microclimate quality, producing a general lowering of the hygrometric indicator performance.

This performance reduction is significantly accentuated considering a weighting factor doubled compared to the one related to temperature. People thermal comfort for the entire monitored period was good (*P* 0.48) (see Table 11.15).

In Table 11.16 is plotted the frequency of deviation from the thermal neutrality with regard to three key moments of the certified time interval. It is remarkable that the building ensured optimal thermal comfort during the hottest period of the year (August–September). In this period, the total deviation from the optimal thermal comfort was negligible (*P* 0.01). It is worth remembering that the building is not equipped with a cooling system.

The building ensured good thermal comfort also during the first heating period; the total deviation from the thermal neutrality was 0.41. During this period the values were observed below and above the range of thermal neutrality meaning that slight cool and slight warm sensations occurred concurrently. However, during the second heating period, due to the lowering of the indoor temperature below the one outdoor, the thermal comfort quality was moderate (*P* 1.04).

11.7 Conclusions

The monitoring activities and analysis presented in this chapter allowed to obtain a clear understanding of microclimate inside the exhibition space. Moreover the implemented certification methodology delivered an overview of the microclimate quality with respect to the comfort need for people and collection.

In the monitored space, the vapor concentration increased or strongly varied as a consequence of several concurrent factors related to both building state of material conservation and building management. Among the investigated factors, there are some of them unlike to be solved if not restoring the building envelope, both masonries and stained glasses (and their connections). The removal of water from the moist masonries and the reduction of the air infiltration should be considered among the priorities of the any restoration intervention in the building.

Another issue is related to the introduction of vapor from equipment and visitors. The vapor concentration controlled by means of punctual humidifiers should be cautiously evaluated especially during the summer period. In the most severe scenario, it was calculated that the quantity of vapor emitted by the humidifiers in 1 h might overcome the one emitted from people in an entire winter visiting day.

It was calculated that visitors, especially during high occupation rate such as the concert events, released up to 5 kg of vapor in less than 3 h. One-fourth of this vapor was observed to be persistent in the exhibition space air mass also after 15 h from the end of the concert. With this purpose it is worth considering a subtraction of vapor by means of ventilation of the space (only in case the outdoor environment is less rich in vapor than the one indoor) immediately after highlighting frequented events. Nevertheless, the building thermal comfort both for people and for collection was good throughout the monitored year.

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