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Edited by

Fundación de Casas Históricas y Singulares

Fundación Ars Civilis

Coordinated by

Mónica López Sánchez. Fundación Ars Civilis

Ana Yáñez Vega. Fundación de Casas Históricas y Singulares

Sofia Gomes da Costa. Fundación de Casas Históricas y Singulares

Lourdes Avellà Delgado. Fundación Ars Civilis

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Table of contents

DESIGN OF A CONTROL SYSTEM FOR THE ENERGY CONSUMPTION IN A WALL-HEATED CHURCH: SANTA MARIA ODIGITRIA IN ROME

MANFREDI, C.; FRATERNALI, D.; ALBERICI, A.

MANFREDI, C.: Politecnico di Milano, Laboratorio di Analisi e Diagnostica del Costruito. Milano – Italia. carlo.manfredi@polimi.it
FRATERNALI, D.: Servizi Territorio srl. Cinisello Balsamo, Milano – Italia. daniele@serviziterritorio.it
ALBERICI, A.: Servizi Territorio srl. Cinisello Balsamo, Milano – Italia

ABSTRACT

Our contribution aims at showing a particular control system, designed and set up in order to monitor both the operating parameters ad finally the yearly energy consumption of the wall heating system installed in a church in Rome.

The goal of our study is to illustrate a different way of controlling indoor environment in order to improve the plant efficiency.

Our targets are both a more immediate answer to climatic changes and a deeper understanding of the close interaction between comfort and radiant effect, beyond simple temperature values. Furthermore, a higher degree of control in managing the system would allow also a reduction of energy consumption.

Santa Maria Odigitria is the church of the Archconfraternity of the Sicilians in Rome. It is a late Renaissance building, and its interior has been consistently reshaped in the 19th Century. It had never been provided with a heating system before last winter.

In order to minimise the intervention on a well-preserved building, the heating system adopted is a wall-heating system, already well-known as Temperierung. The system settled in Santa Maria Odigitria consists in a few pipes running hot water, placed in the lower part of the walls.

Temperierung systems are already well-known since an early experimentation in German-speaking Countries in the Eighties and Nineties, particularly in some museums in Bavaria. Further plants has been installed in Austria and Italy. The radiant effect allows to reach preservation purposes (both of the building itself and of artworks) and meets comfort requirements.

Indoor climate of the church is constantly monitored through both conventional indoor climate sensors (RH and T) and InfraRed temperature sensors. Data are continuously recorded in order to set up a climatic history of the building. The heating unit and zone controlling thermostatic valves are effectively managed through an electronic control unit. A dedicated software algorithm evaluates and processes sensors output data.

It should be noted that, as expected, surface temperature depends on many factors besides the heating system: sun radiation, neighbouring buildings, crowding and so on. A special role is played by the inertial behaviour due to the thermal capacity of massive buildings.

In more general terms and taking into account a wider range of buildings, it should be pointed out that a general approach is going to be defined in order to reach different purposes, such as building and artworks preservation as well as well-being requirements and reduction of fuel consumption.

Key words: Temperierung, monitoring, wall-heating, S. Maria Odigitria

1 INTRODUCTION

The relationship between preservation and Building Services Engineering has been investigated only in the last few years. On the contrary, in order to preserve buildings to use and inhabit them, taking care of them for future generations, different aspects have been examined, such as structural behaviour and, consequently, structures design, removal of architectural barriers and related design. Nevertheless, it has to be remembered, that building services such as sewerage systems and water supplies, heating and lighting, safety devices and data networks, have hugely increased since the 19th century, and they are still increasing, deepening the gap between our concept of architecture and construction and the one kept in the past.

In order to analyse such a matter some aspects should be pointed out briefly. First of all, it has to be taken into account that every building is a witness, a source of information about the time and culture that contributed to its birth, and it should be preserved for its historic and documentary value, including handicrafts and industrial devices. On the contrary, demonstrations of human work have been often neglected, when considered repeatable. Such an attitude has been depicted as “integrated preservation” [1]. It consists in respecting architectural image, as well as material features, such as plasters and windows, technical devices and furnishing.

Secondly, it has to be considered that the notion of human well-being greatly changed over the ages. Comfort requirements ordinarily accepted in 19th century are not suitable today. In 1850 in the just opened Sainte-Geneviève library in Paris the comfort temperature was fixed at 15°C by the architect Labrouste: it is evident that nowadays trade-unions, workers and students could not agree with him. In the same years, in the same town, the National Library used to close at four o’clock in the evening, because of lack of lighting. Many further examples of this sort may be displayed.

Thirdly, an increasing anthropic footprint is irreversibly changing climate on Earth: reduction of power consumption is now imperative. Against the idea that old buildings would be necessarily worst built under a technical and technological viewpoint, a wider idea of sustainability is now progressing, showing that an object must be considered paying attention to all aspects involved, from the age of construction to the intended and actual uses. The improvement of historic buildings behaviour from an energetic standpoint should be reached without losing artistic, historic and material values of the constructions. [2]

Valuable results can be reached through “the organization of the works with a craftsmanlike approach” and following “the concept of “improvement” as opposed to the one of “adjustment”, employed in the field of structural consolidation, with excellent results for cultural objects and their protection, can now at last be applied also to system engineering and energy issues.” [1]

In other words, almost in every case, a building built for past uses can hardly reach present-day levels of comfort, as required by current norms and well-being as expected by people, without compromising the construction itself. Under these circumstances, just improving the performance may be sufficient. The idea of *improvement* had been suggested also by the European guidelines, at least since the Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings. The norm points out that in every case “Renovation requirements for existing buildings should not be incompatible with the intended function, quality or character of the building”. [3]

Image 1: Oratorio di Santo Stefano, Lentate sul Seveso (Milan).*Temperierung* runs under the plaster at the walls' foot

Image 2: Museo del Paesaggio, Palazzo Dugnani Viani, Pallanza

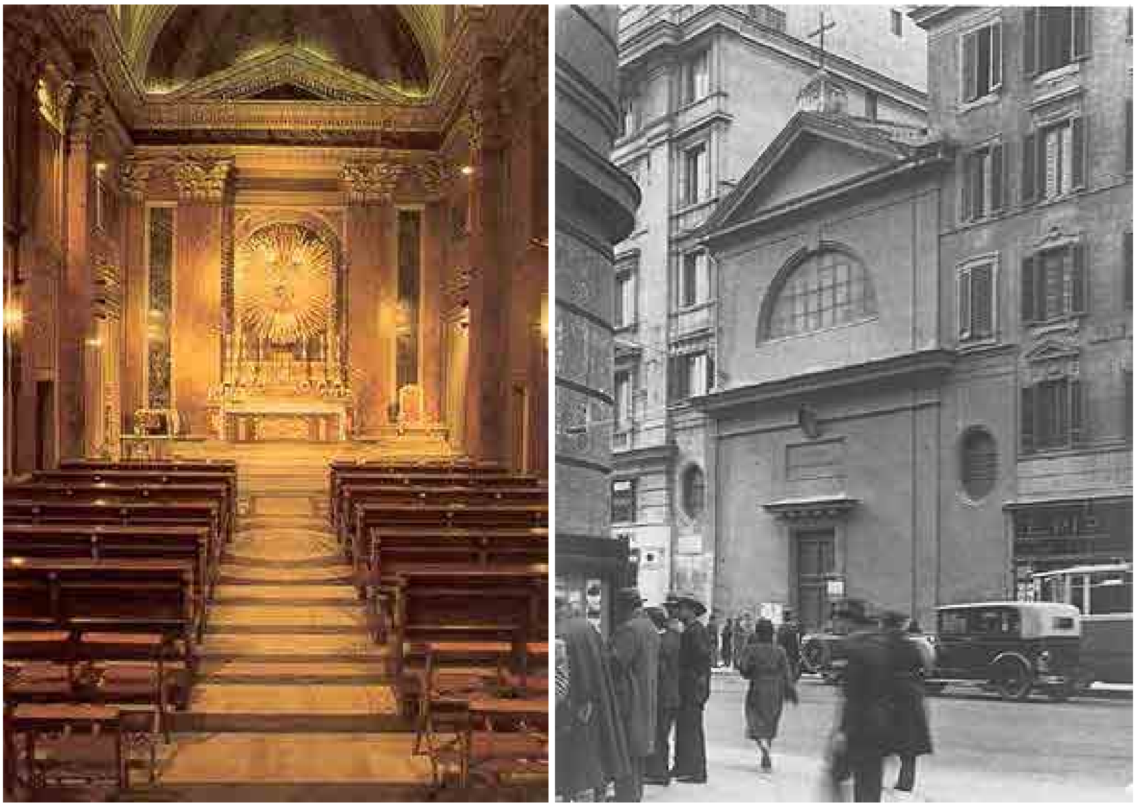

Image 3: Church of Santa Maria Odigitria, Rome (Courtesy by G. Pagliarulo, Rome)

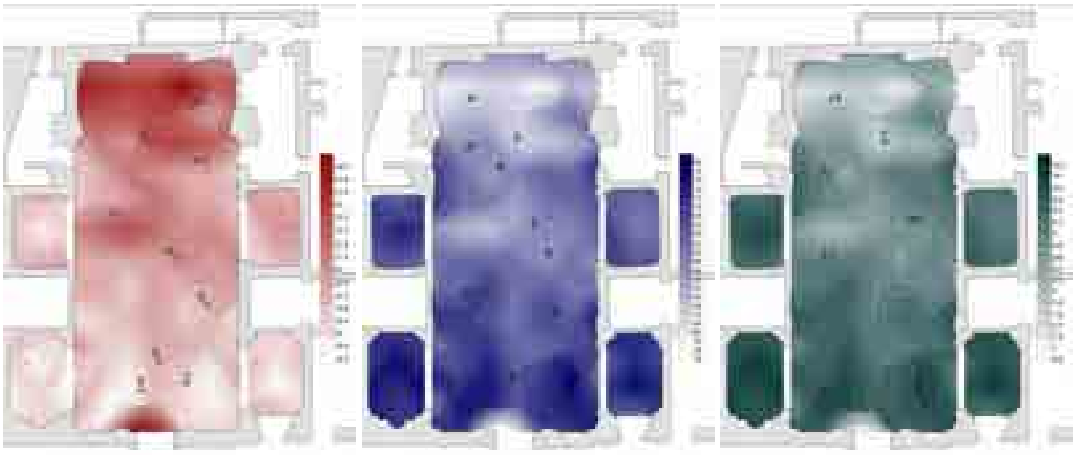

Image 4: Santa Maria Odigitria. Psycrometric survey of the microclimate. From left: Temperature, Relative Humidity and Mixing Ratio maps. June 20, 2013. Outdoor T: 34°C; Outdoor RH: 24%. Graphic processing by L. Valisi

At the end of such a short outline a further aspect, last but not least, must be taken into account. It descends from what we have described so far but is not so evident. I mean the conscious energy design made by architects and engineers in the past. In every time and every part of the world buildings have been built paying attention to the actual climate and to the way to spare fuel. According to Dean Hawkes, “The climate exists. The building, in various manner and degrees, responds to this. But in taking a historical standpoint, buildings may be seen, in some respects, both to represent and to interpret the climate that shaped them.” [4]. Even though building physics is a field of science comparatively recent, it must be assumed that the architects and designers of the past had some knowledge of the topic, allowing them to build with a certain assurance with regard to the thermal behaviour of their buildings, paying attention to the passive side of the building components, such as thermal inertia, orientation, shading systems.

In this field of research, works carried out are very few. The research to be carried on consists in collecting drawings, documents and inventories about the building and connecting these data with the results of a monitoring campaign on the microclimate. This analysis is aimed at describing how the building really works compared to the use foreseen at first, and subsequent changes in use and shape.

2. THE *TEMPERIERIUNG* SYSTEM

Temperierung developed from the experiments carried out by the *Bayerische Landestelle für die Nichtstaatliche Museen in Bayern* (Bavarian Office for non-state museums) since the beginning of the Eighties of the 20th century and was conceived as a support for the preservation of works in museums. The system was especially suitable for local museums (*Nichtstaatliche Museen*) that, unlike state museums, could not rely on the financial resources necessary to build and then maintain expensive air conditioning systems. Existing heating systems (based on convective hot air emitted by fan coils or radiators), determined significant damage to works not only for the variations in relative humidity, but also – as pointed out by several recent studies such as the congress "Climate for Collection" [5] in 2012 – for the effect of the thermal stress produced by hot air flowing along cold walls. In order to balance the temperatures on the opposite sides of the artworks, at first systems based on electric heating elements were developed. Then they decided to directly heat the wall itself and, quite surprisingly, they found that this solution also produced an improvement in well-being for the visitors: this was the result of the combined effect of reduction of "the cold wall effect" and limitation of the hot air motion. So, *Temperierung* can be considered as "a process that, through direct heating of the building envelope, aims at optimizing the physical conditions of building elements, internal climate and physiological well-being."[6] Particularly, "Its main characteristic is the continuous heating of the building shell, which normally is done with two heating pipes installed under the inside plaster at the base of outside walls on all floors. Without additional measures, tempering stops capillary rise of moisture, condensation, and damaging salt effects while stabilizing room climate and providing physiologically and conservationally appropriate as well as energy saving room heating." [7]

In the intentions of the early proponents – notably Henning Großeschmidt – *Temperierung* has its roots in the hypocaust used in Roman Baths and other ancient buildings: hot smoke spreading both under the floors and through cavities into the walls. Even if, obviously, the ways of application and the materials used have changed, actually both *Temperierung* – and *Hypocaustum* – rely on the "radiation effect", where heat radiation is produced by the wall structure itself [7]. However, given the radically different context, this reference is so remote that it may seem too generic. A new but perhaps stronger analogy could be found in the applications developed for the architectural integration of hot water systems by John Soane in the early 18th century. Architect Soane too was prone to find classic roots to new devices, i.e. the pipe called "draco" by Vitruvius and his works combine a high formal quality to a shrewd sensitivity in design technique. Those systems are known as Hot Water High Pressure (HWHP), or Perkins' heating systems.

In England, during the age of the first industrial revolution, besides the pioneering works of Soane, several public buildings began to be built with one-inch-pipes circulating steam or superheated water at the base of the walls. This system experienced a wide diffusion throughout Europe since the first half of the 19th century [8].

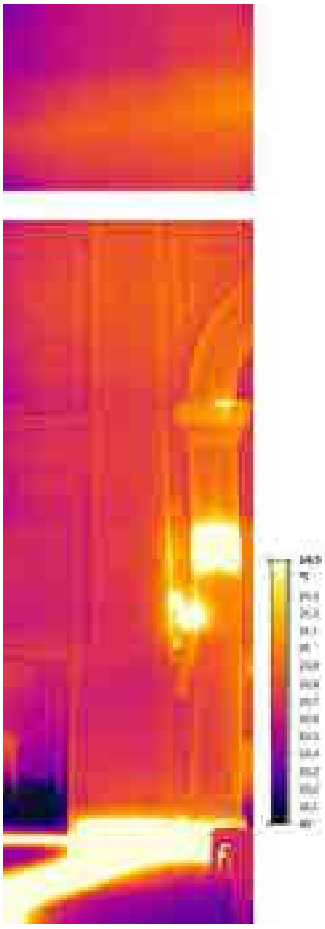

Image 5: Thermographic picture (Infra Red thermographic camera) of a warming wall. Graphic processing by L. Valisi. October 22, 2013. Thermal range from 22°C to 24,5°C. The Temperierung was just switched on

Image 6: Photographic correction of the east side (Courtesy by G. Pagliarulo, Rome)

Beyond the intentions of the *Bayerische Landestelle für die Nichtstaatliche Museen in Bayern*, the experiments, conducted at first in an empirical way, and a wide number of installations, have started a fruitful debate, still on especially in Austria and Germany, about advantages and disadvantages of the system. The debate has centred mainly on certain clearly defined problems to which *Temperierung* offers some solutions. They are listed below.

- How to counteract the decay due to moisture (originated by capillary rise or condensation in walls);
- How to prevent the transmigration of salts inside the masonry;
- How to reach comfortable environmental conditions;
- How to reduce energy consumption;
- How to ensure environmental conditions suitable to the preservation of artworks.

The description that follows will try to evaluate the possibilities and limitations offered by such systems, in particular the prevention of damage that may result from unfavourable humidity and temperature conditions, through the case study of the Church of Santa Maria Odigitria in Rome.

Assuming that there was no rising damp, or water infiltration due to positive water pressure, and therefore ignoring the issues relating to the transport of salts, the goal was to achieve favourable environmental conditions, without prejudice of the preservation and protection of artworks and building substance.

German literature distinguishes between *Heizungs-* and *Temperierungs-anlage*: the terms are not synonymous. [9] In other words, *Temperierung* is not essentially an intervention aimed at achieving optimal conditions in terms of well-being, or at least not only and not always. [10]

In fact, there are deep differences among several ways to utilize this technology. The use of *Temperierung* control is primarily bounded by the thermal storage capacity of a building (environment tempering) and the decay state (building tempering). "The main goal of *Bauteiltemperierung* (localized Temperierung) is small part and building component protection, while *Groundtemperierung* (base temperature) refers to the entire Building building and the room temperature control for the use of space." [6]

The system has been successfully applied in a number of cases in Germany, Austria and Slovenia [10]. In Italy, following the first, pioneering intervention of Palazzo Cattaneo in Cremona, the experimentation continued in other buildings, among which it is worth recalling at least some significant cases. [11]

Palazzo Pallavicino in Cremona, a noble residence now turned into a school for the restoration of musical instruments, is the building where *Temperierung* has been applied in a wider and complex way. For a detailed description of the ongoing monitoring on the building climate, see the contribution dedicated to it, presented in this Congress.

In 2007 a system was installed at the Oratorio di Santo Stefano in Lentate (fig. 1). In this case it consists in a simple copper ring circuit, placed at the foot of the wall, at the height of the plaster peeled off the wall due to the action of rising damp. The wall was plastered again, including (and hiding) the copper circuit sticking to the masonry, which makes the radiant effect more effective. It aims at avoiding that the most exposed part of the wall to the condensation could reach temperatures below the dew point. The system also allows a moderate warming, in order to keep acceptable the indoor climate for sporadic guided tours, lasting max one hour, as the present use of the building requires [12].

In 2009 another Temperierung heating system was installed in Palazzo Viani Dugnani in Verbania-Pallanza (fig. 2), where the oldest Museum of the Landscape of Europe, founded in 1914, is housed. The building was built over different ages, but in its current appearance probably goes back to a late-eighteenth-century refurbishment to be used as a summer residence. No heating system was therefore foreseen; when it became a museum, the building used to be visited only in summer. In order to extend the opportunity to visit it also during the cold season, the Museum direction gave origin of the program for the installation of *Temperierung*. In addition to ensuring minimum conditions of environmental comfort, it would assure that changed environmental conditions did not produce damage to the artwork collections, largely paintings and plaster statues made between the late 19th and the first half of the 20th century. [13, 14]

Following the requests of the curators themselves, that acknowledge Temperierung a good behavior in terms of preservation, it has reached in Bavaria a wide diffusion, and in general throughout Germany where it is installed in hundreds of museum buildings. Therefore, a monitoring program of some systems has been recently launched in Germany, and the project was presented during a workshop in November 2012. In that occasion the Italian experiences have been described as well. [15]

3. THE CASE OF SANTA MARIA ODIGITRIA

The Confraternity of Santa Maria Odigitria was established on February 5, 1594, by the Papal Bull "Pastoris Aeterni," with which Pope Clement VIII granted the honor of Cardinal Protector. The association began its activity on April 12 of that year: it has continued without interruption ever since. The brothers immediately set about building the church and hospice. One of them, Matteo Catalano, secretary of Cardinal Tagliavias, provided 4,000 scudi, and some buildings of his own. Upon a part of the area occupied by them the Church was built while the other buildings were adapted to hospice. All the brothers contributed to meet the expenses. The Catholic King Philip II came to help with generous donations. The Church and the hospice arose where they still are, and of course the church has been rebuilt more than once over the centuries. The church was solemnly consecrated and opened on August 15, 1596. A few years later the Confraternity had acquired so much prestige that Paul V, by the Bull of March 8, 1606, granted her the privilege of releasing every year a person sentenced to death. On August 7, 1650 the Vatican solemnly consecrated the image of the Virgin, erroneously held to come from Constantinople and therefore also called "Madonna of Constantinople". The church and the Confraternity prospered thanks to the protection, over time, of His Catholic Majesty the Viceroy of Sicily, the Sicilian Parliament, the Bourbons, the royal dynasty of Naples and the Two Sicilies. During the upheavals followed in Italy to the French Revolution, in February 1798, French troops occupied Rome, Pope Pius VI was imprisoned and the Roman Republic proclaimed. Ferdinand IV, King of Naples and Sicily, succeeded in expelling them from the city in November of the same year, stirring up the joy of the Sicilians, who, in their Church, sang a solemn Te Deum for the victory of their sovereign. Just seventeen days after the French came back and took revenge for that outrage: in January 1799 they plundered the temple dispersing the sacred and precious furnishings, reducing the building to a heap of ruins, which were then sold to private citizens to be used as small shops. Under the following Pope, Pious VII, the brothers claimed back and obtained these ruins, and after dispelling some doubts, on November 18, 1804 they decided to rebuild their temple on the same site, facing considerable debts and economic sacrifices. They did not, however, resurrect the hospice: they preferred to turn the building into private homes in order to derive some income to pay their debts.

The church was rebuilt following a design by Francesco Manno and was solemnly reopened on May 22, 1817. On the main altar they put on display, where they can be still seen, the golden candlesticks offered by the Queen of Etruria wife of Louis of Bourbon. The decoration could be completed only in 1840, when the brothers made and donated the paintings for the altars to the church. Only two of these paintings remain: the one portraying St. Rosalia, work of Natale Carta, donated by the brother Giuseppe Count Ludolf, Minister Plenipotentiary of the King of Naples, and the other portraying St. Leo II, Sicilian Pope, work and gift of the brother Ferdinando Raimondi. The decoration in chiaroscuro was painted by Angelo Soldani. In this circumstance under the altar of St. Leo II they placed the relics of St. Gaudenzia, Roman virgin and martyr. [16, 17] Since then the church has not been modified; in 2011 to 2012 it has been consolidated on the trusses and at the same time, the façade of the church was restored as well as the façade of the adjoining building. On that occasion a new efficient LED lighting was installed. In 2013 the walls, pillars and arches of the chapels of St. Lucia and St. Rosalia were consolidated, entering from the basement of the adjoining shop. In October 2013 the restoration of the painted surfaces in the chapels of St. Lucia and St. Rosalia has begun.

The Church is located in a densely built block, and the south facade looks out on Via del Tritone, in the Rione Colonna. It has a single nave, with two chapels on each side. Behind the altar, two storage rooms and a courtyard partially protect the building from the outside. The church space is 20 meters long, 9 meters wide and 15 meters in height (up to the vault keystone). The plans of the Chapels are 4,5 for 3 meters, about 7 in height.

The *Temperierung* system provided has been designed to meet the requirements of thermal comfort in the church. Three copper pipes circuits have been placed under the marble socket following the nave perimeter. The operations were carried out with extreme attention to the substance of existing materials. It was in fact necessary to disassemble the marble slabs at the base of the decorative vertical coatings and the stone rises of the steps delimiting the chancel and the aisles, in order to accommodate the above mentioned three circuits. The stone bands were then reassembled into the original location. The chapels and the altar area are therefore not affected by the intervention.

The system is equipped with a sophisticated monitoring system that constantly registers the indoor and outdoor environmental conditions and the operating conditions. More details on the monitoring system are reported hereafter.

3.1. Microclimate monitoring

The church building is oriented with the apse to the north and the entrance to the south, on via del Tritone. Before choosing the right heating system and its design a careful microclimatic analysis has been carried out to understand the environmental behavior of the place. The analysis has been carried out using a psychrometer, which detects both dry bulb and wet bulb temperatures. It also returns Relative Humidity and Mixing Ratio data.

The survey (fig. 4) was made in the central part of the day on June 20th 2013 with an outdoor temperature of 34°C and RH of 34%. Starting from the entrance and going towards the altar the temperature distribution shows a constantly growing positive range. The storm door placed at the main entrance had been left open during our data collection, which produced a strong imbalance and an extremely marked thermal bridge, clearly shown also by RH and MR values. Relative and Specific Humidity distribution follows a similar trend as temperature, with a very marked gradient near the entrance door from which very dry air enters (RH: 36% - MR: 6,8 g/kg) compared to the inside remarkably higher values (RH: 76% - MR: 9.8 g/kg). It must be remarked that climate in the chapels is considerably affected by their clear-cut separation from the nave. It is, on average, damper, in particular compared with the area of the altar.

Our survey clearly shows that the building has the expected behaviour in Spring.[18] Due to hot and damp air coming in from outside in a place that has preserved a lower temperature, going from the entrance towards the apse there is a sudden fall in air temperature with a consequent increase of RH values. As usual, MR values contour lines distribution can be used as heat fluxes tracer. The air movement is very clear in spite of the storm door at the entrance.

3.2. The Temperierung and the control system

Several experiments carried out with *Temperierung* systems have been generally positive especially from the preservation point of view. The possibility to adapt the system, consisting in "wall heating through pipes mounted in or on the inside of the walls"[19], to specific cases, namely different buildings and situations, assumes considerable importance in conservation aspects both for the collections preserved indoor and for the building itself. These issues will be treated below.

Even if the system has been widely in use for more than thirty years "Only a few investigated the effects of *Temperierung* to the indoor climate and evaluated the indoor climate for the questions of preventive conservation in detail" [20], nor to the effects on energy savings.

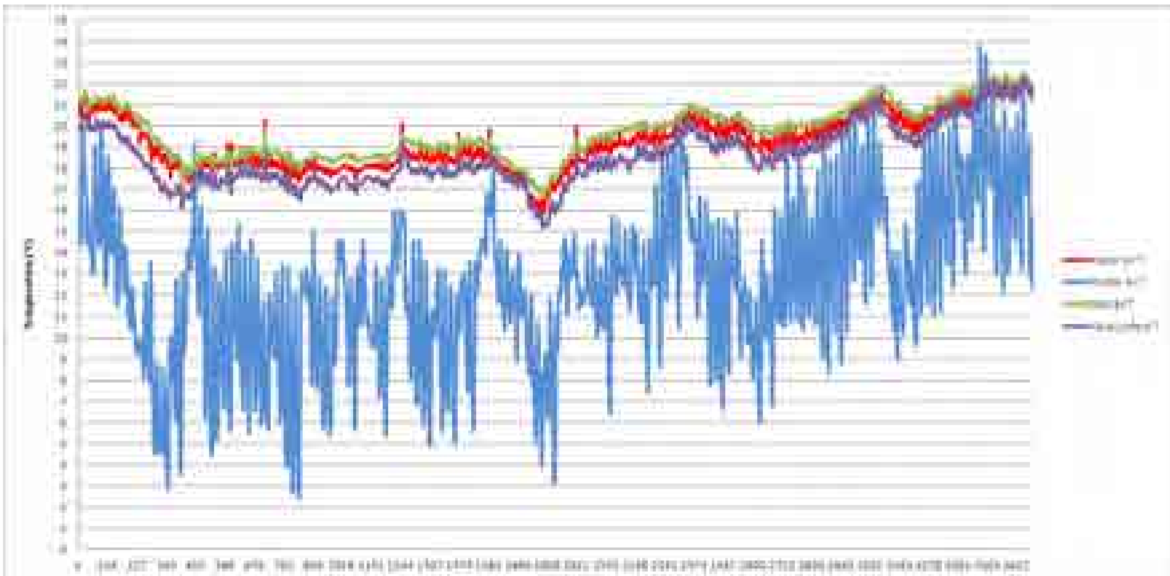

Image 7: S. Maria Odigitria. Monitored values (average temperature data): surfaces temperatures; indoor and outdor air temperature from November 13, 2013, to April 15, 2014. From above: green: indoor air T; red: wall surface T; violet: barrel vault T; blue: outdoor T. © HypoThermos, Servizi Territorio srl.

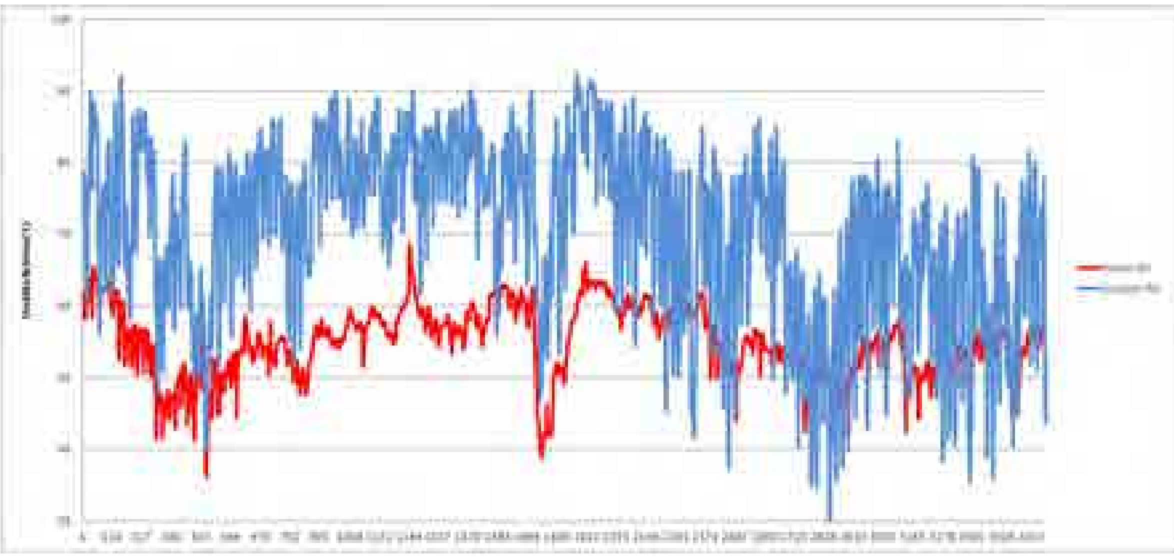

Image 8: S. Maria Odigitria. RH monitored values graph during winter heating time (indoor and outdoor average RH data). From November 13, 2013 to April 15, 2014. Red: indoor RH; blue: outdoor RH . © HypoThermos, Servizi Territorio srl.

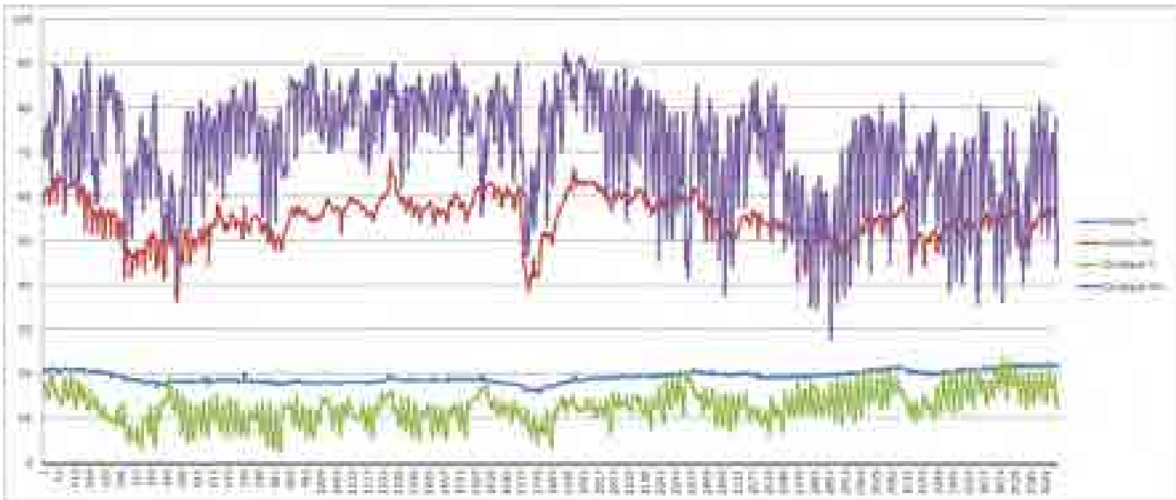

Image 9: S. Maria Odigitria. Comparison between RH and T values from October 23, 2013 to April 24, 2014. From above, violet: outdoor RH; red: indoor RH; blue: indoor T; green: outdoor T. © HypoThermos, Servizi Territorio srl.

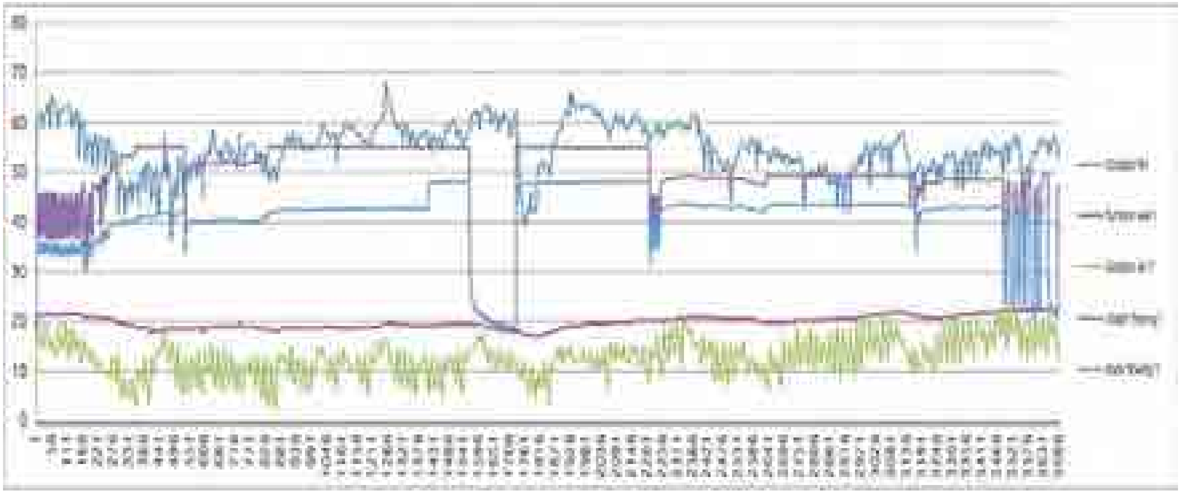

Image 10: S. Maria Odigitria. Comparison between indoor RH and T values, and water flowing T. Cyan: outdoor RH; violet: surface wall T; blue: back flowing T; red: indoor T; green: Outdoor T. © HypoThermos, Servizi Territorio srl.

Furthermore, Temperierung is based on the thermal inertia of the walls and strictly connected with the environmental behaviour of the building more than any other system. Therefore the system cannot be analysed considering the usual standards and conventional parameters. Its effect on the building has to be evaluated as a whole. Besides, due to the slow reaction of the system, the control devices have to be properly set.

For the church of Santa Maria Odigitria we proceeded to the installation of a monitoring system that at the same time is used to gather and evaluate (in real time) data from the sensors and to decide the correct operation of the heating system. Since optimal surface radiating temperature is the main reference for the Temperierung system, two optical pyrometers have been installed (IR surface temperature detectors; emissivity setting fixed at 0,95; field of view 15:1). The first one detects the surface temperature of the vault at about half the nave, in correspondence with the keystone; the second one has been set to detect the temperature of a pilaster between the two chapels on the right. RH and air temperature sensors (Output resolution: T 0,01°C; RH 0,03% - Accuracy: T ±0,4°C; RH ±4%). have been placed inside the church at the height of about 2.5 m. and outdoor in the courtyard to the North. Thermometers have been set on the flow and return of the distribution manifold of the circuits. The data are collected by a data logger.

This kind of configuration has been determined, as a preventive measure, for fear that the vault surface, exposed on a not insulated attic, could lose heat in a differentiated way, and much more in absolute terms, compared with the perimeter walls that, except for the one to the South (façade, facing the street) and the one to the North (apse, adjacent to the storage rooms) adjoin with unheated rooms. On the contrary, during the first winter with the heating system operating, the collected data show that the gap between the two surfaces did not exceed one degree centigrade.

With regard to the management of the system, the main rules are not controlled by the indoor air temperature: the main reference is the gradient of the surface radiating temperature. The water flow temperature is controlled by the software in a way that it is proportional to the difference between the actual surface radiating temperature and its target value. In any case, above a predefined maximum value of the surface or indoor air temperature the heating switches off.

The system is regulated according to a function that causes a rise in the flow temperature when surface temperatures collected inside, themselves related to the ambient temperature, decrease. In this particular case the aim is to satisfy the comfort standards but it is clear that in case the heating system were to have only a preservation function, for example with regard to surface condensation, the system could be set to provide only the amount of energy needed to maintain the temperature slightly above the value of dew point.

4. CONCLUSIONS

Temperierung involves many topics about preservation of buildings as well as artwork collections.

Firstly, it has to be remarked its use as a tool for preventive conservation. Providing a comfortable climate often means modifying indoor conditions of a construction almost completely. On the contrary *Temperierung* allows to provide stable climate and RH control, only by avoiding convective motions and supplying moderate and constant warming. This feature plays an important role for the conservation of collections and exhibits. [20] It involves also a change in the physical behaviour of the building envelope. The heating of the walls is an important tool to prevent damage to the building caused by condensation, as repeatedly demonstrated. [21] [22]

Secondly, *Temperierung* represents a way to improve indoor climate without compromising the construction substance. Installing a heating system in an ancient building may cause damage to its material consistency. Plants and ducts, a thermal power plant, lighting, electrical and thermal devices generally need space to work efficiently. An ancient building has not been built to host such devices: losses could be higher than expected. On the contrary, *Temperierung* allows a soft approach towards the building, juxtaposing a light network to the existing walls. Above all, the system can be installed in many different ways in order to suit particular conditions: into the walls, on the walls, into a cavity along the walls etc. These aspects have already met wide acceptance in the scientific debate, as described above.

A further, subtler way to protect buildings and their substance must be considered. We refer to the relationship between *Temperierung* and the construction. In massive masonry buildings it generally compensates the heat losses through the envelope, without upsetting the energy behavior (based on thermal inertia and heat storage) of the construction itself. Pipes circulating hot water transfer heat to the walls, and the walls in their turn transfer heat to the environment. In other words, a *Temperierung* system needs a building to work well. The system and the building work together to reach suitable indoor conditions. In this way, the building works by exploiting its features. It benefits by the constructive skills acquired long time ago.

Nevertheless, this connection has not been widely examined due to the difficulty in relating heat transfer parameters with ancient (and not completely known) walls.

Moreover, a controversial topic to discuss and examine is that of the energy consumption of such a system. It is clear that heating an envelope cannot avoid heat losses, especially when the insulation (as intended nowadays) is not enough, but it is also clear that whatever the heating system, the building shell can never be improved enough. Any system supplying energy to such a building will lose a large part of the heat. Many simulations have been carried out, but it has to be remembered that it is not easy to make reliable measurements upon real buildings. Anyway, the understanding of how ancient buildings actually work, from an energy point of view, is one of the most complex challenges for the future.

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