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The restoration of severely damaged churches – Implications and opportunities on cultural heritage conservation, thermal comfort and energy efficiency

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Abstract

Indoor microclimate and energy performance analyses of historic buildings require tailored methodologies, because of their complexities, e.g. presence of artworks, lack of documents or project data and employed structure and materials. Given such difficulties, there are a few interdisciplinary methodologies, capable of carrying out multi-objective analyses for this kind of buildings, and they are often based on in-situ monitoring that, however, may not be able to predict the effects deriving from different conceivable technologies and control strategies. In this work, an interdisciplinary methodology is employed for evaluating cultural heritage conservation conditions, occupants 'thermal comfort and energy performance of a specific historic building category, such as churches, on the basis of experimental and numerical approach. The methodology was applied to the case study of an ancient Italian church, recently restored following the earthquake that hit L'Aquila in 2009. After the refurbishment of the church, the statistical analysis of temperature and relative humidity experimental data allowed to observe that the conservation conditions of artistic heritage just restored may be non-correct, due to remarkable thermo-hygrometric fluctuations of the indoor microclimate. Therefore, starting from the current condition of absence of HVAC system, calibrated dynamic simulation models of the church allowed to hypothesize different technological solutions able to control the indoor microclimate and to evaluate the effects on artworks preservation, thermal comfort, and energy performance. The results of the multi-scenario analysis showed that suitable conservation conditions (PIs > 90%) and thermal comfort can be obtained by employing a complex heating/cooling and humidification/dehumidification system which determines a significant increase in energy consumption.

Keywords: historic church; microclimatic monitoring; dynamic simulation; cultural heritage conservation; energy efficiency; HVAC systems.

1. Research aims

In our work, the application of an interdisciplinary methodology to the case study of the Church of Santa Maria Annunziata of Roio in L'Aquila (Italy), recently restored following the earthquake that struck L'Aquila in 2009, is presented. The refurbishment of the building components of the church was followed by a careful restoration of the artworks it preserves. This restoration led to a new debate involving experts from various fields (restorers and technicians), who discussed the need of equipping the church, currently without HVAC (Heating, Ventilation and Air Conditioning) system, with technologies for the indoor climate control, in order to minimize the thermo-hygrometric fluctuations and the potential internal fracturing and mechanical damages due to the "new" acclimatization phase.

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The interdisciplinary methodology includes an experimental phase of in situ monitoring, the creation of simulation models, statistical analyses of the results (both experimental and simulated), and finally the use of simulation models for carrying out a multi-objective analysis of the effects on cultural heritage conservation, occupants' thermal comfort, and energy efficiency arising from climate control strategies.

2. Introduction

The conservation of artistic-architectural value and artworks kept inside churches is strongly dependent on indoor environmental conditions. In many cases, churches represent buildings without HVAC systems and, therefore, the indoor microclimate is strongly influenced by the outdoor climatic conditions. Some of the works proposed in the literature state that the absence of indoor air conditioning systems is a necessary condition for the proper conservation of cultural heritage in churches. In [1, 2], it is stated that a heating system introduces into the churches perturbations, in terms of temperature and relative humidity (RH), such as to favor deterioration phenomena of artworks. This effect is mainly due to the fact that the heating systems are often designed solely to satisfy the users thermal comfort without considering, in any way, the conservation of artworks. The thermal emission localized in the areas occupied by people (usually to the pews) was considered one of the possible choices of heating systems installation, since it allows to leave unperturbed the rest of the church [3]. Moreover, also the control strategies of the heating systems are often not aimed at the conservation of cultural heritage; indeed, the plants are turned on just before the start of the religious services and switched off immediately afterwards, pouring into the environment a huge amount of energy with consequent drastic variations of temperature and relative humidity, such as to generate thermal and mechanical stress for the artworks. Therefore, the control strategies of the HVAC systems should be identified bearing in mind the principles of cultural heritage conservation as well as thermal comfort and, possibly, the energy efficiency maximization.
On the other hand, if the optimal parameters of indoor microclimate for artistic heritage preservation are considered, it is possible to verify that the dependence of indoor environment from outdoor climate conditions often determines non-optimal indoor hygrothermal conditions. In the work presented by Corgnati et al. [4], a useful methodology for evaluating the Indoor Microclimate Quality (IMQ) is proposed, which allowed to define a Performance Index (PI) helpful to guarantee the absence of risks for the artworks' preservation. The study proposed by Corgnati and Filippi [5] showed that a fundamental phase for the analysis of indoor thermo-hygrometric quality and the definition of suitable microclimate control strategies is represented by the in-situ monitoring. This phase, in fact, makes it possible to apply a statistical approach to evaluate the operating system performance, i.e. the possibility of satisfying a certain performance over the time.
Therefore, this scenario might seem contradictory: on the one hand it would seem that the installation of a heating system could be a source of disturbance for the artworks conservation, on the other it would appear essential to eliminate the influence of outdoor climatic conditions on the indoor microclimate, thus ensuring correct temperature and relative humidity values. The evaluation of the effects deriving from the presence of HVAC systems in churches would require suitable assessment tools able to predict thermo-hygrometric effects obtainable with different technologies and different control strategies.
However, when artworks are subject to significant restorations, their conservation in a climate not affected by significant temperature and relative humidity fluctuations could become essential. For this reason, even in buildings such as churches, less investigated than other historic buildings, it is fundamental to develop multi-objective methodologies to assess the effects of presence/absence of HVAC systems and control strategies on the indoor microclimate.
The aim of this paper is to propose the application of an interdisciplinary methodology to analyze the indoor microclimate conditions of a church subject to a considerable restoration phase and the effects on cultural heritage conservation conditions, occupants' thermal comfort, and energy efficiency, deriving from different

HVAC system solutions and control strategies. The methodology, based on in-situ monitoring and on calibrated dynamic simulation modeling, whose necessary calibration phase is favored by the frequent possibility of having monitoring data, such as indoor temperature trends [6], was applied to the case study of the church of Santa Maria Annunziata of Roio in L'Aquila, Italy. The selected building, representative of a territory under reconstruction following the earthquake of L'Aquila in 2009, was considered an archetype of the many churches recently refurbished and currently lacking in HVAC systems. The careful restoration of the artworks preserved in the churches and the frequent absence of HVAC systems has opened a new debate between restorers and technicians about the opportunity to equip churches with technologies capable of limiting the indoor thermo-hygrometric fluctuations.

In fact, by referring the standard EN 15757 [7], it states that: "*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*". Hence, leaving the just restored artworks in an uncontrolled indoor microclimate (without HVAC), strongly subject to the outdoor climate, determines a new phase of acclimatization, during which the cultural heritage may suffer damages which jeopardize its proper preservation.

Therefore, the main research questions that this work attempts to answer are:

- following the artworks restoration, is it possible to predict what would happen with and without HVAC systems in terms of cultural heritage conservation setting tolerances on thermo-hygrometric fluctuations?
- is it possible to establish the effects of HVAC systems on occupants' thermal comfort?
- is it possible to define control strategies for the indoor microclimate that also guarantee the optimization of energy performance?

The paper is divided into 6 sections, as follows: after this introduction section (Section 2), a literature review of papers deemed useful for this work is presented in Section 3. The proposed methodology, the case study description, the monitoring phase, and creation, calibration and validation of the simulation model are presented in Section 4. The results and the multi-scenario analysis are discussed in Section 5, and, finally, Section 6 summarized the main findings of the work.

3. Related works

The correct balance between cultural heritage conservation and thermal comfort inside the churches is a much-discussed topic in recent years, since these two goals are generally conflicting. In many cases, in fact, the hypothesis of installing heating systems has been exclusively linked to the satisfaction of thermal comfort, while the need to preserve correct storage conditions was rarely considered [8]. However, for many years, the artistic heritage has been preserved in good condition (sometimes optimal) in environments without heating systems that, where installed, have led to rapid deterioration. In this sense, it is of great importance to know the problems related to operation mode of heating systems (e.g. central or local heating) and control strategies (e.g. continuous, intermittent or mixed heating).

As specified in standard EN 15759-1 [9], heating strategies can be different: 1) *conservation heating*, that aims to improve indoor climate in order to optimize conservation conditions by checking that RH values are stable and appropriate, 2) *heating for thermal comfort*, whose aim is to improve occupant comfort conditions by acting mostly on temperature control. Therefore, the research for a compromise between the different heating strategies is necessary to have a proper balance between conservation and thermal comfort. In the work presented by Varas-Muriel et al. [10], the authors state that, until 2012, the installation of heating systems in Spanish churches had the sole objective of improving thermal comfort, without considering in any way the effects on artworks conservation. Therefore, new heating system were developed (as for example radiant floor and thermal pews) trying to better control the temperature without modify the indoor environment. Moreover,

as specified in [11], whatever heating system is hypothesized for a church, giving priority to less invasive systems characterized by reversibility of the installation is fundamental.
To date, the scientific literature concerning the study of indoor microclimate for the preservation of cultural heritage and thermal comfort in churches is often linked to methodologies mainly based on in-situ monitoring. However, the results of experimental monitoring may not always be able to predict the effects deriving from different conceivable technologies and their control strategies. In this sense, the creation of simulation models would provide useful multi-scenario analyses.
The literature concerning the indoor microclimate monitoring of historic buildings is quite extensive and the duration of monitoring is very variable. Bonacina et al. [12] proposed a long-term monitoring (20 years) to study the degree of conservation of frescoes and structural elements of the Scrovegni Chapel (Padova, Italy) performing measurements before and after the refurbishment phase. The monitoring allowed to provide information about the characteristics that HVAC system should have and its control strategies, in order to obtain acceptable air velocity values and suitable temperature and relative humidity ranges to be maintained in summer and winter. However, monitoring of such duration may not always be possible. Andretta et al. [13] discussed the results of a measurement campaign carried out in two different periods of the year, "extreme" from the climatic point of view, for the Classense Library of Ravenna (Italy) comparing the internal pollutants concentrations (NO_2 and O_3) and the thermo-hygrometric data with the values measured outside. The results of the measurement campaign showed that the Historical Library has high inertia (both thermal and hygric), although temperature and relative humidity values resulted often out of the ranges set by standard for the preservation of books of great value. Varas-Muriel and Fort [14] presented the microclimatic monitoring of the Lady of the Assumption Church of Algete (Spain) for the evaluation of the effects deriving from the installation of an underfloor water-hot heating system measuring the main thermo-hygrometric quantities and CO_2. The monitoring phase allowed to observe the indoor microclimatic stability; the non-uniform effects on the thermo-hygrometric quantities were mainly attributed to the interior architecture and to the fan coils positioning inside the church. These inhomogeneities could have been evaluated in advance if the case study had been analyzed through dynamic simulation modeling, thus allowing to carry out several hypotheses of fan coils installation. Silva and Henriques [15] discussed the indoor microclimatic monitoring of the church of St. Christopher in Lisbon (Portugal) by applying the standard EN 15757 and comparing the results with other case studies in different European geographical areas to propose a new method of analysis specifically dedicated to temperate climates. The conclusion of the study proposed a review of the standard EN 15757 to adapt the methodology to temperate climates. Aste et al. [16] have recently proposed an interesting monitoring of the Milan Cathedral carried out in two distinct phases: a first preliminary monitoring phase, to characterize temperature and relative humidity profiles, and a second continuous long-term monitoring phase to perform a detailed microclimatic analysis of air temperature and relative humidity, surface temperatures and air velocity. In their work, they proposed a non-invasive monitoring methodology to keep the building intact and to allow its normal operation. Anaf and Schalm [17] discussed the indoor microclimate monitoring of a chapel in Antwerp (Belgium) to demonstrate that the knowledge of peaks and drops of temperature and relative humidity allows to identify fluctuations with different frequency ranges (low, mid and high) potentially dangerous for the cultural heritage preservation. On the basis of experimental campaign, the authors proposed interventions to mitigate the indoor microclimate and to obtain stable conditions. Cardinale et al. [18] proposed the indoor microclimate evaluation of the Matera Cathedral before and after its restoration, that also included a floor heating system installation, analyzing thermal comfort and the effects on artworks and construction materials conservation. The analysis has allowed to affirm that the installed heating system permits to satisfy people's thermal comfort, the excellent conservation of the artistic heritage from the thermo-hygrometric point of view, and considerable energy savings. Camuffo et al. [19] discussed the experimental monitoring of the indoor climate fluctuations of a mountain church located at Rocca Pietore (Italian Alps). By measuring air temperature values, relative humidity, specific humidity and dewpoint, the authors observed that the internal air temperature

variability was modest during working days, while it was excessive during religious celebrations (variations of 20 °C in one hour). Furthermore, they observed that the air moisture content is more sensitive to external conditions than the indoor air temperature. Therefore, they pointed out that rapid changes in the indoor climate could cause dangerous stress in the wooden objects contained in the church.

The study of the artworks conservation conditions displayed within the churches, in terms of transport and deposition of particulate pollution, is discussed by Spolnik et al. [20], who considered different heating systems: electrically heated pews, hot air blow heating and provisory electrical (infrared) heaters. The results obtained by considering two churches (Church of Rocca Pietore in Italy and Church in Szalowa, Poland) have shown that all heating systems tend to re-suspend the particulate matter brought in from outside; however, the extent changes in relation to the chosen system. Frasca et al. [21] presented the assessment of indoor climate conditions of the Basilica of the Holy Cross in Mogiła Abbey at Cracow (Poland) by experimentally measuring temperature, relative humidity and carbon dioxide in the period between March 2012 and April 2014. They found that 15% of the time, temperature and relative humidity did not meet the limits proposed by ASHRAE Class B and, therefore, during this time there was a high risk that the artworks preserved in the church (mostly wooden artworks) were subject to mechanical damage, especially due to relative humidity fluctuations. The effects of the presence of gas pollutants under the influence of electrical IR heating are discussed by Bencs et al. in [22]. The authors proposed the monitoring of the spatial distribution and temporal concentration variation of gaseous air components such as CO_2, CO, H_2CO and H_2O for two different Polish churches: the stone Saint Catherine's church in Cracow and the wooden Saint Michaels Archangel church in Szalowa. The results showed that the use of IR heating redistributes pollutants in the indoor air of churches.

For what concerns the use of simulation models to analyze the performance of historic buildings, it is worth noting an increasing diffusion in literature [6, 23]. Pagliaro et al. [24, 25] discussed archeological and structural hypotheses concerning the operation of storagerooms in Ancient Rome thanks to validated CFD (computational fluid dynamics) numerical simulation applied to a model of one of Portus warehouse for wheat storage. The work is based on the combination of numerical simulation and historical information, and it derives from the collaboration between experts of different disciplines.

The dynamic simulation modeling is mainly used for the study of historic buildings energy performance, while its use to model churches and to predict artworks preservation and thermal comfort conditions is still rare. In fact, the cases in which churches are modeled via dynamic simulation are few and often very recent. In the recent work proposed by Munoz-Gozalez et al. [26], the effects on indoor microclimate provided by passive, active and combined actions for the church of Nuestra Senora de la Merced of Seville (Spain) are analyzed. Thanks to dynamic simulation modeling, the work concludes that the sole hypothesis of passive interventions does not guarantee the complete elimination of mechanical risks and biodeterioration of movable heritage, but this result can be achieved with a combination of passive and active actions. Aste et al. [27] discussed the opportunity to provide the Basilica of Collemaggio in L'Aquila (Italy), also subject to restoration following the 2009 earthquake, with a hydronic pew-based heating system. In their work, the calibrated CFD simulation is employed as a performance analysis tool of the chosen heating system, which is based on a local-comfort strategy. Furthermore, the case study has been modeled via dynamic simulation to evaluate the energy performance obtainable by different heating systems. This modeling has highlighted that, if the goal is to keep the thermo-hygrometric conditions intact, the localized heating system allows to obtain much better results than other possible solutions, e.g. all-air system and all-air system with on-demand operation. Napp and Kalamees [28] proposed the application of dynamic simulation to the case of the church of the Holy Cross in Harju Risti (Estonia) to analyze possible solutions for improving the indoor microclimate. Two different systems have been hypothesized, i.e. adaptive ventilation and air-to-air heat pump (AAHP), to study the effects achievable on the prevention of mould growth and the deterioration of wooden parts. Schibuola et al. [29] discussed the application of innovative technological solutions to the case study of the Crucifer Convent by University Iuav of Venice (Italy) by means of simulation tools. The results showed the possibility of reducing primary global energy consumption by 36% compared to a traditional HVAC system. Acierno et al. [30] proposed the ontological analysis of the conservation process of the 6th century San Saba Oratory in Rome (Italy) via Building Information Modeling (BIM), to highlight that the creation of simulation models allows cross-cutting analysis among the various scientific sectors, thanks to the possible interconnections between the different simulation tools, such as EnergyPlus and BIM. An interesting multi-objective methodology, applied to the museum Palazzo Blu in Pisa (Italy), is presented by Schito et al. [31]. Their methodology, based on experimental thermo-hygrometric monitoring and dynamic simulation (TRANSYS) aims to assess the indoor climate of the museum in order to evaluate the conservation conditions of the artworks, the comfort of the visitors and the energy performance of the HVAC system. In the work proposed by Schellen and van Schijndel [32], the control of the air heating setpoint in the Walloon Church in Delft (Netherlands) is discussed with the aim of minimizing the mechanical effects on the wooden parts inside the church due to the presence of moisture. The control of the operation setpoint of the HVAC system is analyzed through a simulated approach, thanks to the combination of MATLAB, COMSOL and Simulink models. The results obtained have shown that the best condition to avoid mechanical stress is the absence of heating, while penalizing thermal comfort, and that limitation of the changing rate of the relative humidity limits such stress. An interdisciplinary methodology to assess the best opportunities for retrofitting historic buildings in relation to conservation compatibility, thermal comfort and energy needs is proposed by Roberti et al. [33]. The authors proposed the application of the methodology on the Waaghaus historic building in Bolzano (Italy) involving the participation of 10 experts in the field of conservation. The results obtained have demonstrated the compatibility between conservation of cultural heritage, reduction of energy requirements and high levels of thermal comfort.

With regard to the in-situ monitoring phase, in the last few years, the efforts to research new measuring instruments grew and allowed the creation of new experimental set-ups. Thanks to the recent technological developments, which led to a rapid diffusion of low-cost measuring devices, the birth of innovative and customized measuring instruments is increasingly widespread, to meet the different experimental needs. Garcìa-Diego and Zarzo [34], using the Metropolitan Cathedral of Valencia (Spain) as case study, presented a measuring instrument that allows the insertion of the probes directly inside the frescoes demonstrating how much variable the thermo-hygrometric conditions of conservation are over the time. Basto et al. [35] proposed a measuring instrument capable of measuring crack width, internal and external temperatures, and internal relative humidity, to show the great potential of such technologies and to promote the dissemination of cost-efficient monitoring for cultural heritage with reference to Structural Health Monitoring (SHM). Sileo et al. [36] presented the environmental analysis of the Crypt of S. Francesco D'Assisi in Irsinia (Italy) underlining the importance of monitoring as an appropriate tool to define preservation strategies of the cultural heritage and the potential deriving from the use of low-cost monitoring instruments. The authors proposed a monitoring prototype whose test phase highlighted non-optimal microclimatic conditions of the crypt for the preservation of frescoes.

Based on what has been discussed so far, Table 1 summarizes the literature review carried out and it classifies the works in two macro-categories: 1) works related only to in-situ monitoring; 2) works related both to in-situ monitoring and simulation modeling. For each work, the following characteristics are detailed:

- geographic location;
- objective functions: diagnostic methodology, energy efficiency, conservation issue, sensors development, and comfort analysis;
- case study typology;
- in-situ monitoring: type of monitored quantities;
- monitoring campaign duration;
- adopted simulation tool.

Table 1. Research in indoor microclimate assessment studies.

Works based on in-situ monitoring							
Authors	**Ref.**	**Country**	**O.F.***	**Case study typology**	**Experimental analysis**	**Monitoring campaign**	**Simulation tool**
Samek et al.	[2]	Poland	F_3, F_5	Churchs (Saint Michael Archangel in Szalowa and Saint Catherine in Cracow)	Microclimate, air flows, transport and deposition of SPM	March 2004 - March 2005	-
Bencs et al.	[3]	Italy	F_3	Church (small church of Rocca Pietore)	Concentrations of CO2, CO, formaldehyde (H2CO) and water vapour	November 2002, January 2003 and 2004	-
Corgnati et al.	[4]	Italy	F_1	Museum	T and RH measurements	Entire heating season (Oct. to Apr.)	-
Corgnati and Filippi	[5]	Italy	F_1	Museum (Santa Maria della Scala - Siena)	T and RH measurements	October 2003 - march 2004	-
Bonacina et al.	[12]	Italy	F_1	Church (The Scrovegni Chapel - Padova)	T, RH, and TS measurements	20 years	-
Andretta et al.	[13]	Italy	F_3	Hystorical library (Classense Library - Ravenna)	Internal pollutants concentrations and internal/external thermo-hygrometric data	22 July - 6 August 2014 and 15-30 December 2014	-
Varas Muriel and Fort	[14]	Spain	F_3	Church (Lady of the Assumption Church presso Algete)	T, RH, DP, AbsHum, MR, both inside and outside the church, and CO2	September 2012 – November 2013 and from December 2013 - April 2014 for CO2	-
Silva and Henriques	[15]	Portugal	F_1	Church (church of St. Christopher in Lisbon)	Outdoor/indoor T and RH measurements	November 2011 - August 2013	-
Aste et al.	[16]	Italy	F_1, F_3	Duomo (Milan Cathedral)	T and RH measurements for indoor air; infrared temperature sensors for surface temperature; hot-wire anemometer for air velocity	One year (first phase february - july 2016, second phase july 2016 - june 2017)	-
Anaf and Schalm	[17]	Belgium	F_1, F_3	Chapel (Antwerp - Belgium)	T and RH measurements	22 months between 2011 and 2013	-
Cardinale et al.	[18]	Italy	F_3, F_5	Church (The Matera Cathedral)	T and RH measurements	20-30 January 2013 (before plant installation) and 13-23 April 2013 (after plant installation)	-
Garcìa-Diego and Zarzo	[34]	Spain	F_1, F_3, F_4	Church (Metropolitan Cathedral of Valencia)	T and RH measurements	4 months in 2007	-
Basto et al.	[35]	Spain	F_4	Historic building (School of Civil Engineering, UPC-Barcelona)	Crack width, internal and external T, internal RH.	05-30 June 2015	-
Sileo et al.	[36]	Italy	F_4	Crypt of St. Francesco d'Assisi in Irsinia	T and RH measurements	September 2013 - August 2014 and November 2013 - February 2015	-

Camuffo et al.	[19]	Italy	F_3	Church (Church of Rocca Pietore)	T, RH, SH, and DP	5 days (from 31/12/96 to 04/01/97)	-
Spolnik et al.	[20]	Italy and Poland	F_3, F_6	2 Churches (Church of Rocca Pietore and Church in Szalowa, Cracow)	Aerosol samples inside and outside the churches	January 2003, January 2004, beginning of March 2004	-
Frasca et al.	[21]	Poland	F_3	Church (The Basilica of Holy Cross in Mogila Abbey, Cracow)	T, RH, and CO_2	From March 2012 to April 2014	-
Bencs et al.	[22]	Poland	F_3, F_6	2 Churches (Saint Catherine's, Cracow, Saint Michaels Archangel, Szalowa)	CO_2, CO, H_2CO and H_2O	19 - 25 November 2004	-

Works based on in-situ monitoring and simulation modeling

Authors	Ref.	Country	O.F.*	Case study typology	Experimental analysis	Monitoring campaign	Simulation tool
Camuffo et al.	[1]	Italy	F_3, F_5	Churchs (Santa Maria Maddalena in Rocca Pietore, and S. Stefano di Cadore, Italy)	Indoor and outdoor microclimate, heat diffusion and control, internal air motions and building response	3 years	CFD numerical simulations
Cornaro et al.	[6]	Italy	F_2	Historic building (Villa Mondragone - Rome)	T and RH measurements	May/June 2013	IDA ICE 4.5
Sciurpi et al.	[23]	Italy	F_2, F_3	Museum (La Specola - Firenze)	T and RH measurements	March 2012 - March 2013	Energy Plus
Pagliaro et al.	[24, 25]	Italy	F_1	Warehouse of Portus (Rome)	None	None	CFD numerical simulations
Munoz-Gonzalez et al.	[26]	Spain	F_2, F_3, F_5	Church (Nuestra Senora de la Merced - Seville)	Indoor: T and RH Outdoor: T, RH, wind and pressure	1 year	Energy Plus
Aste et al.	[27]	Italy	F_2, F_3, F_5	Church (Collemaggio – L'Aquila)	Environmental test chamber for prototype bench performance analysis	n/a	Energy Plus and ANSYS-Fluent
Napp and Kalamees	[28]	Estonia	F_2	Church of the Holy Cross	T and RH measurements	April 2012 - December 2013	IDA-ICE
Schibuola et al.	[29]	Italy	F_2, F_5	Historic building (Crucifer Convent - Venice)	Weather data, energy demand profile, T and RH	October 2013 - September 2014	not specified
Acierno et al.	[30]	Italy	F_3	Oratory (San Saba Oratory - Rome)	None	None	BIM
Schito et al.	[31]	Italy	F_2, F_3, F_5	Museum (Palazzo Blu Museum of Pisa)	T and RH measurements	Four months	TRNSYS and MATLAB

Schellen and van Schijndel	[32]	Netherlands	F_3	Church (The Walloon Church in Delft)	None	None	MATLAB, COMSOL and Simulink
Roberti et al.	[33]	Italy	F_2, F_3, F_5	Museum (Waaghaus in Bolzano)	n/a	n/a	EnergyPlus

* O.F.: Objective functions. F1: diagnostic methodology; F2: energy efficiency; F3: conservation issue; F4: sensors development; F5: comfort analysis; F6: pollution analysis.
Legend: T for temperature, RH for relative humidity, DP for dew point, AbsHum for absolute humidity, MR for humidity mixing ratio, TS for surface temperature, SPM for suspended particulate matter, SH: for specific humidity.

4. Methodology

The European building stock is characterized by a significant number of buildings of high historical, architectural and cultural value. However, the necessary reduction in energy consumption leads to the search for solutions that can minimize the energy requirements of these buildings while respecting the cultural heritage they preserve. In this sense, European standards have recently been issued that define interdisciplinary approaches for these purposes, such as EN 16883 [37], which provides guidelines to be followed to improve the energy efficiency of historic buildings.

Based on the literature review above presented and to the best of the authors' knowledge, it can be said that there are numerous interdisciplinary methodologies discussed in the literature that propose the integration of experimental analysis and multi-objective simulation. In most cases, such methodologies have been applied to specific historical buildings, such as museums [31, 33, 49], while the applications of interdisciplinary methodologies to churches are still very limited [26] and often only related to energy efficiency.

In this work, the analysis of the indoor microclimate conditions of a church recently restored after the earthquake that struck L’Aquila in 2009 and the effects of different HVAC systems on cultural heritage preservation, thermal comfort conditions, and energy efficiency are analyzed through an interdisciplinary approach able to combine the know-how of restorers and technicians, as shown in Fig. 1.

The first step of the methodology, applied to the case study of the church of Santa Maria Annunziata of Roio in L’Aquila, is the collection of info on the building: drawing, architectural records, past restoration, and artistic heritage preserved in the church.

Secondly, the monitoring phase is performed, on the basis of standards and discussion between restorers and technicians about the quantities to be monitored. This step is divided into two sub-phases: 1) a first phase needed to quantify the fluctuations of the analyzed quantities and the number of probes required for the second phase; 2) a second phase to evaluate artistic heritage conservation conditions, together with thermal comfort conditions.

Then, the third step concerns the simulation modeling of the building, that can be divided into three sub-phases: 1) the model construction, calibration, and validation carried out thanks to the experimental data; 2) the proposal of refurbishment and restoration interventions, where the discussion between restorers and technicians is crucial for identifying the best actions on passive and active elements; 3) the evaluation of the obtainable effects, in terms of cultural heritage conservation, thermal comfort and energy efficiency. In this work, the dynamic simulation modeling was performed through EnergyPlus™ engine coupled with DesignBuilder.

Finally, in the fourth step, not dealt with in this work, there is the fulfillment of the interventions hypothesized and a new experimental phase to verify the benefits obtained [38].

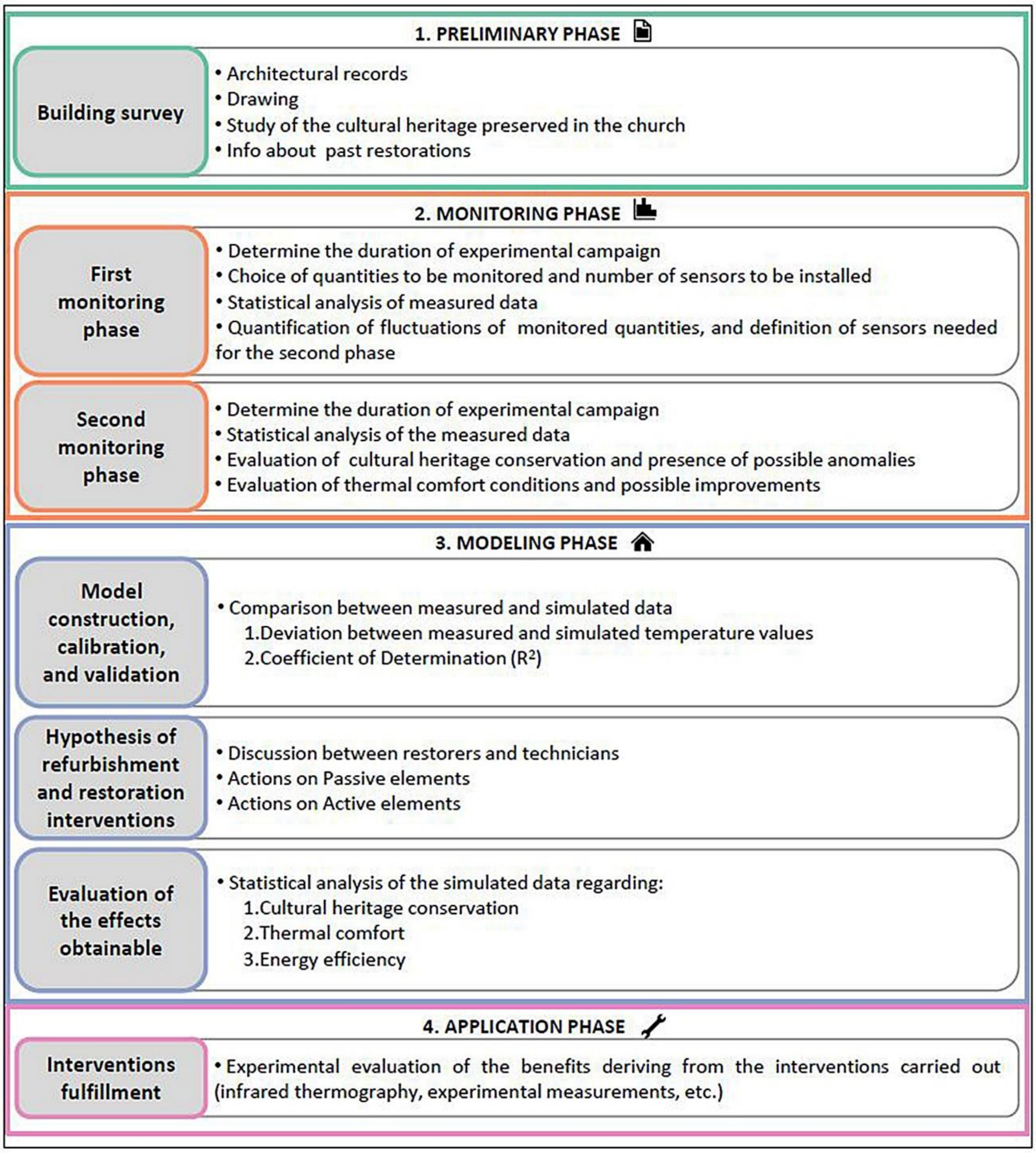


Fig. 1. Interdisciplinary methodology employed for the analysis of cultural heritage conservation, thermal comfort and energy efficiency analysis.

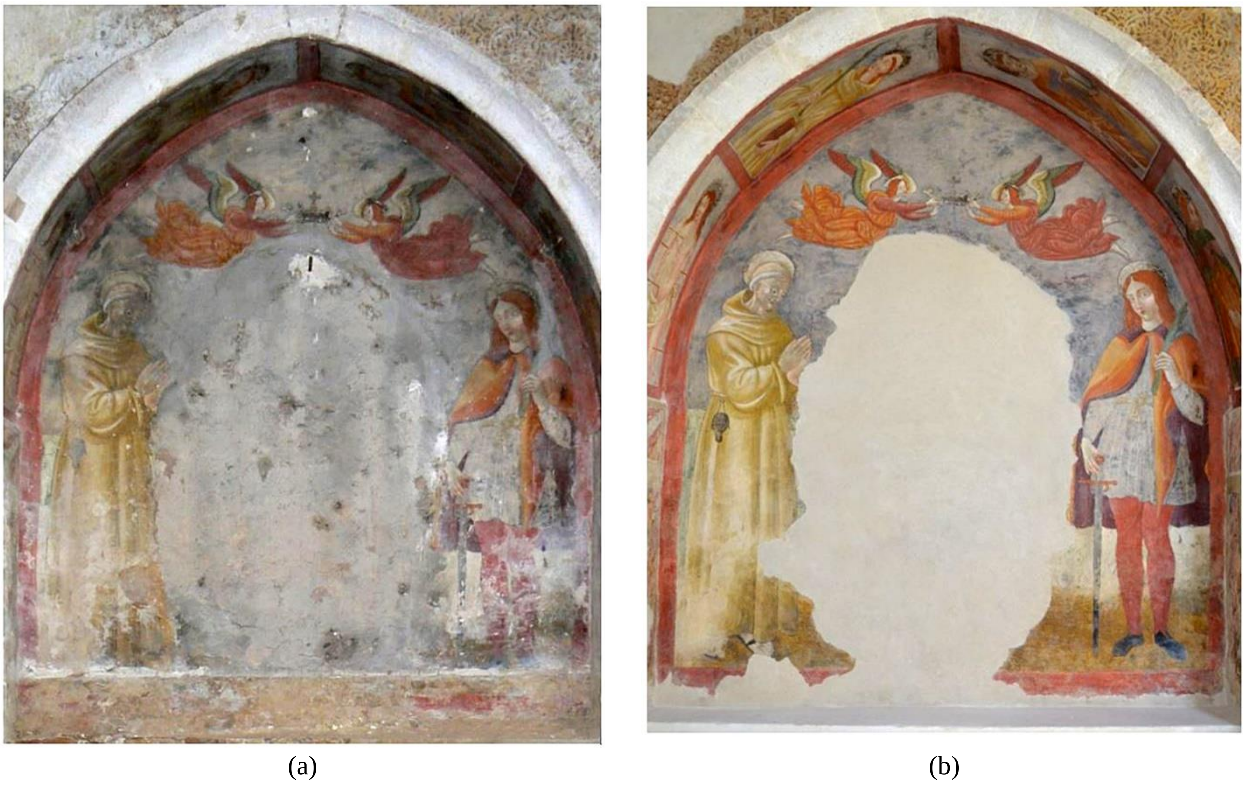
4.1. Case study description

The Church of Santa Maria Annunziata of Roio (Fig. 2), located in the outskirt of L'Aquila (lat. 42° 16′, long. 13° 32′) dates back to the 12th century [39]. It is made of resulting materials from the Romanesque age and it has a single-nave plan. The masonry structure consists of limestone blocks and mortar, and the roof is characterized by a wooden structure. The rectory, built with the same materials, is adjacent to the church and it is not object of the present work. Currently, the church has no HVAC system and it has undergone renovation works following the earthquake that struck L'Aquila in 2009.

(a)

Fig. 2. The South-east main façade of the church of Santa Maria Annunziata of Roio.

Following the earthquake, the bearing structure of the church has been consolidated in order to improve the seismic vulnerability. Before the recent restoration, it could be assumed that the artworks were "*acclimatized*" to the indoor microclimate (without HVAC) and therefore suffered damages (fissures, cracking and other mechanical damages), due to the thermo-hygrometric fluctuations and the ageing. Therefore, from the point of view of the cultural heritage restoration, the artworks preserved in the church were characterized by very different conservation conditions and, therefore, for each of them specific interventions have been carried out. In general, after a historical and archival documentation acquisition of the church, graphic and photographic documentation of the artworks has been acquired. The restoration of the painted surfaces of the church followed the pre-consolidation of the plaster layers, the uncovering of the plaster layers superimposed on the paintings, the consolidation of the plaster layers underneath the paintings, the cleaning of artwork surfaces, the micro-infill and infill of the lacunas in the painted surface, and then the pictorial reintegration. Fig. 3 shows the fresco depicting the "Annunciazione", the intrados of the arch and the wooden choir, before and after the restoration.



(a) (b)

(e) (f)

Fig. 3. Restoring interventions. Fresco depicting the "Annunciazione" (a) before and (b) after the restoration. Intrados of the arch (c) before and (d) after the restoration. [Courtesy of Dr. Jenny Rolo and Dr. Noemi Muselli]. Wooden choir (e) before and (f) after the restoration.

The church has the main façade facing south-east and the structure is characterized by bearing masonry walls with thickness ranging from 50 cm to 90 cm, internally covered with mortar plaster. Therefore, a total of five different types of wall were considered on the basis of thickness values. The thermal properties of each layer were taken from the standard UNI 10351 [40] (i.e. thermal conductivity equal to 1.5 W/mK and 0.9 W/mK, density equal to 1900 kg/m^3 and 1800 kg/m^3, and specific heat equal to 920 J/kgK and 840 J/kgK, respectively for stone and mortar plaster) and the thermal resistances were calculated according to the recommendations provided by the standard UNI EN ISO 6946 [41] considering internal and external surface resistances (R_{si} and R_{se}), respectively equal to 0.13 and 0.04 m^{2}K/W. The church's roof, consisting of double wooden layer (3 cm each) covered with waterproof bitumen sheet, air gap and clay tiles, has a thermal transmittance equal to 1.17 W/m^{2}K. The floor, renovated in the 80s and consisting of 2.5 cm tiles, was laid on 10 cm of reinforced concrete and 7 cm of screed. The thermal transmittance considered for the floor is equal to 1.99 W/m^{2}K. Since the floor of the sacristy and part of the nave have the rectory on the lower floor (not analyzed in the present work), a further floor with transmittance equal to 1.11 W/m^{2}K is considered. The windows are made of single pane (thickness 6 mm) and iron frame, with a total transmittance value equal to 5.7 W/m^{2}K. Table 2 summarizes the thermal properties of the building envelope.

Table 2. Thermal properties of the church's envelope.

Wall #1	Thk [m]	λ [W/mK]	R [m^{2}K/W]
Plaster	0.02	0.90	0.02
Masonry	0.50	1.50	0.33
U_{50} = 1.90 W/m^{2}K			
Wall #2	Thk [m]	λ [W/mK]	R [m^{2}K/W]

Plaster	0.02	0.90	0.02
Masonry	0.60	1.50	0.40
U_{60} = 1.69 W/m²K			
Wall #3	Thk [m]	λ [W/mK]	R [m²K/W]
Plaster	0.02	0.90	0.02
Masonry	0.66	1.50	0.44
U_{66} = 1.58 W/m²K			
Wall #4	Thk [m]	λ [W/mK]	R [m²K/W]
Plaster	0.02	0.90	0.02
Masonry	0.76	1.50	0.51
U_{76} = 1.43 W/m²K			
Wall #5	Thk [m]	λ [W/mK]	R [m²K/W]
Plaster	0.02	0.90	0.02
Masonry	0.90	1.50	0.60
U_{90} = 1.26 W/m²K			
Roof	Thk [m]	λ [W/mK]	R [m²K/W]
Clay tiles	0.025	1.00	0.025
Air gap	0.08	0.30	0.27
Bitumen sheet	0.008	0.23	0.03
Double wooden layer	0.06	0.12	0.50
U_{Roof} = 1.17 W/m²K			
Floor	Thk [m]	λ [W/mK]	R [m²K/W]
Concrete	0.10	1.13	0.09
Screed	0.07	0.41	0.17
Tiles	0.025	0.80	0.03
U_{Floor} = 1.99 W/m²K			

4.2. Monitoring phase

The monitoring phase carried out in this work has a twofold objective:
1) to provide the experimental data necessary to carry out the calibration and validation phases of the dynamic simulation model of the church;
2) to obtain an evaluation of the indoor thermo-hygrometric conditions, in order to define any fluctuations to be taken into account.
The monitoring campaign performed is divided into two phases:

- Phase I: creation of a measurement grid for thermo-hygrometric detection at the nodes in which to analyze the spatial fluctuations of the quantities considered (i.e. temperature and relative humidity) and to define the necessary number of sensors to be used for the second monitoring phase (Phase II).
- Phase II: based on the results obtained during the Phase I, a continuous monitoring of indoor thermo-hygrometric conditions is performed identifying a new measurement grid that considers the number of necessary points identified in the Phase I as a function of the thermo-hygrometric fluctuations observed.

Similarly to the duration of many of the works proposed in the literature [3, 6, 13, 18, 35, 49], the total time span of the monitoring phase was 40 days, divided into 16 days for the Phase I and 24 days for the Phase II, in the period between September and November, 2017. The technical specifications of the measuring instruments employed during the experimental campaign are summarized in Table 3.

Table 3. Technical specifications of the measuring instruments employed.

Manifacturer	Model	Measurement range	Accuracy
Elitech	RC-4	-30.0 °C to 60.0 °C	± 0.5 °C*
Hobo	H08-003-02	-20.0 °C to 70.0 °C for temperature	± 0.7 °C
		25% to 95% for RH	± 5%*

* in accordance with the requirements provided by the standards EN 15758 and EN 16242 [42, 43].

Furthermore, the outdoor weather condition was also measured (i.e. dry bulb temperature, wind speed, atmospheric pressure, relative humidity, and solar radiation) by means of a weather station owned by CETEMPS Center of Excellence of the University of L'Aquila [44].

4.2.1. First monitoring phase

Based on the size of the church (about 26.0 x 5.5 m), the first monitoring phase was carried out by constructing a measurement grid with nodes placed at less than 5 m from each other and at 1.5 m height from the floor. This phase lasted 16 days, from September 28th to October 13th, 2017, with a sampling time-step of 15 minutes. A total of six measuring probes have been used (no. 4 Elitech and no. 2 Hobo) arranged as shown in Fig. 4.

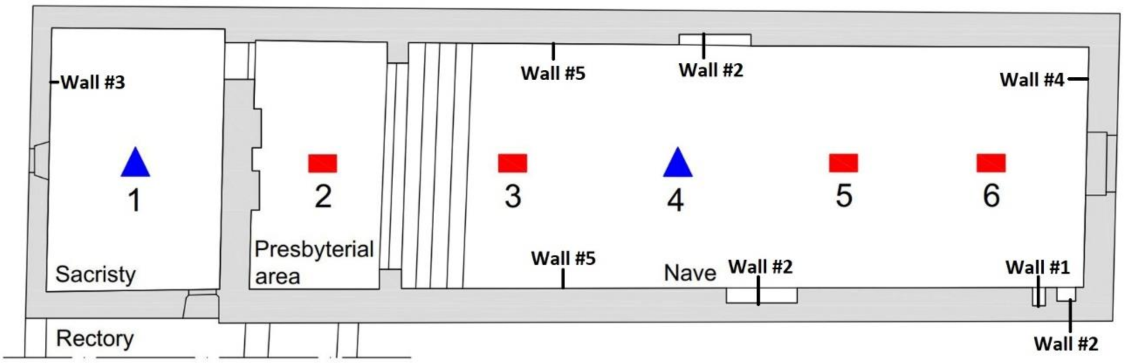


Fig. 4. Measuring instruments positioning – First monitoring phase. Legend: blue triangle for T/RH (temperature/relative humidity) measuring instruments (Hobo), red rectangle for T measuring instruments (Elitech).

The results of the first phase in terms of minimum, average, and maximum values of temperature and relative humidity are shown in Table 4. As regards the measurement of relative humidity, one of the two sensors (#1 in the measurement grid – Fig. 4) got partially broken during the early measurements and, therefore, it was not possible to acquire relative humidity data in the sacristy.

Table 4. Minimum, average, and maximum temperature and relative humidity values – First monitoring phase.

Datalogger	T_{MIN} [°C]	T_{AVE} [°C]	T_{MAX} [°C]	RH_{MIN} [%]	RH_{AVE} [%]	RH_{MAX} [%]
Sensor #1 (T/RH)	10.9	14.3	16.5	failed	failed	failed
Sensor #2	14.3	15.5	16.5	-	-	-
Sensor #3	13.7	15.1	16.4	-	-	-
Sensor #4 (T/RH)	13.3	14.9	16.8	41.0	58.5	66.3
Sensor #5	14.0	15.5	16.7	-	-	-
Sensor #6	14.1	15.4	16.4	-	-	-

The analysis of temperature differences between two adjacent measurement nodes allowed to verify the presence of possible fluctuations within the church. Fig. 5 shows the temperature trends and the spatial comparisons between two adjacent points as defined by the measurement grid (Fig. 4).

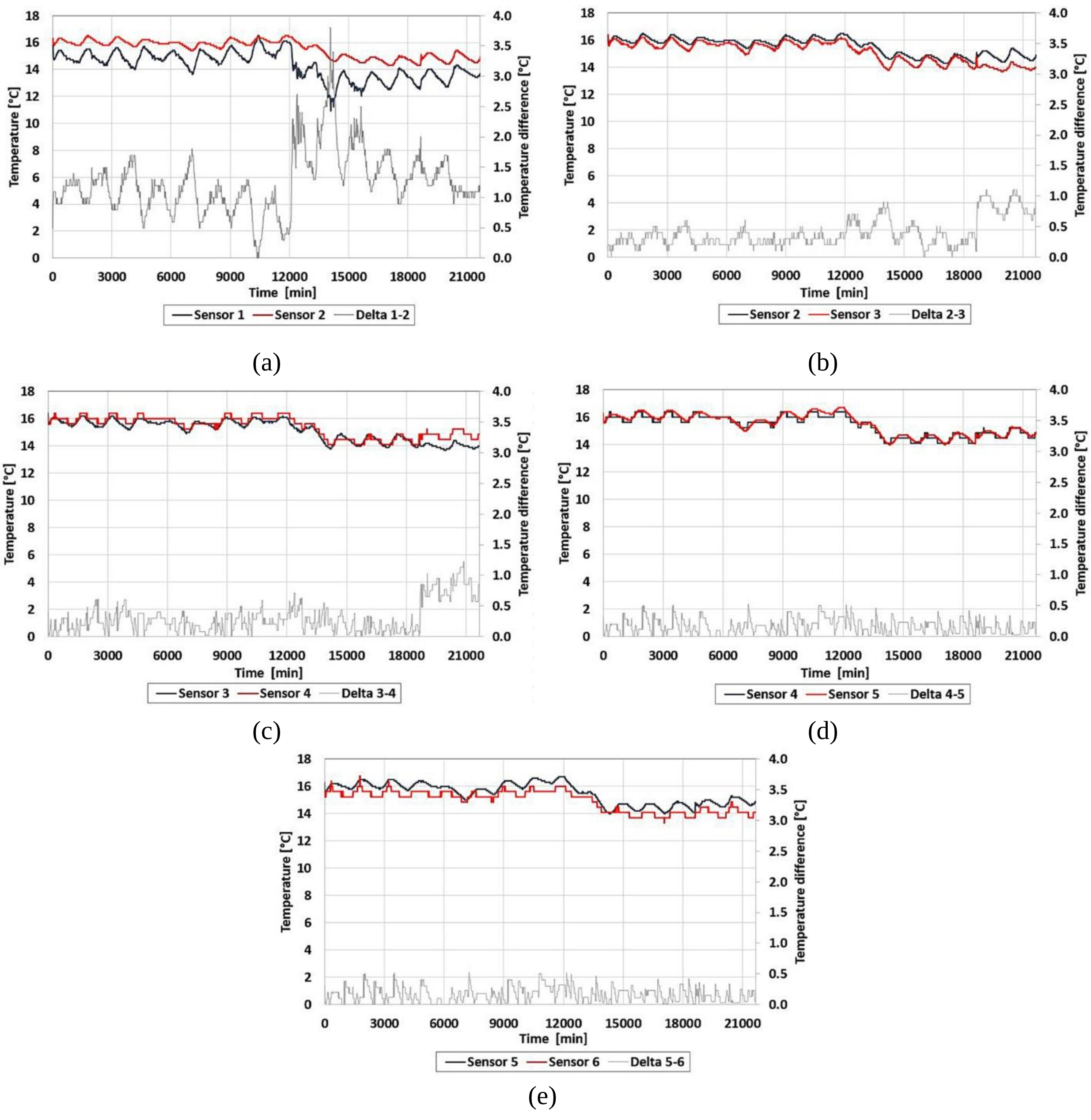
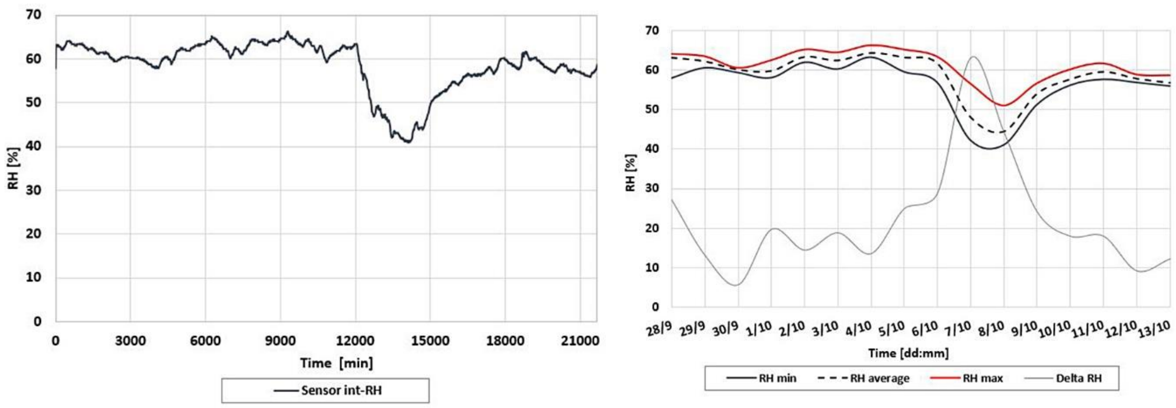


Fig. 5. Sub-hourly trends of the temperatures measured (with a sampling time-step equal to 15 minutes) and differences between adjacent points of the grid – First monitoring phase. (a) Sensor 1 vs sensor 2. (b) Sensor 2 vs sensor 3. (c) Sensor 3 vs sensor 4. (d) Sensor 4 vs sensor 5. (e) Sensor 5 vs sensor 6.

It is worth noting that the comparison between adjacent points inside the nave never shows differences greater than 1.23 °C (Figs. 5b, 5c, 5d, 5e), while the comparison between the temperature measured in the sacristy (sensor #1 in Fig. 4) and that detected in the presbytery area (sensor #2 in Fig. 4) shows differences up to 3.80 °C (Fig. 5a). The probable reason for this deviation is the presence of walls with reduced thickness for the sacristy, as well as the fact that the sacristy has a direct communication with the rectory, damaged by the earthquake and not yet refurbished.

The standard UNI 10829 [45] places a thermal fluctuation limit between two adjacent points, which must be ≤ 2 °C for homogeneous thermal conditions. The measured data highlighted that, for the monitored period, the temperature fluctuation inside the nave resulted negligible, i.e. always < 2 °C. However, the differences measured between sacristy and presbyterial area are not trivial, although they are not alarming, because no artworks are preserved inside the sacristy.
Therefore, based on these results, it can be established that the Phase II takes place using only two sensors (one placed in sacristy and one in nave).
Because of the damage suffered by the relative humidity sensor #1, it was not possible to analyze the relative humidity fluctuations between nave and sacristy. However, the relative humidity values of the nave measured in the first experimental phase and shown in Fig. 6 highlighted that the indoor conditions are strongly dependent on the outdoor climate (plotted in Fig. 7); in fact, the maximum and minimum values recorded were variable between 66.3% and 41.0% and the maximum daily deviation reached 14.4%.



(a) (b)

Fig. 6. Trends of the measured relative humidity – First monitoring phase. (a) Sub-hourly trend (15 minutes). (b) Daily trend.

For a better understanding of the measured data, a statistical analysis was carried out based on the frequency distribution, both of temperature and relative humidity values. The modal value of temperature resulted equal to 16.1 °C and the 60.6% of the values was concentrated between 15.0 °C and 16.0 °C, while the modal value of relative humidity was equal to 63.5% and the 57.7% of the values was within the range 60-65%.
Moreover, the measured outdoor dry bulb temperature and relative humidity during the experimental campaign are shown in Fig. 7.

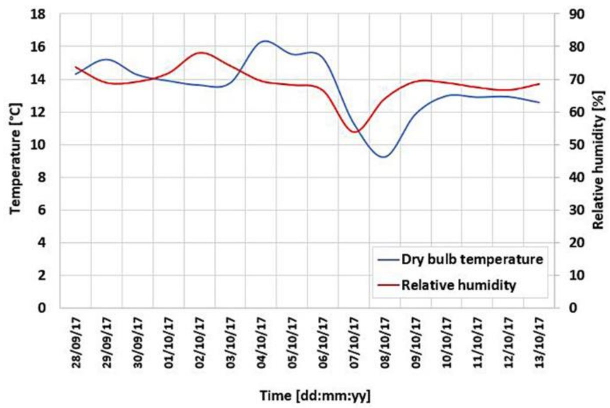


Fig. 7. Outdoor daily dry bulb temperature and relative humidity (Phase I).

4.2.2. Second monitoring phase

Thanks to the information provided by the first monitoring phase, a systematic sensor positioning layout has been defined. Since temperature fluctuations between adjacent point of the nave were < 2 °C, the installation of only one sensor was considered. Differently, thermal fluctuations between sacristy and nave, i.e. between sensor 1 and sensor 2 (Fig. 4), resulted > 2 °C and imposed the installation of a dedicated sensor inside the sacristy. Therefore, the second monitoring phase was performed using two temperature/RH measuring instruments, whose characteristics are summarized in Table 3, placed in the sacristy and at the center of the nave. The second phase lasted 24 days, from October 31st to November 23rd, 2017, and the data were acquired with a sampling time-step equal to 15 minutes.

Unfortunately, as in Phase 1, the sensor placed in the sacristy did not measure the relative humidity because of the partial breakage.

The analysis of the measured data was carried out considering the threshold values indicated in the standard UNI 10829 and after a debate with the restorers. Table 5 summarizes these threshold values, defined according to the type of artworks preserved in the church, i.e. frescoes and wooden choir.

Table 5. Threshold values for correct artworks conservation.

Artwork	Temp. [°C]	ΔT_{MAX} [°C]	RH [%]	ΔRH_{MAX} [%]
Frescoes	10 - 24	-	55 - 65	-
Wooden objects	19 - 24	1.5	50 - 60	4.0
Considered in this work	19 - 24	1.5	55 - 60	4.0

The results of the second experimental phase in terms of minimum, average and maximum temperature and relative humidity values are shown in Table 6.

Table 6. Minimum, average, and maximum temperature and relative humidity values – Second monitoring phase.

Datalogger	T_{MIN} [°C]	T_{AVE} [°C]	T_{MAX} [°C]	RH_{MIN} [%]	RH_{AVE} [%]	RH_{MAX} [%]
Sensor #1 (T/RH)	6.7	9.1	12.2	n/a	n/a	n/a
Sensor #2 (T/RH)	7.3	9.5	12.7	40.8	56.2	63.6

Considering Figs. 8a and 8b, that show the measured temperature and relative humidity values with sampling time-step equal to 15 minutes, and the threshold values (indicated in Table 5), it is possible to observe that:

- the temperature trends are always out of the range (19-24 ° C) and the temperature in the nave is always slightly higher than the temperature in the sacristy;
- the trend of relative humidity is often out of the range (55-60%).

More in detail, the statistical analysis of the data carried out in the second monitoring phase has underlined that the conservation conditions of the artistic heritage just restored and preserved in the church could be improved. In fact, the frequency distribution of the temperature values (Fig. 8c) obviously shows that they are always out of the acceptable range (19-24 °C). Moreover, for the monitored period, the average temperature value, equal to 9.1 °C, is far from the value of thermal comfort generally considered for this kind of building, i.e. 20 °C [46]. The frequency distribution of relative humidity (Fig. 8d) shows that the measured values are not always suitable for the correct conservation of the artworks. Indeed, for the monitored period, the 33.3% of measured values is out of the acceptable range (55-60%).

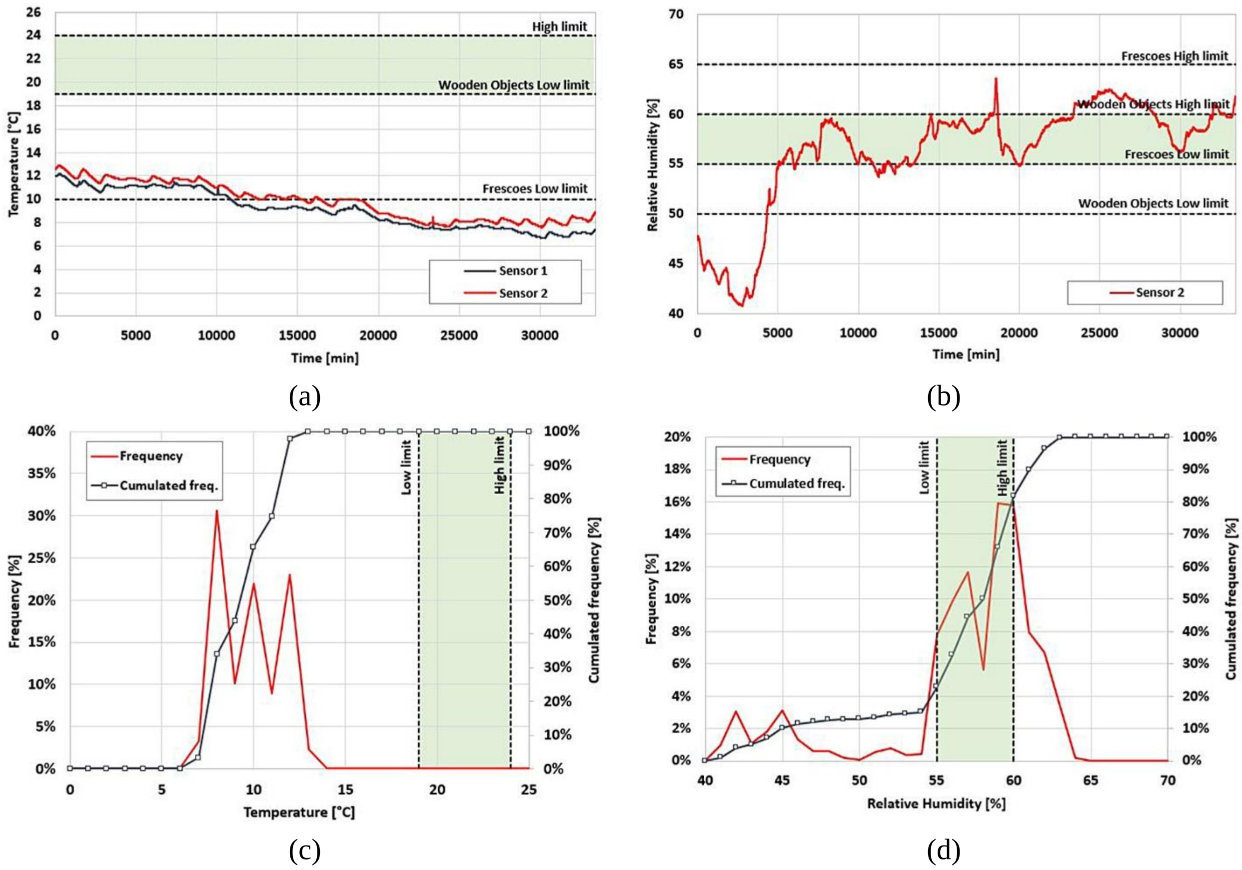


Fig. 8. Second monitoring phase. (a) Temperature. (b) Relative humidity. Frequency distribution and cumulated frequency of (c) temperature and (d) relative humidity. Note: the green area represents the limit values considered in this work.

Introducing the concept of Variance Indicator (VI), defined by the standard UNI 10829 [45] as percentage of time in which the quantity under consideration remains outside the chosen acceptable range (on the basis of the cumulated frequency), useful information are provided by the results of such approach, as shown in Table 7.

Table 7. Variation Indicators for temperature and relative humidity.

	UNI 10829				In this work			
Object	Range for temp. [°C]	Range for RH [%]	VI_{TEMP}	VI_{RH}	Range for temp. [°C]	Range for RH [%]	VI_{TEMP}	VI_{RH}
Frescoes	10-24	50-60	43.9%	31.1%	19-24	55-60	100%	33.3%
Wooden objects	19-24	55-65	0.0%	15.1%	19-24	55-60	100%	33.3%

It is worth noting that, with respect to the ranges required by the standard UNI 10829, more restrictive tolerances were established in this work, to guarantee the correct conservation of the cultural heritage preserved in the church. These tolerances were identified during consultations between technicians and restorers to assess the different opportunities available in terms of indoor climate control strategies, also taking into account thermal comfort performance to maximize the exploitation of the potential arising from the dynamic simulation modeling. The professional restorers defined the tolerances on the basis of the most vulnerable objects, i.e. wooden objects, as also indicated by the standard EN 15757 [7].

Therefore, the statistical analysis performed on the data measured during the second monitoring showed that the indoor microclimate of the church would seem not to guarantee either suitable thermo-hygrometric conditions for the conservation of the artworks therein contained (and recently restored) or thermal comfort of the occupants.

During the second monitoring phase, also outdoor weather condition was measured, and Fig. 9 shows outdoor dry bulb temperature and relative humidity.

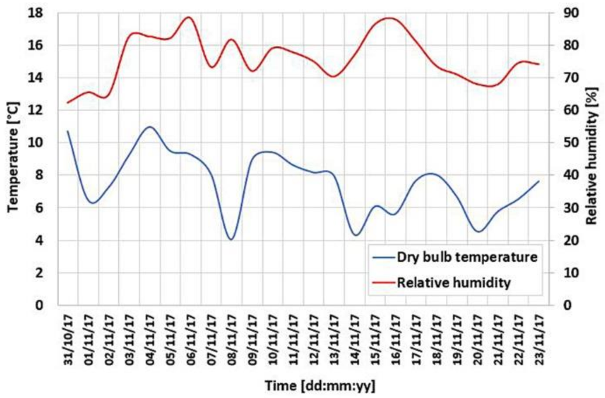


Fig. 9. Outdoor daily dry bulb temperature and relative humidity (Phase II).

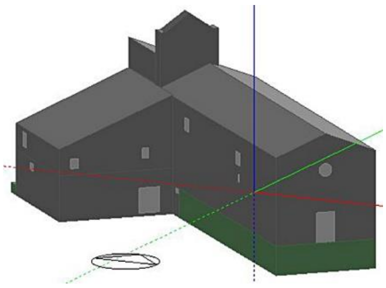
Although the entire monitoring period (September 28th - November 23rd, 2017) is not characterized by a particularly harsh outdoor climate, the church was significantly affected by the outdoor thermo-hygrometric conditions, due to the absence of HVAC system needed for the indoor microclimate control. Therefore, following the request of the restorers and their indications, the hypothesis of investigating potential results obtainable through the introduction of HVAC systems was carried out. In fact, the reduction of the influence of outdoor climate conditions could be possible by adopting appropriate control strategies of the indoor climate that can ensure not only proper preservation of the artworks but also thermal comfort for the occupants and energy efficiency maximization.

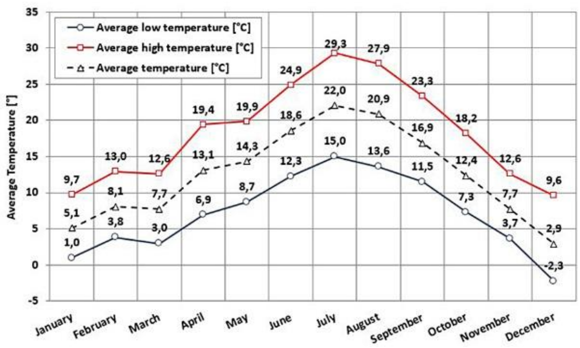
The study of possible HVAC system solutions is therefore dealt with the creation of a simulation model of the church of Santa Maria Annunziata of Roio.

4.3. Model creation and calibration

The use of dynamic simulation tools represents a great opportunity to predict the behavior of extremely dynamic systems such as buildings. However, because of a model always represents a simplification of real cases, the prediction provided by simulation models is only reliable if the models are subject to a thorough calibration phase. Therefore, to define the uncertainty of a model it is necessary to perform an in-situ experimental data acquisition phase to compare the predicted output of the model to the actual measured data. In the work of Roberti et al. [47], the authors stated that an uncalibrated model can lead to unreliable results, especially in the case of historical buildings for which building construction is often little known. They proposed a calibration methodology based on the minimization of Root Mean Square Error (RMSE) through particle swarm optimization algorithms implemented in the Genopt software and apply it to a medieval building called Waaghaus, located in the historic center of Bolzano (Italy), obtaining a remarkable accuracy of the model validated on hourly indoor air and surface temperatures in winter. Considering a 13th century church in Lisbon (Portugal), whose indoor conditions were monitored over a year, Coelho et al. [48] discussed a validation process of historic building simulation models by comparing measured and simulated temperature and water-vapour pressure quantifying coefficient of determination (R^2), coefficient of variation of the root mean square error, normalized mean bias error and goodness of fit. The authors tested the effects of outdoor climate and the temperature between soil and slab interface on the model calibration, by conducting a sensitivity analysis for three parameters, i.e. air change rate, solar heat gain coefficient and short-wave radiation absorption coefficient. They concluded that the best results are obtainable by considering monitored weather file rather than data provided from databases, and that the soil and slab interface temperature has a fundamental role. Pigliautile et al. [49] discussed an innovative methodology based on experimental monitoring and dynamic simulation to assess the effects obtainable through passive solutions on occupants' thermal comfort and artworks preservation. They considered the castle of Pieve del Vescovo located near Perugia (Italy) as case study and its simulation model, performed via DesignBuilder with EnergyPlus engine, has been iteratively calibrated by modifying the external wall packages and the internal thermal gains. The calibration phase was performed via statistical analysis by considering mean bias error and root mean square error. Thanks to the application of the proposed methodology, the authors have obtained an increase in the performance index (PI) up to 65.0% considering relative humidity range both for artworks preservation and occupants' comfort. The analysis of thermo-hygrometric conditions of the church of Santa Maria Annunziata of Roio was carried out by means of EnergyPlus dynamic simulation coupled with DesignBuilder. The simulation model (Fig. 10a) has been realized taking into account all the building's characteristics, such as orientation, geometry, air leakages and air changes. The building components were modeled by assigning the properties discussed in Section 4.1 and Table 2.

The weather file used for the simulation has been specifically created using the data (i.e. dry bulb temperature, wind speed, atmospheric pressure, relative humidity, and solar radiation) provided by CETEMPS – Centre of Excellence [44] measured by their nearby weather station. Fig. 10b shows the average temperature trend of L'Aquila.





(a) (b)

Fig. 10. (a) Simulation model of the church of Santa Maria Annunziata of Roio. (b) Average monthly temperature of L'Aquila.

Currently, the church has no HVAC system and it is closed to the public; therefore, the internal gains were not taken into consideration in the modeling.

The main information of the church's model are summarized in Table 8.

Table 8. Main characteristics of the model.

Description	Value	U.M.
Orientation	South-east	-
Length of the nave	21.3	m
Length of the sacristy	5.0	m
Width of the church	5.5	m
Occupancy	Unoccupied	-
Air leakage	0.5	vol/hr
Air change rate	4.0	l/s*person

Aware of the difficulties arising from the calibration phase of a building simulation model, the approach employed in this work is divided into two steps: 1) calibration phase of the model; 2) validation of the calibrated model. The first "calibration" phase of the model was performed by comparing measured and experimental indoor air temperature, and manually and iteratively varying parameters of the model, namely temperature setpoints and air leakage, to improve its accuracy. Instead, the "validation" phase of the calibrated model was carried out to analyze the ability of the model to predict the behavior of the building, but without making any changes to the parameters previously modified in the calibration phase. In particular, the assessment of the model accuracy was carried out by comparing: 1) simulation results and data measured during the Phase I of the monitoring, for the calibration phase; 2) simulation results and data measured during the Phase II of the monitoring, for the validation phase.
Since there are no clear standard limits for the analysis of the accuracy of a simulation model carried out on the basis of temperature trends, the model calibration was performed by considering Mean Bias Error (MBE), Coefficient of Variation of the Root Mean Square Error (CV(RMSE)), the deviation between simulated and measured indoor air temperature trends and the Coefficient of Determination (R^2), as fundamental indexes to show different aspects of the model accuracy. Indeed, while MBE and CV(RMSE) (Eqs. 1 and 2) evidence the distance between simulated and experimental data and the overestimation or underestimation, R^2 (Eq. 4) evidences the capacity of the simulated temperature trend to be in phase with the experimental one.

$$MBE(\%) = \frac{\sum_{Period}(S-M)_{Interval}}{\sum_{Period} M_{interval}} \times 100 \tag{1}$$

where (M) is the measured indoor air temperature and (S) is the simulated one.

$$CV(RMSE_{Period}) = \frac{RMSE_{Period}}{A_{Period}} \times 100 = \sqrt{\sum \frac{(S-M)^2_{Interval}}{N_{Interval}}} \times \frac{1}{A_{Period}} \times 100 \tag{2}$$

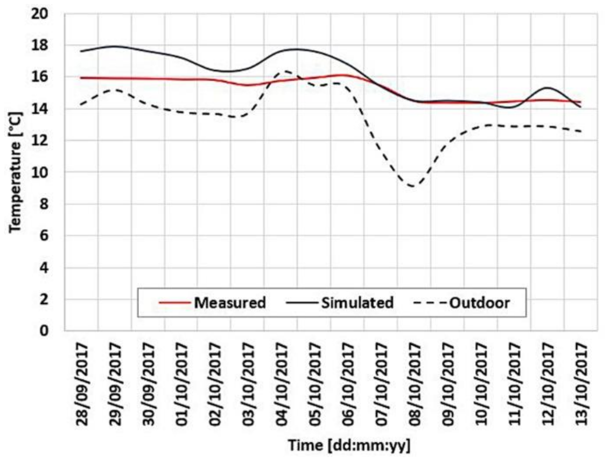
where (A_{Period}) is the mean of the measured data for the period, calculated using Eq. (3), and ($N_{Interval}$) is the number of time intervals in the monitoring period.

$$A_{Period} = \frac{\sum_{Period} M_{Interval}}{N_{Interval}} \tag{3}$$

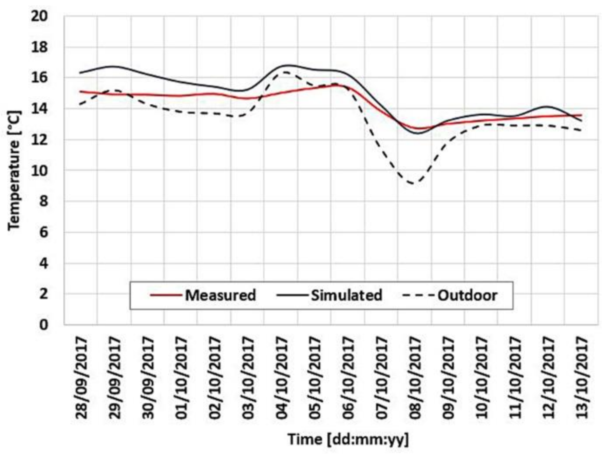
The R^2 was calculated using the following equation:

$$R^2 = \left(\frac{\sum_{i=1}^{N}\left(X_{i,meas} - \overline{X_{meas}}\right) \times \left(X_{i,sim} - \overline{X_{sim}}\right)}{\sqrt{\sum_{i=1}^{N}\left(X_{i,meas} - \overline{X_{meas}}\right)^2 \times \sum_{i=1}^{N}\left(X_{i,sim} - \overline{X_{sim}}\right)^2}} \right)^2 \tag{4}$$

As previously described, the calibration, carried out for both the nave and the sacristy of the church, was accomplished by comparing simulated indoor temperature values with the experimental values measured during the first monitoring phase (28th September – 13th October), as shown in Fig. 11.



(a)



(b)

Fig. 11. Model calibration (a) for the nave and (b) for the sacristy (by considering the first monitoring, i.e. 28th September – 13th October).

The results of the statistical analysis, the Coefficients of Determination (R^2) and the deviations between measured and simulated indoor air temperatures are summarized in Table 9.

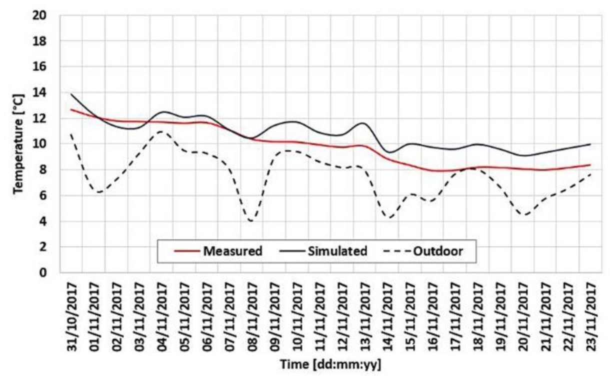
Table 9. Results of model calibration.

				Indoor air temperature deviation [°C]	
Description	MBE [%] *	CV(RMSE) [%] *	R^2 *	Min	Max
Nave	4.91	15.00	0.87	- 1.99	0.34
Sacristy	4.73	14.56	0.92	- 1.77	0.39

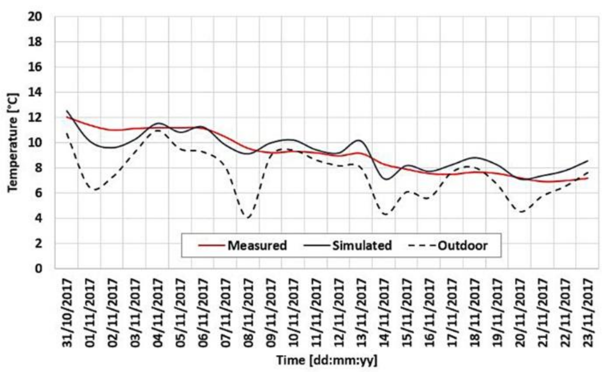
* limit values considered for the calibration: MBE < 5%, CV(RMSE) < 20% and R^2 > 0.75 [48- 50].

Therefore, since all the considered indexes are in agreement with the imposed limit values, the simulation model can be considered well calibrated.

The validation of the calibrated model was performed by comparing simulated indoor temperature values with the experimental values (Fig. 12) measured during the second monitoring phase (31st October – 23rd November), without making any changes to the parameters previously modified in the calibration phase.



(a)



(b)

Fig. 12. Model validation during the second monitoring (31st October – 23rd November) (a) for the nave and (b) for the sacristy.

The results of the validation phase, in terms of statistical analysis, Coefficients of Determination (R^2), and deviations between measured and simulated indoor air temperatures are summarized in Table 10, demonstrating the ability of the model to reproduce the real behavior of the church.

Table 10. Results of model validation.

Description	MBE [%]	CV(RMSE) [%]	R^2	Indoor air temperature deviation [°C]	
				Min	Max
Nave	9.76	17.71	0.83	- 1.81	0.50
Sacristy	1.49	18.86	0.78	- 1.37	1.39

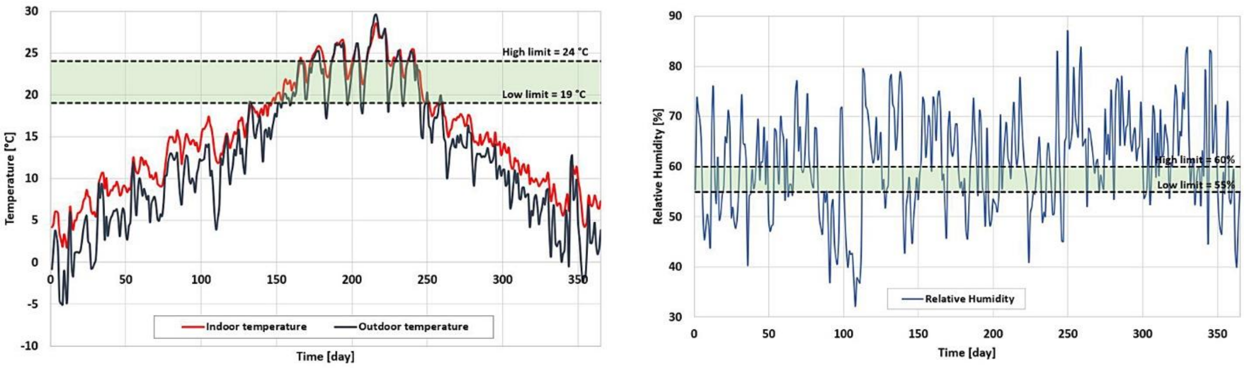
5. Results and discussion

Based on the calibrated and validated model, the simulation was employed to analyze indoor microclimate conditions of the church and to evaluate the incidence of anomalous values and the effects deriving from possible intervention scenarios on the preservation of cultural heritage, occupants 'thermal comfort and energy consumption resulting from the different control strategies of HVAC systems. The simulation results described hereinafter are referred only to the nave, since it preserves the cultural heritage and it will be frequented by occupants, although they can also be extended to the sacristy.

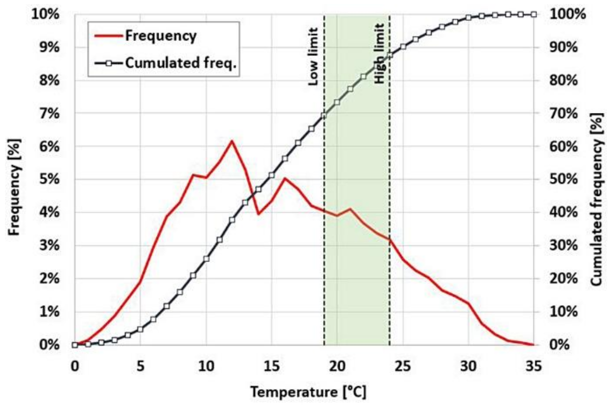
With regard to the analysis of thermal comfort, it was carried out on the basis of similar works already published in the literature [1, 26, 27], in which thermo-hygrometric threshold values, such as to ensure well-being for the occupants, were set. In particular, temperature values between 20 °C ± 2 °C in winter season, 26 °C ± 2 °C during summer, and relative humidity in the range 50% ± 10% were set in this work to perform the thermal comfort analysis [46].

Figs. 13a and 13b show the average daily temperature and relative humidity values throughout the year and they highlight the remarkable dependence of the indoor microclimate on the outdoor climate.

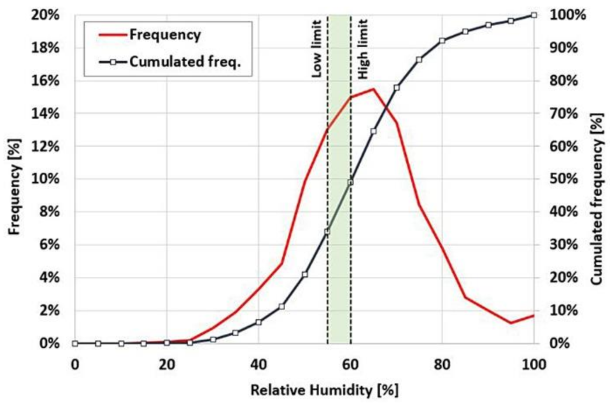
The annual hourly temperature and relative humidity values were used to perform a frequency distribution analysis to find out the Performance Indexes (PIs) of the nave, defined by Corgnati et al. [4] as the percentage of hours of the year in which the quantity under consideration lies within the required range. The results of the statistical analysis (Figs. 13c and 13d) provided PI_{TEMP} and PI_{RH} respectively equal to 22.3% and 28.0%, far from the imposed acceptance values equal to 90% [5].



(a) (b)



(c)



(d)

Fig. 13. Indoor microclimate of the nave. (a) Average daily temperature. (b) Average daily relative humidity. Frequency distribution and cumulated frequency of (c) temperature and (d) relative humidity. Note: the green area represents the limit values considered in this work.

The results obtained highlight that in the current condition (absence of HVAC system) the indoor microclimate would seem not to guarantee either the correct conservation conditions of the artistic heritage or the occupants' thermal comfort, and that the recent restoration of the artworks could be rapidly compromised.

Therefore, based on the results provided by the simulation model, different technological solutions and control strategies have been hypothesized, and their performance on indoor microclimate control have been analyzed to look for the best cultural heritage conservation conditions, occupants' thermal comfort, and energy efficiency. The hypothesized HVAC systems and control strategies of the indoor climate have been proposed by the technicians on the basis of the thermo-hygrometric threshold values indicated by the restorers. To balance the climate needs for artworks conservation, thermal comfort, and energy efficiency, and following the standard EN 15759 [9], a strategy based on continuous operation of HVAC system and on a spatial distribution of the entire church was chosen. The scenarios considered in this work, summarized in Table 11, are based on the initial hypothesis of installing a floor water-heating system (SC-1). This hypothesis involved some modification of the slab to foresee the correct installation of the floor heating system. Indeed, a new slab consisting of cast concrete (thk: 10 cm), EPS (expanded polystyrene – thk: 5 cm), cement screed (thk: 4 cm) and tiles (thk: 2.5 cm) was conceived, with a thermal transmittance equal to 0.622 W/m^{2}K. A set point temperature equal to 21 °C has been imposed, with a temperature attenuation at 20 °C. Moreover, an occupancy profile schedule has been defined considering one service during weekdays (6.30/7.30 pm) and three services during weekends (9.00/10.00 am, 11.30/12.30 am, and 6.30/7.30 pm). The second scenario (SC-2) provided for the installation of an air handling unit (AHU) with countercurrent plate-type heat exchanger (efficiency 75%), post-heating electric battery and air recirculation. The efficiency of supply air and air-exhaust fans has been set at 90%. With the third scenario (SC-3), it was assumed to equip the AHU with a humidistat to control the relative humidity whose set point was assigned to 57%. For the last case (SC-4), the installation of refrigerating unit and dehumidifier has been conceived considering a temperature set point equal to 24 °C during the summer.

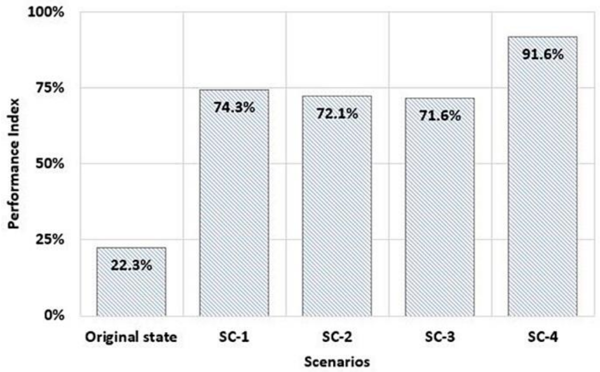
The control of complex HVAC systems requires powerful climate control systems. In this work, the indoor air temperature control strategy was envisaged using thermostats through which activate the opening/closing of electronically controlled valves of hydraulic manifolds that supply the individual circuits of the floor heating system; while, the relative humidity control strategy was envisaged by means of humidistats with which to control the air flow rate provided by the air handling unit.

Table 11. Different HVAC system solutions for indoor microclimate control strategies.

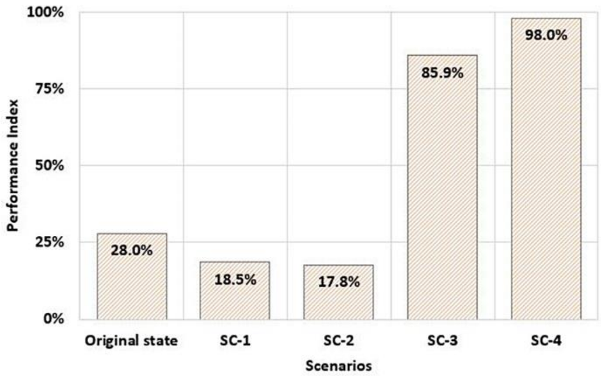
Scenarios	Floor heating system	Air handling unit (AHU)	AHU and humidifier	Dehumidifier and cooling systems
SC-1	✓			
SC-2	✓	✓		
SC-3	✓	✓	✓	
SC-4	✓	✓	✓	✓

The hypothesized scenarios allowed to obtain simulated hourly temperature and relative humidity values through which statistical analyses were performed to determine the new PIs. The PIs obtained for the various scenarios and the daily temperature and relative humidity trends are shown in Fig. 14. It is worth noting that the only one scenario suitable to guarantee compliance with the imposed PIs limit values, equal to 90% [5], is the SC-4, i.e. the case in which the church is equipped with the most complex HVAC system (heating/cooling and humidification/dehumidification). All other scenarios determined PIs less than the limit values, although the SC-3 scenario provided results close to the threshold values which were not achieved due to the lack of temperature and relative humidity control during the summer season, as can also be seen from Figs. 14c and 14d. Clearly, the PIs limit values are not mandatory, and they depend on technical evaluations discussed with the restorers. From a thermal comfort point of view, the SC-4 scenario determines thermo-hygrometric values suitable to guarantee the comfort throughout the year, while the SC-3 scenario is very close to ensure comfort except for some sporadic temperature value which exceeds 26 °C (design value [46]) in summer.

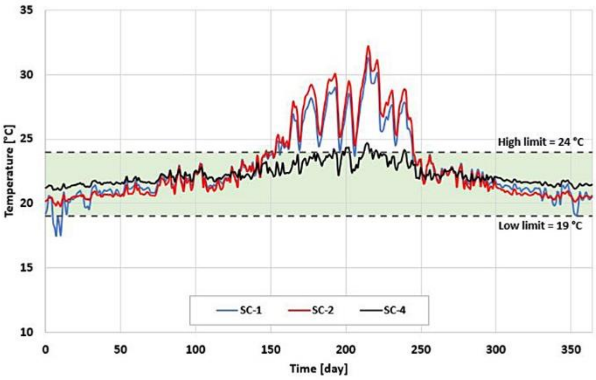
The simulations results related to the annual energy consumption, shown in Fig. 14e, highlighted that, although SC-1 and SC-2 are quite equivalent in terms of indoor microclimate control (i.e. they have similar PIs values, as shown in Figs. 14a and 14b), the SC-2 scenario allowed for a lower energy consumption (equal to 90.7 MWh/yr) than the SC-1 scenario (110.9 MWh/yr), thanks to the installation of the air handling unit with heat recovery. The increase in energy consumption verified for the SC-3 scenario (176.3 MWh/yr) is due to the relative humidity control obtained considering the air humidification system. Moreover, the best PIs values, both for temperature and relative humidity (Figs. 14a and 14b), are possible only with a greater complexity of the HVAC system (SC-4 scenario) that determines the highest energy consumption (equal to 209.0 MWh/yr), as shown in Fig. 14e.



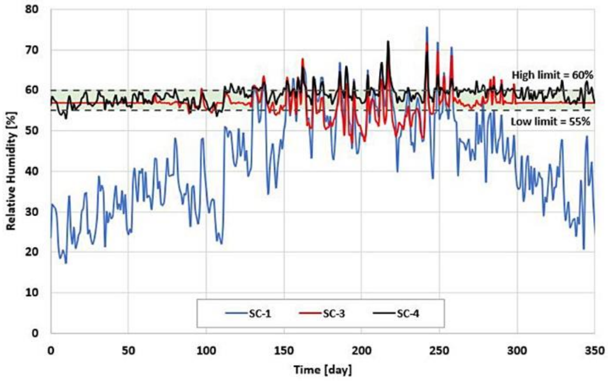
(a)



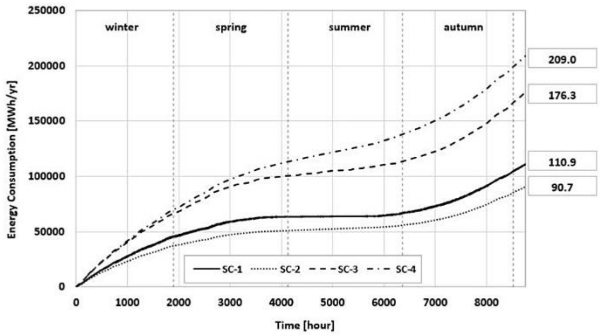
(b)



(c)



(d)



(e)

Fig. 14. (a) PIs for temperature. (b) PIs for relative humidity. (c) Temperature trends. (d) Relative humidity trends. (e) Cumulative energy consumption distribution.

Note 1: in Fig. 14c the SC-3 is not plotted because it is very close to SC-2. Note 2: in Fig. 14d the SC-2 is not plotted because it is very close to SC-1. Note 3: the green area represents the limit values considered in this work.

6. Conclusions

In this work, the implications on cultural heritage, thermal comfort and energy efficiency derived from a post-restoration phase of a severely damaged church were discussed by means of an interdisciplinary methodology based on experimental measurements and dynamic simulation modeling. The case study of the church of Santa Maria Annunziata of Roio in L'Aquila (Italy) was analyzed, being representative of a large number of churches that, hit by the earthquake that destroyed L'Aquila in 2009, are now subject to refurbishment and restoration of the artworks they contain.

The main findings of the work are:

- the monitoring campaign has shown that the indoor thermo-hygrometric fluctuations, due to the absence of HVAC systems, would not guarantee the correct conservation of the artworks;
- in the present state, due to the considerable thermo-hygrometric fluctuations, the artworks just restored will be subject to a new "acclimatization" phase, during which they could suffer internal fracturing, cracks and mechanical damages, which would compromise the carried-out restoration;
- the experimental analysis and the simulation results showed that the indoor microclimate conditions of the church would not guarantee thermal comfort conditions for the occupants;
- the achievement of PIs suitable to satisfy correct conservation conditions and thermal comfort (i.e. PIs > 90%) required complex HVAC system capable of heating/cooling and humidifying/dehumidifying the church;

- the hypothesis of employing complex HVAC system led to significant increase in energy consumption. Indeed, the only one scenario able to guarantee PIs values > 90% and thermal comfort conditions was the SC-4 scenario which has determined the highest energy consumption, equal to 209.0 MWh/yr.

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