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Review

Microclimatic Monitoring—The Beginning of Saving Historical Sacral Buildings in Europe

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Abstract: A suitable indoor climate positively affects the lifespan of historical building structures. The path to an agreeable climate begins with monitoring current conditions. Considerable attention is given to monitoring the indoor climate of historical buildings. The motivation for monitoring air temperature and surface temperatures, relative air humidity or airflow can be, for example, the installation of heating, the occurrence of biotic damage, and others. Through the analysis of the most frequently used keywords, a strong connection was found, for example, between thermal comfort and the church. This review also summarises the various reasons for conducting microclimate monitoring studies in historical religious buildings on the European continent. It is supplemented with an evaluation of the monitoring methodology from the chosen period of the year point of view, the measured parameters, and the length of the interval between the recordings of quantities. It was found that in more than one-third of the cases, the recording time was less than or equal to 15 min, but mostly less than or equal to 1 h. Quite often, monitoring results are used to calibrate a simulation model describing the hydrothermal behaviour of a historical object under various operation alternatives (e.g., influence of ventilation, climate change, occupancy, etc.). This way, it is possible to test various intelligent systems in the virtual world without much risk before they are used in an actual building application.

Keywords: historical building; climate; monitoring; temperature; humidity; cultural heritage

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1. Introduction

A historical site or heritage site is an official location where articles of cultural, religious or political history have been preserved. A historical site may be any building that is of local, regional, or national significance. Usually, this also means the site must be at least 50 years or older [1]. Modern monument care has its foundations in respect for the preserved historical object as an original. The basic effort and priority task of architectural heritage care is preserving existing historical structures, elements, and surfaces [2]. According to the International Council on Monuments and Sites (ICOMOS), conservation means developing a place to preserve its cultural significance [3]. Heritage conservation is one of the priority goals of the United Nations expressed in 2015 in the 2030 Agenda for Sustainable Development as Goal 11 [4]. Because historical buildings archive technologies and solutions that are no longer in use, they act as a testimony to technical and architectural–historical paradigms. The preservation of historical buildings itself is a very broad topic that has several paths. In addition to creating suitable microclimatic conditions, for example, lightening traffic around a specific historical building can reduce facade pollution, adapting modern construction techniques to the restoration process sometimes leads to the invention of the most cost-effective and sustainable interventions [5].

Appropriate microclimatic conditions in the interior space can have a positive impact on the durability of the structure [6]. These conditions can be influenced mainly by ventilation and outdoor weather conditions [7,8]. However, on the other hand, the thermal storage capacity of a stone masonry wall and ceiling construction stabilises the temperature [9,10].

At a minimum, partial use is an important reason for preserving historical buildings. Occupancy of these buildings is associated with the following problems: proper cladding of structures with the elimination of thermal bridges; the arrangement of efficient and easy-to-operate joinery and sufficient ventilation; and an often neglected very important aspect, ensuring the building has the ability to breathe, or removal of humidity from the inside of the building to the outside (Figure 1). In addition, reduced hygienic–sanitary comfort in a part of a building leads through time to the degradation of the entire building [11].

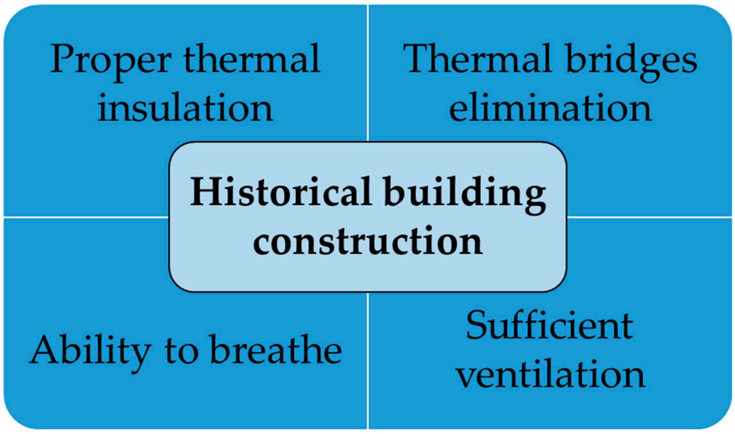

Figure 1. The problems of historical building construction associated with occupancy.

2. Methodology for Literature Selection

2.1. The PRISMA 2020 Statement

The selection of appropriate literature for this review was made in accordance with the PRISMA 2020 statement. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement, published in 2009, was designed to help systematic reviewers transparently report why the review was performed, what the authors did, and what they found. The PRISMA 2020 statement replaces the 2009 statement and includes new reporting guidance that reflects advances in methods to identify, select, appraise, and synthesise studies [12].

Systematic reviews serve many critical roles [12]. One of these roles can be to summarise the state of knowledge in an area of interest, which can be used to identify priorities for future research. Systematic reviews, therefore, generate various types of knowledge for different users of reviews [12]. Thus, in this review, we chose to focus on microclimate monitoring in historical religious buildings on the European continent.

According to the PRISMA 2020 statement, the literature selection methodology consists of three main steps—identification, screening, and inclusion of the report in the review. A report can be a journal article, a book chapter, a book, a conference paper, or any other document providing relevant information.

2.1.1. Identification of Literature

The Scopus database, operated by Elsevier, was primarily used to identify relevant literature. The Scopus database was chosen due to its multidisciplinary nature and large coverage. Two of the main advantages are the broad coverage of scientific and technical journals and the inclusion of more European content compared to WoS [13].

The literature search included all records in the databases that were available through the end of October 2022, which were identified based on previously estimated keywords. These were subsequently searched within article titles, abstracts, and keywords.

The keywords were chosen as follows: historic building(s); historical building(s); church(es); cultural heritage; indoor climate; indoor environment; microclimate; monitoring; humidity; temperature; CFD; computational fluid dynamics; simulation; ventilation; airflow.

2.1.2. Screening of Literature

This phase received 1990 records, of which 1875 records were removed based on the screening of the article title, abstract, and keywords. The remaining records, which were 115, were thoroughly screened. Based on reading the records, 35 records were subsequently removed—21 records were removed due to irrelevance (e.g., studies that did not present the results of measurements of microclimatic parameters relevant to us), and 14 records were removed due to similarity with other records already included (e.g., studies that focused on the same building, presented the same data from microclimate monitoring, and differed only in the objectives—the main motivation).

2.1.3. Inclusion of Literature

The final phase included 100 records. The analysis of these records extracted data on the country, monitoring season, measured microclimate parameters, frequency of temperature and relative humidity measurement, attic monitoring, and, in the case of the indoor environment simulations, the simulation tool used. Additional records were used to supplement the information presented.

2.1.4. PRISMA 2020 Flow Diagram

The flow diagram (Figure 2) illustrates the flow of information at the identification, screening and inclusion of a record in the review stage. It maps the number of records identified, included and excluded, and the reasons for exclusions [14].

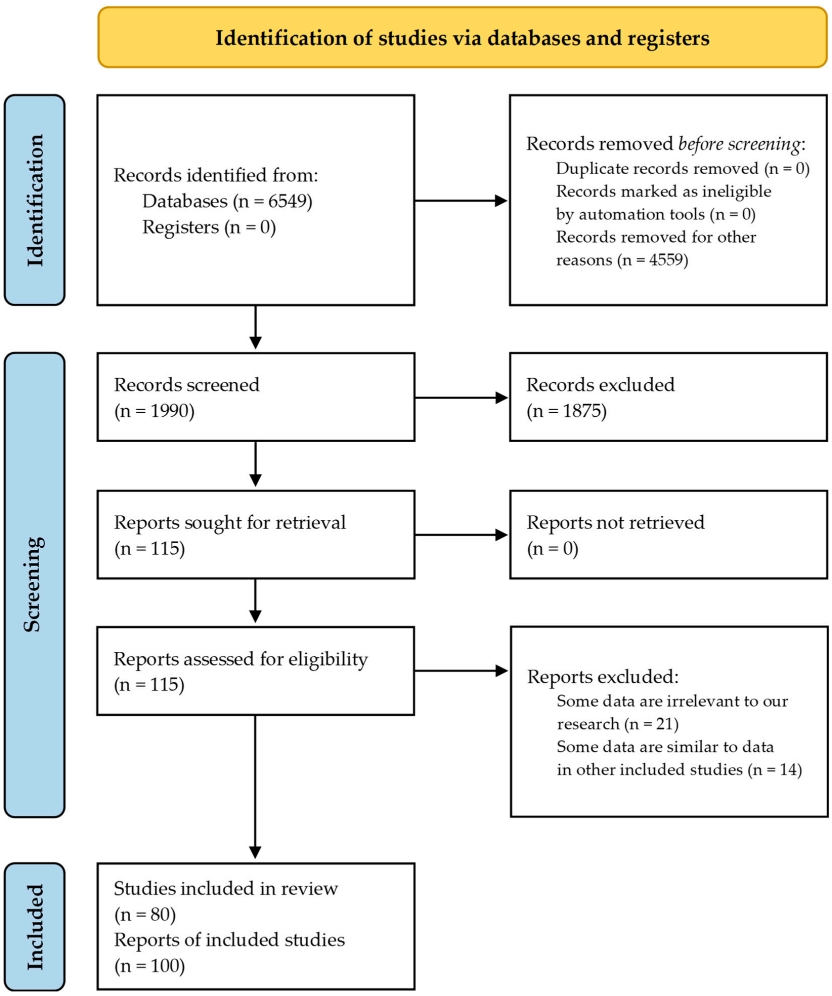

Figure 2. Methodology for literature selection according to the PRISMA 2020 flow diagram for a new systematic review that included database and registry searches.

2.2. Keywords Analysis

The procedure of the literature selection methodology in terms of the PRISMA 2020 statement contributed to the identification of the most relevant keywords used by the authors of the monitoring studies in relation to this area of interest.

Selecting and analysing keywords is an important part of a research paper and another way to identify research gaps in related fields. This might be beneficial to researchers to manoeuvre the research direction, and it gives an idea as to which topic or field needs to be emphasised [15].

The 20 most relevant keywords were analysed in the widely accepted software VOSviewer, version 1.6.18 (Figure 3). VOSviewer is a software tool for constructing and visualising bibliometric networks [16]. The relatedness of keywords is determined based on the number of records in which these keywords co-occur. The most common co-occurrence was between historical building and cultural heritage, cultural heritage and microclimate, temperature and humidity, and between thermal comfort and church.

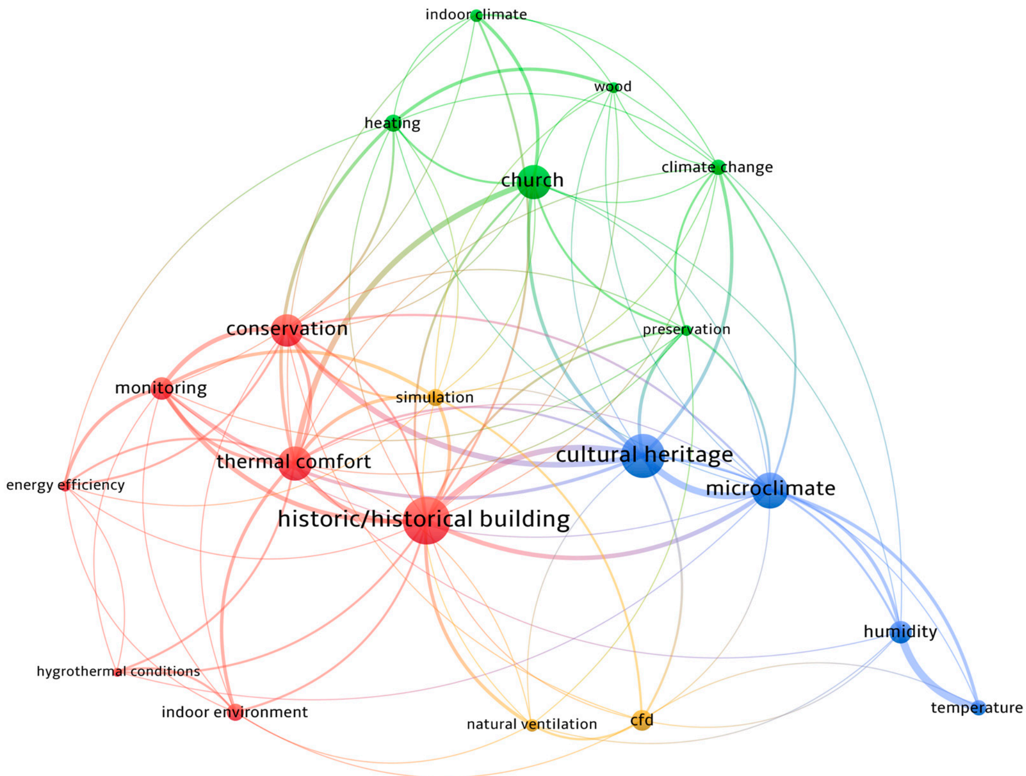

Figure 3. Analysis of the most commonly used keywords and their co-occurrence in the VOSviewer software tool.

The nodes of this network represent the most relevant keywords. It can be seen that the sizes of the nodes depend on the frequency of occurrence in the literature. The terms historical building (sometimes as a historic building), cultural heritage, microclimate, conservation, thermal comfort, and church were most frequently encountered. The terms monitoring, humidity, and CFD were also common.

The 20 keywords are divided into 4 colour groups. The higher the number of members in the group, the more interest there is in the research area. Of course, the reverse is also true, i.e., the lower the number of members in the group, the less interest there is in the research area. Thus, based on the keyword analysis, there is sufficient scope for research on historic religious buildings focusing on the use of dynamic airflow simulations.

3. Selection from the Literature on Monitoring Studies

Many monitoring studies have been devoted to in situ microclimatic monitoring of original Christian religious buildings across the European continent.

Some of the studies address the impact of HVAC on visitors and their thermal comfort. Other monitoring studies analyse different types of risks, for example, from a heritage conservation perspective. Nevertheless, in many cases, these are monitoring studies that combine these focuses.

The main motivation that can be found in almost all scientific works devoted to indoor microclimate monitoring is the protection of monuments from degradation caused by different impacts, in particular:

- Biotic damage, mould and fungal growth, e.g., [17,18];
- Climate change associated with global warming or the urban heat-island effect, e.g., [19,20];
- Change in ventilation due to building interventions or changes in operation, e.g., [21,22];
- Increased humidity due to a sudden increase in the number of visitors during a short period (especially in the case of wooden buildings), e.g., [23,24];
- Introduction of heating to improve comfort, e.g., [25,26];
- Flooding and subsequent drying out of flooded structures, e.g., [27].

Finally, a strong motivation for monitoring studies is the benchmark establishment for the simulation model calibration.

The main monitored indoor microclimate parameters are the same and repetitive in almost all scientific works with the same motivation (Figure 4).

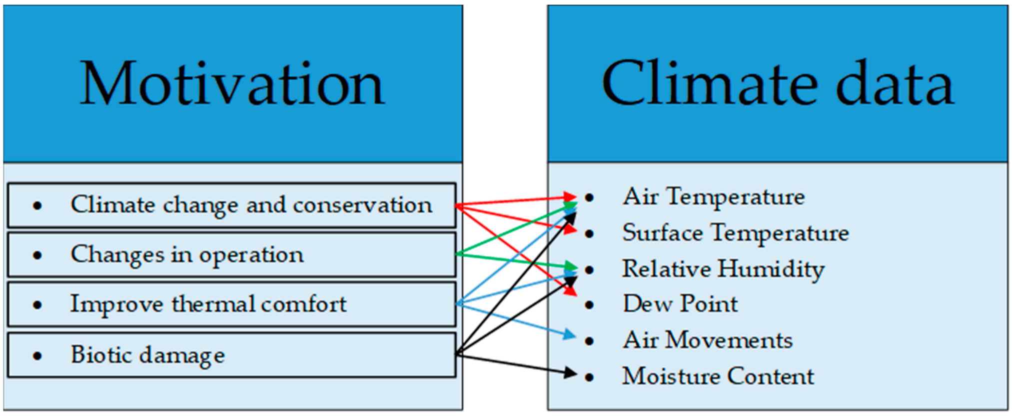

Figure 4. The main motivation of scientific works dedicated to indoor microclimate monitoring and their main monitored parameters. Each of the main motivations is assigned its own arrow colour.

3.1. Monitoring Parameters

3.1.1. Monitoring the Impact of Indoor Air Temperature and Humidity

The indoor climate in historical buildings differs significantly from contemporary buildings. Vella et al. [28] preferentially attributed this to the lack of thermal mass of newer churches and, in addition, to higher solar gains through large glazed areas, as such areas provide minimal thermal inertia.

Several researchers have attempted to assess the impact of microclimate variables on cultural heritage [29–39]. All studies indicate that temperature and relative humidity are two of the most important indoor microclimate parameters. Tabunschikov and Brodatch [40] in their study presented that degradation due to relative humidity is more severe than degradation due to temperature. Anaf and Schalm [41] also considered it important to analyse the fluctuations in temperature and relative humidity, which could help to identify the hazards that these fluctuations can cause.

Cannistraro and Restivo [42] presented the results of a study that focused on the use of wireless sensors in indoor microclimate monitoring. They reaffirm that, in order to prevent critical processes from occurring, it is necessary to keep the indoor microclimate parameters within constant limits. Wireless sensors were also used by Ramírez et al. [43] in their study, which aimed to characterise the temperature gradients according to height in a baroque church. The system for monitoring indoor microclimate parameters described by García-Diego and Zarzo [44] in their study was exceptional because some of the sensors were embedded in the paintings during the restoration process. Because monitoring studies are often associated with the high cost of purchasing commercial sensors, Silva et al. [45] focused on using low-cost data loggers that they designed.

Numerous research works in the field of conservation and preservation of cultural heritage have been carried out by Camuffo et al. By using the example of the Basilica of Santa Maria Maggiore in Rome, Camuffo et al. [46] demonstrated how ancient buildings with thick walls can reduce the impact of external changes in temperature and humidity. The study mainly focused on the thermodynamic exchanges between the outer boundary layer and the indoor microclimate in terms of the conservation of artwork and tried to find correlations between indoor and outdoor environmental parameters. Another study [47] addressed the design of a heating system based on low-temperature radiant heaters mounted on benches that could provide the required heat distribution to the feet, legs, and hands of the visitors. The methodology and results of this comprehensive and multidisciplinary study have been included in drafting three European standards for use in the study and environmental control of cultural heritage objects.

In normal museum practice, it is recommended to ensure that the temperature and relative humidity levels are as stable as possible. Typically, a temperature of 15–25 °C and a relative humidity of 40–65% are considered optimal and safe [48]. Nevertheless, it is important to keep in mind individual differences in the microclimate of buildings, as these differences depend on the characteristics of the building and the parameters of the outdoor environment. A case study of a trio of churches from different geographical locations or materials was carried out by Bratasz et al. [49]. The study was based on the assumption that it is not possible to determine the best relative humidity level for the conservation of artwork containing organic materials, as they have adapted over many decades to the particular indoor climate in which they were conserved. The results of the study provided a practical example of a specification for allowable variation in relative humidity based on knowledge of the historical climate of a particular building in its environmental context (Figure 5). The specifications were derived from past short-, medium-, and long-term fluctuations in building relative humidity due to diurnal variations, weekly weather variability, and annual average levels. Therefore, the case study presented primarily a possible approach to establishing and assessing these tolerable ranges of short-term relative humidity fluctuations, which are, however, individual for each building.

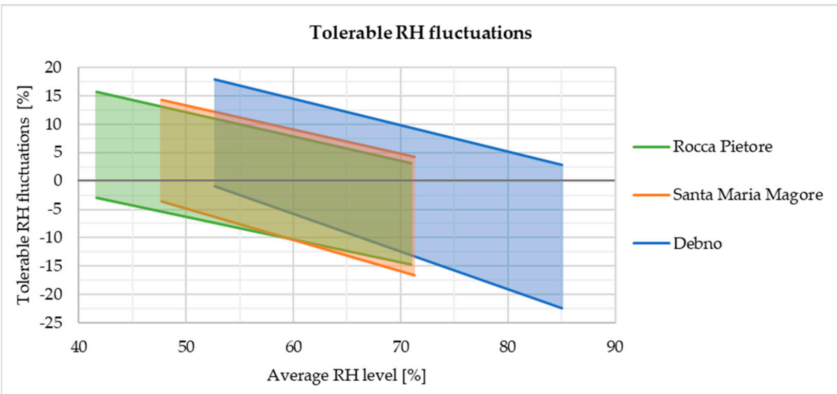

Figure 5. Tolerable relative humidity (RH) fluctuations in a trio of churches [49].

Onecha and Dotor [50] focused on one of the Barcelona basilicas. The first phase involved collecting basic data about the building, the environment, and the visitors. In the second phase, the authors carried out temperature and relative humidity monitoring, calibrating the obtained climatic data against weather station data in order to account for the urban heat-island effect. In the third phase, they developed dynamic simulations for different use and ventilation scenarios.

Perhaps the most extensive microclimatic study was carried out by Kalamees et al. [51], focusing on up to 30 Estonian churches. Temperature and relative humidity were measured in all churches. Furthermore, in some churches, the surface temperature of the building envelope and the horizontal spatial distribution in temperature and relative humidity were measured. The results showed that the most common problem in the unheated churches was very high relative humidity throughout the year, which resulted in a high risk of algae and mould growth. This risk was not reduced by the use of intermittent heating. However, in the case of heated churches, this risk was significantly lower.

Monitoring the indoor climate, especially in wooden religious buildings, helps to find the causes of rot, fungi, and mould, and to make recommendations for their prevention and control [17,52,53]. Indoor environmental conditions have to be improved in order to reduce/eliminate potential sources of fungal contamination and to achieve optimal environmental preserving conditions [54]. One who focused on the measurement of temperature and relative humidity was Marcu et al. [18], who stated that indoor microclimate parameters, in the case of wooden churches without HVAC, correlate very closely with outdoor environmental parameters. The study states that the greatest fluctuations in microclimatic parameters occur especially during winter (very high humidity combined with low temperatures), which can cause degradation of the structure, valuable objects (e.g., icons, textiles, and books), and the appearance of bacteriological microflora. Combined with the fact that the winter period is one of the peak times of the year in terms of religious services, this creates unfavourable conditions for human health. In order to preserve the structure, valuable objects, and visitor comfort, the parameters of the indoor microclimate should not be significantly altered and, ideally, should be kept to a limited extent, which can often be unrealistic or impractical.

Recent years have also seen a proliferation of studies addressing the issue of climate change and its impacts on the indoor microclimate of original Christian religious buildings, the preservation of works of art, thermal comfort, or energy consumption [19,20,55,56].

The issues addressed differ across the European continent. This is confirmed by the Clima for Culture project [57]. This project identified four climate zones in Europe that reflect similar thermo-hygrometric differences (Figure 6). These climatic conditions differ from those in America, Asia, etc.

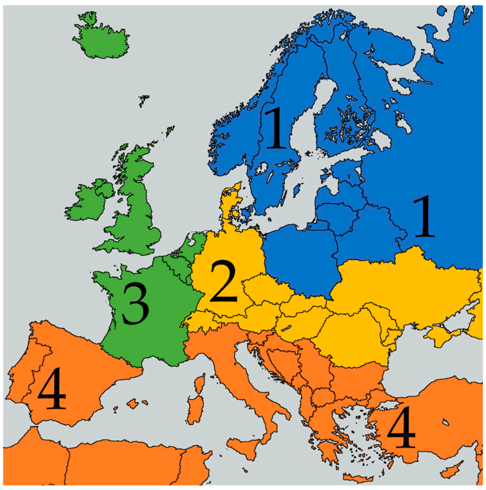

Figure 6. Practical climate zoning for Climate for Culture outcomes evaluation [57] (1-Northern climate, 2-Eastern-Continental climate, 3-Western-Island climate, 4-Southern climate).

3.1.2. Monitoring the Impact of Ventilation and Air Movements

In the context of indoor microclimate monitoring, Björling et al. [21] made measurements related to air movement. Since indoor surfaces reflect the average temperature, they are usually cooler than the infiltrated air during a warmer summer day and, therefore, can cause condensation on these surfaces. Excessive material moisture and high local relative humidity can cause or encourage the growth of wood-borne fungi, algae, and moulds. As it is not easy to install a new ventilation system in historical buildings for heritage reasons, relying primarily on open-door ventilation is often possible. Such ventilation is an easy way to temporarily improve the ventilation of interior spaces in historical buildings.

Most of the previous research on ventilation, especially single-sided ventilation, has usually been related to windows, while only a few studies related to doors exist. Based on measurements made and published in the study by Hayati et al. [58] showed that an average air change of 0.6 ACH was achieved when ventilating through open doors. This value was approximately 10 times higher than the air change rate during normal air infiltration through the gaps. At small temperature differences between indoors and outdoors (i.e., 3 °C), the air change ranged from 0.2 to 0.5 ACH; at larger temperature differences (i.e., 10 to 15 °C), the air change ranged from 0.5 to 1.0 ACH. However, the calculations used in the study included only the air change due to buoyancy. The wind component was not included in the calculations. Hayati [22] also focused on air movement measurements in another study. The increased flow velocity generated during ventilation can be used to refresh the interior and remove pollutants generated, for example, by large numbers of people and lit candles during religious services.

In Slovakia, the measurement of microclimatic parameters in the space of a historical church roof truss was addressed by Kysela et al. [59]. For a proper understanding of the microclimate, measurements of temperature, relative humidity and their distribution were made in the attic space. The conditions were then evaluated in terms of annual behaviour and in terms of a typical winter and summer week. This work was followed by Ponechal et al. [60], who simulated the airflow in the roof space of this historical truss. Ponechal et al. created a computational fluid dynamics (CFD) simulation model for a detailed airflow and temperature distribution analysis. The air volume through the vents and surface temperatures were taken from a multizone airflow model. The study simulated four different airflow scenarios for a sunny summer day. Two states feature more intense airflow, which occurs at noon and night, and is caused by a significant difference between air temperature and surface temperature. After these states, there are the states with the less intense flow, when the air is so mixed that the environment in the attic stabilises in temperature. The images from the CFD simulation demonstrate an increased airflow not only around the ventilation openings but also on hot (roof) and cold (gable wall) surfaces. Their existence helps the air movement in the building when there is no wind. Structural changes (e.g., applying roofing foil) can deprive the attic of these important surfaces. This can cause a fundamental change in ventilation.

3.1.3. Monitoring the Impact of Humidity Fluctuations

Wysocka [23], in her study, presented the opinion that church buildings are specific in their microclimate. A large number of visitors are in these buildings in short time intervals, resulting in rapid changes in air quality. In this case, it can be noted that the relative humidity level also exceeds the recommended values.

Other researchers wanting to highlight the specificities of the indoor climate in churches and how the microclimate can be affected by religious activities were Califano et al. [61], who monitored a church in Norway; Mihincău et al. [24] and Bucur et al. [62], who monitored a wooden church in Romania; and lastly Napp et al. [63] and Napp and Kalamees [64], who assessed the adaptive ventilation solution in a church in Estonia.

Most medieval churches used to be heated in winter and unheated in summer. The consequence of this heating method is significant changes in relative humidity. Klenz

Larsen [65] saw a solution to such a problem in year-round heating, which would regulate relative humidity and temperature based on the annual cycle. He also noted that some churches have the ability to humidify the indoor climate by capillary moisture migration.

3.1.4. Monitoring the Impact of the Introduction of Heating

Clarifying the influence of the heating method on the indoor climate of historical churches or the evaluation of heating strategies has been attempted in several studies [25,26,66–68]. Several past studies confirm the fact that heritage conservation can be compromised by heating systems that can alter indoor microclimatic stability [69,70]. Schellen et al. [71] view hot-air heating systems as particularly problematic, which lead to sudden changes in relative humidity, endangering monumental sacral organs, especially in winter. On the contrary, Broström and Hansson [72] state that intermittently heated churches in the Scandinavian climate should have the most stable indoor microclimate.

3.2. Monitoring Methodology

In terms of monitoring time, the range is very wide: from measurements lasting only a few days or months [73] to long-term measurements over 20 years [74].

Parameters of the outdoor environment can be measured in the same way as the indoor environment, or data from a foreign source can be used, as in the case of measurements in two Latvian churches presented by Metals et al. [75]. In this way, the measurement technique can be spared in favour of monitoring the indoor microclimate at the cost of some compromise on the outdoor environment values.

Measurement can also be performed in two phases, as done by Aste et al. [76] in measuring a Milan Cathedral, or by De Rubeis et al. [77] in a case study from another Italian church. The first phase consisted of a preliminary collection of microclimatic parameters for planning long-term monitoring. The second phase was already focused on comprehensive microclimatic monitoring. Sensors were installed at the most prominent and accessible locations inside the church.

The use of thermography as a suitable tool for a nondestructive technique to improve the knowledge of hygrothermal dynamics of original Christian religious buildings has been used by several researchers in their studies [78–83].

For example, thermography has also been used by Ridolfi et al. [84], who carried out two measurements of environmental parameters. The first measurement was carried out during the reconstruction of facades and roofs. One year later, a second measurement evaluated these renovations. The presented study showed that after the renovation (in which thermal insulation was installed), heat accumulated under the ceiling without temperature fluctuations.

The combination of sensors to measure environmental parameters using thermographic images and CFD simulations appears to be a very interesting approach to the microclimatic assessment of the building environment. In particular, the use of thermography can provide real data to validate CFD simulations. This claim is based on a study by Lerma et al. [85]. In the study, they compared data from the temperature and relative humidity sensors with thermographic images and CFD simulations. This analysis focused on the most extreme cases—one summer and one winter day. The study concludes that CFD simulations do not provide an exact value but a certain confidence interval. Those locations where the in situ measurements differ from the CFD simulations should be studied in more detail as they may indicate critical zones.

3.3. Combination of Monitoring and Dynamic Simulations

3.3.1. Monitoring and Dynamic Simulation in the Main Space

Whereas in the past, builders relied more on empirical experience than they do today, they can now use computer simulation models to analyse how a building behaves and how it works in principle. Therefore, some monitoring studies of original Christian religious buildings have been extended to include the creation, calibration, validation, and verification of simulation models in various specialised simulation software. However, in such cases, the use of test reference year (TRY) is not the most appropriate for simulation model calibration, as presented by Frasca et al. [86]. Similar to measurement, simulation can be performed in at least two phases, as in the study by De Rubeis et al. [77]. First, the results are compared with the measured results of the first phase (calibration phase), followed by a comparison with the measured results of the second phase (validation phase). This can be followed by another phase where the effects of the alternative solutions are verified from an architectural point of view using dynamic simulation.

A dynamic multizone simulation model was developed by Hayati in his study [22]. This study is specific in that the internal volume of a Swedish masonry church was evaluated using 3D laser scanning. Weather data were obtained from a portable weather station, while NTC thermistors were used to measure the indoor temperature.

Another study, undertaken by Schellen et al. [27], used a multizone simulation model of a chapel to investigate the impact of flooding and groundwater on cultural heritage. In the simulation model, the attic was modelled as a separate zone.

Muñoz-González et al. addressed several simulation studies. For example, in one of the studies [87], they tested different strategies and techniques to modify the indoor climate. At the same time, the study concluded that the cases of Spanish churches are very different from those of churches in northern Europe. The point is that, due to the mild climate, the need for heating is much lower in winter, while in spring and summer, the cooling and dehumidification requirements are higher due to the high temperatures and relative humidity. Another of their studies [88] focused on applying passive, active, and combined environmental techniques in terms of their impact on the conservation of artwork.

It can be seen that simulation models have often been used in studies that were related in some way to the use of HVAC, e.g., [89–91].

Coelho et al. [92] attempted to develop a process for verifying historical buildings based on annual indoor conditions using simulations. Outdoor weather files were simulated to demonstrate the importance of monitoring outdoor environmental parameters. A total of 48 simulations were processed to try to optimise the simulation time while guaranteeing the accuracy of the model.

The combination of measurements, thermography, and CFD simulations was also presented in studies by Țurcanu et al. [93,94], which aimed to study the possibility for preserving the cultural heritage while achieving better thermal comfort.

Three simulation variants for a wooden church in Poland were presented in a study by Nawalany et al. [95]. The variants differed in the different simulated temperatures, with the simulated heating capacity providing sufficient power to maintain this simulated temperature.

Posani et al. also worked with a simulation model [96]. This study focused on a library with an HVAC system. Since the library is located in the original church building, it is included in this review. In the simulation model, the attic was modelled as a separate zone.

The aim of the study by Sadłowska-Sałęga and Radoń [97] was to investigate the prospect of implementing simulation models in order to predict the indoor climate in historical buildings. The results of year-long simulations were compared with the results of a monitoring study, referring to the indexes of evaluation criteria and the criteria for maintaining the accuracy of the model.

3.3.2. Monitoring and Dynamic Simulation in the Roof Space

A specific part of microclimatic monitoring and simulation of original Christian religious buildings is the space of roofs—historical roof trusses. This research confirms that CFD with a finite element modelling approach can provide basic support to the issues involved in the analysis and preventive conservation of ancient ventilation techniques in old buildings [59,60].

In their study, Orzechowski and Tatko [98] used a new approach to monitor the structural behaviour of large historical wooden structures. On that occasion, they measured temperature and relative humidity in the historical truss, together with structural parameters. Furthermore, they had continuous online access to the measured data.

The design and development of a simplified approach for risk assessment on historical timber structures were also addressed by Sola-Caraballo et al. [99]. Therefore, part of their presented study was devoted to the measurement of microclimatic parameters in the space of a historical truss.

4. Discussion

The data extracted from the monitoring studies included in this review have been neatly summarised in a table (Table 1). These data were then evaluated from several aspects.

Table 1. Microclimatic studies on historical sacral buildings on the European continent.

Ref.	Author/Authors	Country	Microclimate Monitoring				Simulation Tool
			Season	Measured Parameters	Frequency of T/RH Measurement	Attic Monitoring	
[17]	Pilt et al.	Estonia	year-round	T, RH	15 min < F ≤ 1 h	in the attic	-
[18]	Marcu et al.	Romania	autumn, winter	T, RH	15 min < F ≤ 1 h	-	-
[19]	Rajčić et al.	Croatia	year-round	T, RH	-	near the attic/ceiling	WUFI Plus
[20]	Muñoz-González et al.	Spain	year-round	T, RH, AH	-	-	DesignBuilder EnergyPlus
[21]	Björling et al.	Sweden	winter, autumn	T, RH, AM	F ≤ 15 min	-	-
[22]	Hayati	Sweden	-	T, AM	-	-	IDA ICE
[23]	Wysocka	Poland	winter	T, RH	F ≤ 15 min	-	-
[24]	Mihincău et al.	Romania	summer	T, RH	-	-	-
[25]	Samek et al.	Poland	winter, year-round	T, RH, MR, AM	F ≤ 15 min	-	-
[26]	Pretlove	UK	winter	T, RH	15 min < F ≤ 1 h	-	-
[27]	Schellen et al.	Netherlands	spring, winter	T, RH, TC, MC	-	in the attic	HAMBase COMSOL Multiphysics
[28]	Vella et al.	Malta	year-round	T, RH	F ≤ 15 min	-	-
[29]	Hnilica et al.	Czechia	year-round	T, RH, DP	15 min < F ≤ 1 h	-	-
[30]	Vuerich et al.	Italy	autumn	T, RH	F ≤ 15 min	-	-
[31]	Loupa et al.	Cyprus	summer and spring	T, RH	F ≤ 15 min	-	-
[32]	Varas-Muriel et al.	Spain	year-round	T, RH, AH, DP	15 min < F ≤ 1 h	-	-
[33]	Costanzo et al.	Italy	winter, summer	T, RH, TC	F ≤ 15 min	-	-
[34]	Bernardi et al.	Bulgaria	summer	T, RH, SH, DP	F > 1 h	-	-
[35]	Frasca et al.	Poland	year-round	T, RH	F ≤ 15 min	-	-
[36]	Dorokhov and Pintelin	Russia	year-round	T, RH	F > 1 h	-	-
[37]	Kontozova-Deutsch et al.	Spain	winter, spring	T, RH	15 min < F ≤ 1 h	-	-
[38]	Iñigo et al.	Spain	year-round	T, RH	F > 1 h	-	-
[39]	Leijonhufvud and Broström	Sweden	year-round	T, RH	-	-	-
[40]	Tabunschikov and Brodatch	Russia	winter	T, RH, AM	-	near the attic/ceiling	-
[41]	Anaf and Schalm	Belgium	year-round	T, RH	F ≤ 15 min	-	-
[42]	Cannistraro and Restivo	Italy	summer	T, RH, TC	-	near the attic/ceiling	-

Table 1. *Cont.*

Ref.	Author/Authors	Country	Microclimate Monitoring				Simulation Tool
			Season	Measured Parameters	Frequency of T/RH Measurement	Attic Monitoring	
[43]	Ramírez et al.	Spain	year-round	T, RH	$F \leq 15$ min	-	-
[44]	García-Diego and Zarzo	Spain	winter and autumn	T, RH, TC, MC	$F \leq 15$ min 15 min $< F \leq 1$ h	near the attic/ceiling	-
[45]	Silva et al.	Portugal	year-round	T, RH	$F \leq 15$ min	near the attic/ceiling	-
[46]	Camuffo et al.	Italy	year-round	T, RH, TC	$F \leq 15$ min	-	-
[47]	Camuffo et al.	Italy	-	T, RH, TC, AM	$F \leq 15$ min	near the attic/ceiling	-
[49]	Bratasz et al.	Italy Poland	year-round	RH	$F \leq 15$ min	-	-
[50]	Onecha and Dotor	Spain	summer	T, RH	specific time	-	DesignBuilder EnergyPlus
[51]	Kalamees et al.	Estonia	year-round	T, RH, TC	$F \leq 15$ min 15 min $< F \leq 1$ h	-	-
[52]	Olstad et al.	Norway	year-round	T, RH	$F > 1$ h	-	-
[53]	Scheiding et al.	Germany	year-round	T, RH, TC, MC	15 min $< F \leq 1$ h	-	-
[55]	Bienvenido-Huertas et al.	Spain	year-round	T, RH	15 min $< F \leq 1$ h	-	-
[56]	Antretter et al.	Germany	year-round	T, RH	-	-	WUFI Plus
[58]	Hayati et al.	Sweden	-	T, AM	-	-	-
[59]	Kysela et al.	Slovakia	year-round	T, RH	$F \leq 15$ min	in the attic	-
[60]	Ponechal et al.	Slovakia	-	-	-	-	DesignBuilder EnergyPlus
[61]	Califano et al.	Norway	year-round	T, RH	$F \leq 15$ min	-	-
[62]	Bucur et al.	Romania	summer	T, RH	-	-	-
[63]	Napp et al.	Sweden	year-round	T, RH, MR, AM	15 min $< F \leq 1$ h	-	IDA ICE
[64]	Napp and Kalamees	Estonia	year-round	T, RH, AM	specific time	-	IDA ICE
[65]	Klenz Larsen	Denmark	year-round	T, RH	-	in the attic	-
[66]	Cardinale et al.	Italy	winter, spring	T, RH	-	-	-
[67]	Maroy et al.	Belgium	year-round	T, RH	$F \leq 15$ min	-	-
[68]	Martínez Garrido et al.	Spain	spring	T, RH, AM	$F \leq 15$ min	-	-
[69]	Varas-Muriel and Fort	Spain	year-round	T, RH, AH, DP, MR	$F \leq 15$ min	near the attic/ceiling	-
[70]	García-Diego et al.	Spain	autumn, spring	T, RH	$F \leq 15$ min	-	-
[71]	Schellen et al.	Netherlands	-	T, RH, MC	-	near the attic/ceiling	Ansys Fluent
[72]	Broström and Hansson	Estonia Latvia Sweden	year-round	T, RH	15 min $< F \leq 1$ h	-	-
[73]	Semprini et al.	Italy	autumn	T, RH	specific time	-	DesignBuilder EnergyPlus
[74]	Bonacina et al.	Italy	year-round	T, RH, TC, AM	15 min $< F \leq 1$ h	near the attic/ceiling	-
[75]	Metals et al.	Latvia	autumn, summer winter, summer	T, RH	15 min $< F \leq 1$ h	-	-

Table 1. *Cont.*

Ref.	Author/Authors	Country	Microclimate Monitoring				Simulation Tool
			Season	Measured Parameters	Frequency of T/RH Measurement	Attic Monitoring	
[76]	Aste et al.	Italy	year-round	T, RH, TC, AM	15 min < F ≤ 1 h specific time	near the attic/ceiling	-
[77]	De Rubeis et al.	Italy	autumn	T, RH	F ≤ 15 min	-	DesignBuilder EnergyPlus
[78]	Georgescu et al.	Romania	summer	T, RH, AM	-	-	-
[79]	Metals et al.	Latvia	autumn, summer summer, spring winter, spring year-round	T, RH	15 min < F ≤ 1 h F > 1 h	-	-
[80]	Sovetnikov et al.	Latvia Russia	summer, winter	T, RH, AM	specific time	near the attic/ceiling	-
[81]	Vella et al.	Malta	year-round	TR, MC	-	near the attic/ceiling	-
[82]	Varas-Muriel et al.	Spain	autumn, spring	T, RH	F ≤ 15 min	near the attic/ceiling	-
[83]	Camuffo et al.	Italy	autumn, winter	T, RH, TC	F ≤ 15 min	near the attic/ceiling	-
[84]	Ridolfi et al.	Italy	spring, autumn	T, RH	15 min < F ≤ 1 h	near the attic/ceiling	-
[85]	Lerma et al.	Spain	year-round	T, RH	15 min < F ≤ 1 h	-	Ansys Fluent
[86]	Frasca et al.	Italy	winter, spring	T, RH, MC	F ≤ 15 min	-	IDA ICE
[87]	Muñoz-González et al.	Spain	year-round	T, RH, AH, TC, TR, AM	F ≤ 15 min	-	DesignBuilder EnergyPlus
[88]	Muñoz-González et al.	Spain	year-round	T, RH, AH, DP	F ≤ 15 min	-	DesignBuilder EnergyPlus
[89]	Hudisteanu et al.	Romania	-	-	-	-	Ansys Fluent
[90]	Erhardt et al.	Germany	winter	T, RH, TC, MC	-	-	WUFI Plus
[91]	Sukhanova	Russia	-	-	-	-	Simcenter STAR-CCM+
[92]	Coelho et al.	Portugal	year-round	T, RH	F ≤ 15 min	-	WUFI Plus
[93]	Țurcanu et al.	Romania	winter, spring	T, RH	-	-	Autodesk CFD
[94]	Țurcanu et al.	Romania	winter, spring	T, RH	-	-	Autodesk CFD
[95]	Nawalany et al.	Poland	year-round	T, RH	F ≤ 15 min	-	WUFI Plus
[96]	Posani et al.	Italy	winter, autumn	T, RH	-	-	HAMBase
[97]	Sadłowska-Sałęga and Radoń	Poland	year-round	T, RH, TC	F ≤ 15 min	in the attic	WUFI Plus
[98]	Orzechowski and Tatko	Poland	year-round	T, RH	F ≤ 15 min	in the attic	-
[99]	Sola-Caraballo et al.	Spain	autumn, winter	T, RH, MC	F ≤ 15 min	in the attic	-

Explanatory notes: T—temperature; RH—relative humidity; AH—absolute humidity; SH—specific humidity; DP—dew point; MR—mixing ratio; TC—contact (surface) temperature; TR—radiation temperature; MC—moisture content; AM—air movements.

4.1. Period of Microclimate Monitoring

In our climate, there are usually four seasons. For the purpose of this review, the meteorological division of seasons has been included.

In terms of the annual cycle, the summer and winter seasons would appear to be critical. In summer, this would be due to high temperatures and low relative humidity. Conversely, it would be due to low temperatures and high relative humidity in winter. Nevertheless, based on the comparison (Figure 7), the highest number of monitoring studies included monitoring of the spring period. In winter and spring, microclimatic conditions can strongly favour condensation, which is associated with several degradation processes. On this basis, the transition between winter and spring could be considered the most interesting period for microclimate monitoring.

However, the comparison shows a high interest in measuring indoor microclimate parameters all year round. It is also worth noting that in several monitoring studies, continuous measurement of indoor microclimate parameters was carried out over a one-year or multiyear period. Therefore, an increasing interest in the long-term measurement of microclimatic conditions can be predicted.

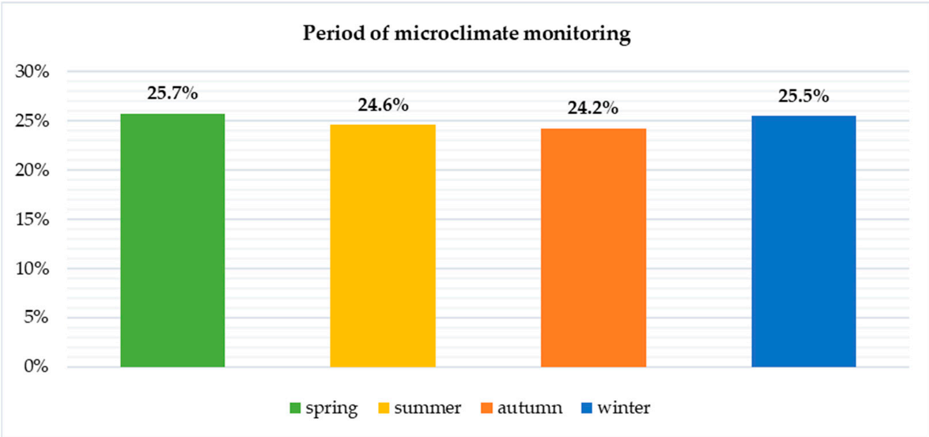

Figure 7. Comparison of the seasons in which microclimate monitoring took place.

4.2. Frequency of Temperature and Relative Humidity Measurement

In general, religious buildings with masonry walls have quite a high thermal inertia and, therefore, react slowly to temperature changes. The opposite situation occurs in the case of wooden religious buildings, which have almost zero thermal inertia. In this case, the indoor climate is often conditioned by outdoor conditions.

In the case of pitched roofs of religious buildings, the thermal inertia is somewhere between the previous cases. Although a timber roof truss structure has almost zero thermal inertia, the thermal inertia of the roof covering used must be considered, which can have a significant effect.

Therefore, the choice of the correct frequency for measuring and recording temperature and relative humidity data is substantially related to, among other factors, the thermal inertia of the building structures.

In this study, the frequencies of temperature and relative humidity measurements were divided into three time intervals. The first limit was 15 min and the second limit was 1 h. Comparisons were made separately for masonry and wooden religious buildings (Figure 8).

Because current measurement technology allows data to be measured and recorded at relatively short time intervals, such time intervals account for more than one-third of all data measurement frequencies. For this review, a short time interval is considered to be up to 15 min (inclusive). The disadvantage of such a relatively high frequency is the large number of measurements that need subsequent processing. For this reason, some monitoring studies average the measured data into larger time intervals, e.g., [31,41,45,70,86].

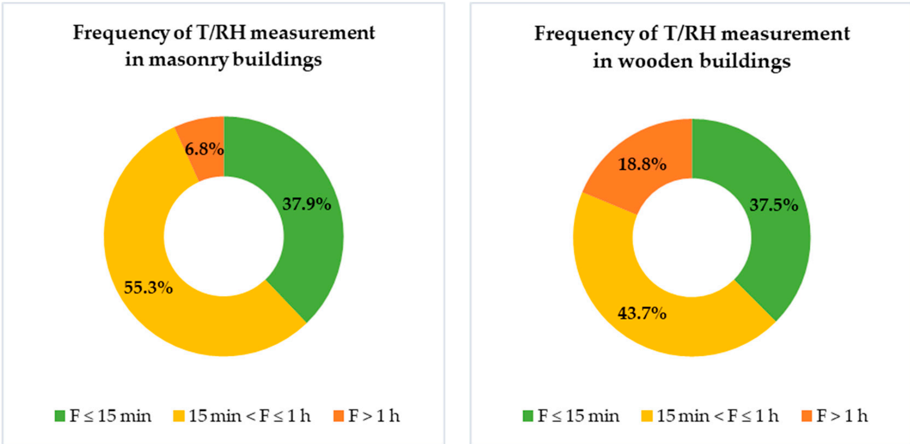

Figure 8. Comparison of the frequency of temperature (T) and relative humidity (RH) measurements in masonry and wooden religious buildings.

To capture the minimum and maximum values within a daily cycle of measurements, it is preferable to measure data within 1 h, which is confirmed by processed comparisons, e.g., [32,37,44,72,84].

When measuring data with a frequency of 1 h or more, the possibility of capturing the minimum and maximum values in a daily cycle is lost. Some of the monitored indoor microclimate parameters may change their values significantly at longer or shorter intervals. It is, therefore, essential to take these into account. In most cases, however, such frequency was implemented in facilities where the data were manually recorded by one of the authorised persons, e.g., [34,36,38,52,79].

5. Conclusions

There is a serious reason to give more attention to the indoor climate of historical buildings—the indoor climate determines the longevity of these old buildings. From the literature review, it was possible to trace a strong connection, for example, between cultural heritage and microclimate, or between thermal comfort and church. Although nothing can be changed on the facade of historical buildings, because they are protected as valuable monuments, their internal operation has recently undergone significant changes. Many researchers are investigating the impact of these changes, and their motivations can be divided into several large groups.

The largest group is concerned with the impact of heating on improving comfort, which was not the case in historical buildings in the past. They demonstrate the evident negative effect of heating on buildings as well as on cultural monuments in their interior. This is especially apparent for hot-air heating, which dries the air too much. Only rarely is heating evaluated as beneficial from the point of view of cultural heritage protection, and that is with light, uninterrupted heating. Many researchers agree that changes in relative humidity have a worse impact than temperature changes. Tolerated relative humidity fluctuations are individual for each building, mainly due to its geographical location. In more northern countries, humidity fluctuations can be greater than in southern ones. This is the reason why a map that divides Europe into four climate zones was created.

Many monitoring studies across Europe have recorded sudden changes in relative humidity due to increased occupancy. Probably because church operations are year-round, monitoring studies are evenly distributed throughout the year. It is impossible to find a period that is most preferred. Cultural heritage is threatened by biotic attacks, moulds and fungi, which arise under certain suitable microclimatic conditions (mainly at the beginning and end of winter). This problem can be partially solved by an intelligent ventilation system. In particular, computer simulations calibrated using monitoring studies would be particularly helpful. The simulation technique is still being improved, but without relevant inputs, it will not be sufficiently accurate. Therefore, most monitoring studies chose an enrolment time step of less than 1 h. More than a third of the studies (37.5% resp. 37.9%) even chose a time step shorter than 15 min. Airflow calculation (CFD) programs predominate in measurement-calibrated simulations, but moisture calculation programs have also been found. High expectations are placed on software that would address not only airflow but also air relative humidity.

A promising strategy for indoor microclimate monitoring is the possibility of continuous data collection with remote transmission. There are several interesting products on the market that can be used for this purpose [100].

What is still missing and less addressed is the monitoring of attic spaces. In most cases, the main space is addressed, and the roof space is declared as subordinate. This is confirmed by the fact that out of 82 studies, the microclimate in attic space was measured in only 7 cases.

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