MICROCLIMATIC CHALLENGES IN THE CONSERVATION OF WOODEN SACRAL MONUMENTS OF CULTURAL HERITAGE: A CASE STUDY OF A WOODEN CHURCH IN RĂSTOLȚU DEȘERT (ROMANIA)

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Abstract
The study aims to investigate the impact of the internal microclimate factors of wooden sacral buildings on the quality of their visitors' experience, using the example of protected cultural heritage objects of local significance, with higher

conservation requirements. The topic of the study is a relevant contribution to the ongoing debate on the sustainable conservation of tangible cultural heritage, especially in the context of polycrisis, particularly climate challenges and the increasing demands of their visitors for an authentic tourist experience. Using the example of a protected wooden religious building from Romania, it highlights the close link between the physical protection of monuments, the health of visitors and the quality of their experience. The research was conducted over a period of one year (February 2024 - February 2025) through continuous measurement of indoor environmental parameters (temperature, relative humidity, CO_2, PM2.5, PM10, VOCs, formaldehyde, lighting and noise) in the cultural monument under study. A second set of primary data, obtained from a parallel survey conducted on a sample of 90 cultural heritage monument visitors, was also examined. The survey focused on the respondents' perception of indoor air quality and its impacts on their health. Generalized regression analysis was used to test the relationship between the indoor environment of the monument and the symptoms described by respondents. The study revealed significant deviations from international standards of protection. Indoor temperatures varied from -6.4 °C to 29 °C, with an average relative humidity of 70.83 %, which favoured the growth of micro-organisms. CO_2 and dust particle levels were highest during religious ceremonies and correlated with discomfort (dry throat, sneezing, stuffy nose). Statistical analysis confirmed that individual characteristics such as medication use and exposure to pollution influenced these symptoms. Visitors most frequently identified dry and stale air as negative factors but they appreciated the authentic atmosphere of the temple. The study provides a unique data-driven perspective on the complex relationship between conservation conditions and the authenticity of the visitor experience at vulnerable cultural sites. It highlights the importance of microclimatic monitoring in preventive conservation and promotes the use of adaptive technologies to preserve heritage while ensuring the health and comfort of visitors. The results can support practitioners in finding a balance between physical protection and meaningful public access to heritage sites.

Keywords
Tourism, cultural heritage, authenticity, cultural heritage conservation, cultural heritage degradation.

INTRODUCTION

Cultural heritage conservation is an essential part of protecting the cultural identity of the place it represents - from the national and regional to the local level. It is a source of national pride but also a basic differentiating feature used in national branding (Matlovicova, 2024; Matlovicova et al. 2016). Thus, the protection of cultural heritage is also pragmatically motivated as a potential source of income generated by tourism and related sectors, or in a broader context, as a tool for the socio-economic development of regions (localities) and indirectly contributes to improving the quality of life of local communities.

Cultural heritage monuments are one of the pillars of tourism development in most tourist destinations. Their potential to attract tourists is developed within the framework of numerous variations of cultural tourism, the basis of which are not only tangible but also have intangible cultural value (Matlovicova et al., 2014; 2015). In some studies, this form of tourism is also referred to as cultural heritage tourism (Matlovicova et al., 2015, 135). In this case, it is based on all manifestations of culture as a whole, both tangible and intangible results of human activities, which are collected, preserved, conserved or evaluated and passed on to the next generations (Matlovicova et al., 2015; 2016). Thus, the conservation of cultural heritage sites represents one of the key challenges in the field of heritage conservation and sustainable tourism development (Sumarmi et al., 2021).

This study focuses on one element of cultural heritage, represented by the monuments of material culture bequeathed to us by previous generations, specifically wooden sacral objects of high cultural and social value, which are subject to protection. Therefore, this study aims to investigate the influence of the factors of the internal microclimate of wooden sacral buildings on the quality of the experience of their visitors, using the example of protected cultural heritage objects of local significance with high conservation requirements. The findings of the research will be used in a broader context to optimise the management of the conservation of historically valuable objects to minimise the risk of deterioration of the monuments and at the same time, promote their active integration into the tourist offer.

In the context of the current socio-economic changes we face, which are strongly influenced by the consequences of the polycrisis, the sustainable conservation of cultural monuments is a significant challenge. It requires a transdisciplinary approach that takes into account the full range of possible impacts on the objects of conservation. The synergistic effects of the interaction of numerous crises (not only environmental but also economic, social and political) make the management of cultural heritage at all levels much more difficult than ever before (see Matlovic and Matlovicova, 2024). This is a very challenging task because any intervention in the historical structure of a monument should take into account not only its physical protection but also the preservation of the authenticity of the experience that this protected object conveys. Authenticity is not only a matter of preserving original materials and techniques but also preserving the atmosphere and feelings associated with the monument. Sustainable conservation of cultural heritage therefore requires the involvement of a wide range of actors—local communities, public institutions, private sector actors and professionals in the fields of conservation, tourism and regional development (Boros et al., 2024; Herman et al., 2020, 2022; Matlovicova, 2008).

CULTURAL HERITAGE CONTEXTUALISATION

The definition of cultural heritage has been the subject of extensive debate for decades. According to Muñoz-Viñas (2023, p. 131), the initial perception of cultural heritage reflected its material—the physical nature of objects of exceptional historical or artistic value. As the author further states, it is only later that a nonaxiological discourse emerged that included the tangible objects of protection as well as the intangible elements of cultures.

According to Ashworth (2012, pp. 4-11), the evolution of views on the content of heritage has been formed successively in three distinct stages: Stage 1 in which conservation and the development of relics of the past are considered contradictorily. "*Development is thus seen as the antagonist in the process of preserving relics of the past for the future. Any attempt to compromise with the paradigm of preservation of the past leads to undermining preservation or underdevelopment. Thus, in this case, the goal of 'save by developing' is ruled out"* (Ashworth, 2012, pp. 4-11), Stage 2 in which adaptive reuse of relics of the past is also accepted, and finally, Stage 3 in which, according to Ashworth (2012), objects of conservation are seen as a transmissive means of historically contributing to many current social, political and economic needs, where selected relics of the past, events or parts of history are presented in the present (Ashworth, 2012, pp. 4-11). Thus, paradoxically, according to Ashworth (2012), the main goal is not so much the preservation of something from the past but the use of the past for present purposes as a determinant of the generation of further resources. In this case, heritage is approached as a product, using sophisticated strategies to increase the 'sale' of heritage—heritage marketing (Matlovicova, Husarova, 2017; 2024).

In the current discourse on the theoretical frameworks of the concept, there is also an approach that blurs the boundaries outlined above by considering everything natural and cultural that currently exists as heritage. However, as Muñoz-Viñas (2023, p. 131) notes, such an approach, which is considerably vague from the perspective of theoretical clarification, can lead directly to some forms of panheritage or even theoretical nihilism.

Conversely, setting boundaries from the perspective of the significant impact of the objects of conservation has been the subject of extensive debate, leading in 1972 to the World Heritage Convention (UNESCO, 2016). The document states that there are exceptional places in the world that deserve special protection to preserve them for future generations for as long as possible. In terms of management for the conservation of World Heritage (not only), the role of local communities is specifically highlighted, for which the Convention (UNESCO, 2016) serves *"as a means to address issues related to climate change, rapid urbanization, mass tourism, sustainable socio-economic development, natural disasters or other contemporary challenges"*.

In this context, drawing on the work of Ashworth (1997; 2012), natural and cultural heritage can be seen as a process through which objects, events, places, practices, personalities and their interpretations *„derived from the past are transformed into experiences in and for the present*" (Ashworth 1997; 2012, p. 2, 3). Heritage represents a deliberate and intentional product of contemporary political, social, or economic exigencies. (Ashworth, 2012, p. 2, 3). Defined in this way, heritage must be understood from the outset not only as an approach that was, but that is, a means for understanding the past in the present (Ashworth, 1997).

Heritage, therefore, needs to be seen contextually and, according to Ashworth and Graham (2005), in the plural, that is to say, bearing in mind multiple possible pasts or cultural and natural heritages concerning a given object. Consequently, this implies a diversity of possibilities for the use and creation of marketing products based on a multiplicity of heritage producers—both public and private, official but also unofficial, own and foreign (in the sense of origin; Ashworth & Graham, 2005). Satisfying them in terms of achieving the intended goals is a major challenge as they are usually quite different. Therefore, often most of the effort in the planning process is devoted to trying to reconcile different ideas about heritage management.

From the perspective of the management of tangible cultural heritage, which is the focus of this study, we are dealing with practices that lead to extending the life of conservation objects for as long as possible.

CONSERVATION OF CULTURAL HERITAGE OBJECTS AND AUTHENTICITY

The conservation of cultural heritage is understood as an active cultural intervention, often also requiring ″sophisticated techniques and skills to modify the objects of conservation so that they can better perform their assigned function″ (Muñoz-Viñas, 2020, p. 7), making them more active from a tourism perspective and thus better able to fulfil an informative and educational function. The protection and conservation of heritage is referred to as a social duty that is meaningful even though every physically existing object has a finite lifespan and will one day succumb to time (Muñoz-Viñas, 2023). Conservation, in the sense of Muñoz-Viñas (2023), is thus understood as a quintessence—a necessary practice that is inherent in the very notion of heritage.

In terms of the focus of our research, numerous studies have been carried out to investigate the impact of external factors on the degradation of heritage objects. For example, Nawalany et al. (2020) and Nawalany et al. (2021) conducted research on the temperature and humidity conditions in a wooden church in southern Poland, and the research results indicated that the temperature and humidity values systematically exceeded the values allowed for historical buildings, and during the use of wooden churches, the number of people in the church influences the oscillations of internal parameters. Regarding the mechanical risk created by the climate, the temperature and relative humidity standards in stave churches in Norway were investigated (Califano et al., 2022). Haisheng Hu analyzed the impact of climatic and meteorological conditions on wooden churches in the vicinity of Krakow, Poland (Hu, 2024). In Latvia, two wooden churches were included in a study, where temperature and humidity behaviour were analyzed and the conservation limits of the microclimate parameters of the indoor air were highlighted (Metals et al., 2024). In wooden churches in Sweden, the risks of deterioration caused by fluctuations in microclimate parameters were assessed for painted wooden surfaces (Califano et al., 2024). Other similarly focused research includes several studies on the topic of indoor microclimate in wooden churches. The air quality in a wooden church in Bucharest was analyzed and interpreted, sampling atmospheric pollutants and microclimatic factors of temperature and relative humidity, to help with preventive conservation (Bucur et al., 2015). The microclimate and its impact were investigated in different environments (Cicort-Lucaciu et al., 2011) indoors in a wooden church and from the point of view of microclimatic and microbiological parameters (Ilies et al., 2018; Ilies et al., 2022). The particularities of the indoor microclimate in three wooden churches in the city of Oradea were highlighted. The analysis and interpretation of the data revealed that the indoor microclimate was not optimal and posed a potential risk to the structure of the building and human health (Mihincau et al., 2019a, 2019b; Ilies et al., 2020). Onet et al. (2020) analyzed the indoor microclimate in a wooden church in terms of temperature, relative humidity, carbon dioxide, and microbiologically. The indoor microclimate of a wooden church in Oradea was investigated for the preservation of textiles, highlighting the importance of microclimatic parameters (Ioan et al., 2020). The wooden church in Boianu Mare was analyzed from a microclimatic point of view. The fungal load of the air and surfaces highlighted the need to preserve the wooden church, and the indoor microclimate posed a potential risk to human health (Marcu et al., 2021).

A question that arises in the context of efforts to conserve cultural heritage objects that are more susceptible to degradation is whether the measures taken to protect them could reduce the level of their authenticity and thereby reduce the quality of the visitor experience.

Some research (e.g. Dai, Zheng & Yan, 2021; Ibbetson, 2000; Gregorini et al., 2019; Fernandes, 2004) shows that proper awareness is key in this regard. In other words, if visitors were sufficiently informed about the significance and cultural and social value of the site they are visiting, they would be willing to endure a higher level of discomfort as a price for the authenticity of the experience. Of course, in this respect, it should be noted that there will always be a group of visitors, and also local residents, who will not perceive the restrictions positively. However, in this regard, it is necessary to search for a compromise that will guarantee the protection of valuable cultural heritage while also allowing for socio-economic development in the area of their location (Chheda et al., 2024; Qi, 2023; Bunu et al., 2021). For example, Samah et al. (2021) underscore the importance of modern technologies, which in many ways provide opportunities not only for the protection of valuable heritage sites but at the same time new ways to enhance the tourist experience (e.g. the use of virtual reality). Although many studies point out that the substitution or augmentation of reality using modern technologies (e.g. immersive virtual reality) cannot replace the authentic experience, it is nevertheless in many respects a suitable (often the only) alternative to enable the development of tourism in sites or objects of high cultural and social value, extremely degradable, or extremely sensitive to external influences, or that are currently showing a high degree of deterioration. On the other hand, modern technologies also bring new possibilities to enhance the quality of the experience (e.g. augmented virtual reality). This is confirmed by numerous studies conducted during the recent COVID-19 pandemic, which showed high levels of visitor satisfaction with virtual experiences (e.g. Alkhaliel, 2022). This is because new digital technologies have been shown to increase the accessibility of information and the acquisition of new knowledge and experiences in an interactive way that the analogue world does not allow. Thus, taking into account all the above-mentioned attributes of cultural heritage protection requires an extremely sensitive approach to setting tourism development plans.

AIM AND OBJECTIVES

The study aims to investigate the impact of the internal microclimate factors of wooden sacral buildings on the quality of the experience of their visitors, using the example of protected cultural heritage object of local significance, with higher conservation requirements.

The object of the research is to examine the risk factors increasing the degradation of the object of conservation over a period of one year. The objects of measurement were: temperature fluctuations, relative humidity, CO_2, volatile organic compounds, PM2.5 and PM10 particles, formaldehyde, natural and artificial light during the mentioned period, which accelerate the degradation of wooden buildings. The above measurements will then be evaluated in relation to their impacts on the overall visitor experience of such buildings. Finally, possible conservation measures for wooden religious heritage buildings will be discussed with regard to the balance in setting appropriate conditions of the indoor microclimate between measures to ensure slowing down the degradation processes of the monument and the quality of the experience of its visitors. In other words, that conservation measures do not lead to limitations in the use of the heritage object and to a reduction in the authenticity of the internal environment.

The object of research is a wooden sacral building—the wooden Church of the Assumption of the Virgin Mary in Răstolțu Deșert (Romania; Figures 1 & 2). The heritage object under research represents an authentic part of the culture of the local community. It is not only used by the local community as an important local centre of social life but also serves visitors who regularly attend local sacred and secular events. The church dates from the early 19th century (Ministry of Culture, 2015). Notable for its high tower, it was built on a rectangular plan with a detached, polygonal apse with five sides (Godea et al., 1978). The church was small and in

1846, to enlarge it, a bay was added to the nave and the altar was moved to the east (Godea et al., 1978; Măruțoiu et al., 2017). On the south side, the nave was closed, creating the deaconry (Godea et al., 1978; Măruțoiu et al., 2017). The painting dates from 1810 and, according to Măruțoiu, was made by Ioan Pop from Românași, where we find the Passion of Christ, the Last Supper, St. Elijah with the Chariot, the Parable of the 10 Virgins and Figures of Myrrh-bearers (Godea et al., 1978: Măruțoiu et al., 2017). The Church of the Assumption of the Virgin Mary in Răstolțu Deșert (Romania) was, and still is, at the centre of several restoration actions. The ARHAIC-Ambulance for Monuments Sălaj Association replaced the church's sheet metal roof with shingles (Monumentum Association, 2020). The Sălaj County Council contributed to the consolidation of the stone foundation, the replacement of the flooring, and the conservation and restoration of the interior painting (Monitorul de Sălaj, 2023).

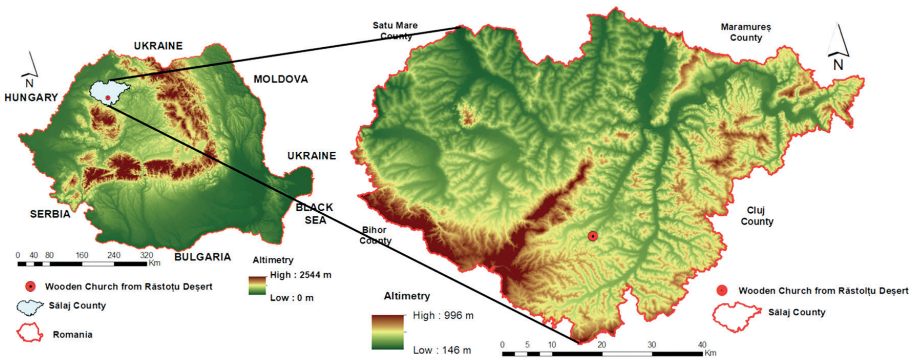

Fig. 1 The location of the wooden church in Răstolțu Deșert at the level of Romania and Sălaj county

Fig. 2 The wooden church is a historical monument in the locality of Răstolțu Deșert

DATA AND METHODS

The research was based on two types of datasets obtained through primary research. The first dataset was obtained from extensive measurements of the indoor microclimate characteristics in the protected wooden heritage structure, which lasted for one year, from 12 February 2024 to 11 February 2025. The time scale of the measurements was determined considering the macro-geographical location of the studied site in the temperate climate zone so that the measurements covered all four seasons of the year. The subjects monitored were the values and maximum annual amplitudes of the monitored indicators, which are considered to be significant determinants of the degradation of vulnerable wooden objects of cultural heritage.

Table 1 Specification of the measuring equipment used

Sensor model	Determined indicators	Precision
CO_2 air quality data logger BZ30	Temperature, RH, CO_2	±1 °C (temperature), ±5% (RH), ±75 ppm / (CO_2)
BL30 climate data logger	Temperature, RH	±1 °C (temperature), ±3% (RH)
CEM DT-96 mini particle counter $PM_{2.5}$, PM_{10}	Temperature, RH, $PM_{2,5}$, PM_{10}	±1 °C (temperature), ±5% (RH), up to ± 5% ($PM_{2,5}$, PM_{10})
CEM DT-93 Formaldehyde and Total Volatile Organic Compounds HCHO/TVOC Detector	HCHO, TVOC	±2% (VOC), ±2% (HCHO)
Split type lux meter GM1030	Temperature, Natural light LUX	±1 °C (temperature) step X1 - ±3%rg +5digits step X10 - ±3%rg +10digits stepX100 - ±4%rg +10digits gearing X1000 - ±4%rg+10digits
Sound level meter SL400	Sound level	IEC 61672-1 class 2, ANSI S1.4 type 2

Source: Trotec (2024); CEM (2024); Benetech (2024)

Monitoring of indoor microclimate indicators of the wooden religious structure was carried out at different times of the day, depending on their nature (Ilies et al., 2022). Temperature, humidity and carbon dioxide were automatically monitored at an interval of 60 minutes, over a period of one year, using a BZ30 CO_2 air quality data logger sensor (Temperature, RH, CO_2) and two BL30 climate data loggers (Temperature, RH). The accuracy of the sensors is indicated in Table 1. The sensors were positioned to cover the area of the church interior maximally, one BL 30 climate data logger sensor in the narthex and altar, and one BZ30 CO_2 air quality data logger sensor in the nave. The sensors were positioned at a height of 1.5m

(Fig. 3). Particulate matter (PM2.5, PM10), total volatile organic compounds (VOC), formaldehyde (HCHO) and natural light (NL) were recorded three times a day, in the morning (07:30), at noon (12:00) and in the evening (19:30), using 23 collection points (6 points in the pronaos, 12 in the nave and 5 in the altar; Fig. 3), covering the maximum area inside the wooden church. Sound level monitoring was done weekly, for two hours during services and a further three hours per week according to a specified schedule.

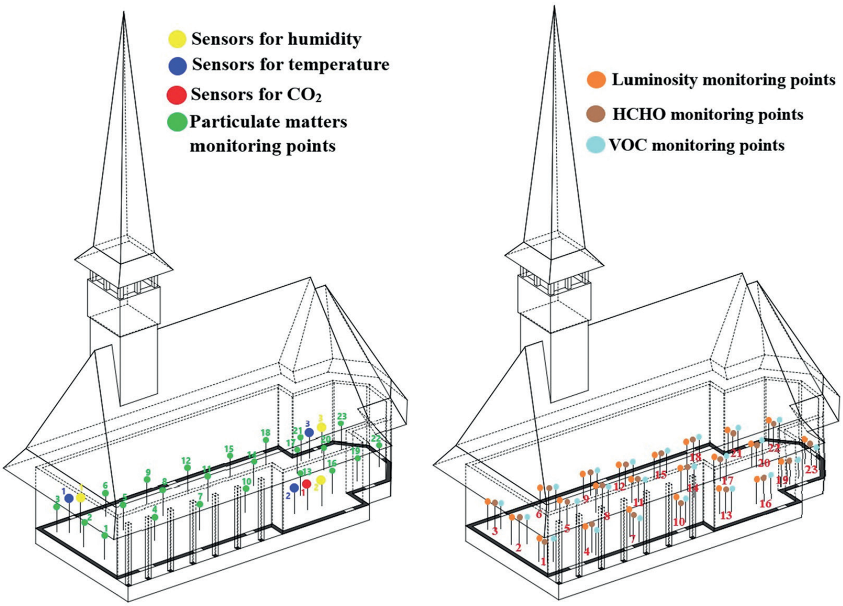

Fig. 3 Spatial distribution of sensors and data collection points

Undue values of the indicators as well as their high fluctuations contribute to the undesirable spread of fungal and bacterial micro-organisms, which not only directly damage the protected structures, but also contribute to an increased level of discomfort of visitors and, in extreme cases, cause damage to their health. For this reason, the above measurements were supplemented by a survey of visitors' perceptions of indoor air quality in the church. The survey was conducted between 01 August 2024 and 15 September 2024 on a sample of 90 respondents, who were visitors to the wooden Church of the Assumption of the Virgin Mary in Răstolțu Deșert (Romania). These were semi-structured interviews based on 31 questions divided into two thematic areas:

(a) perception of disturbances in the space of the object of study,
(b) identification of potential clinical symptoms - adverse reactions of the organism to the indoor air of the object.

Both sets of questions pertained to the activities carried out during the visit to the wooden structure under study, independent predictors of sensitivity to interior disturbances determined by daily activities in the space outside the object under study, as well as independent predictors of symptoms triggered by the visit into the interior of the object of study (both sets of characteristics are described in detail in Table 2) and finally, in relation to other identifying personal characteristics of the respondents (description below).

The demographics of the sample were as follows. 46.7% of respondents were younger than 30 years of age, 10% were between 30-45 years of age, 25.6% were between 45-60 years of age, and 27.8% were 60 years and older. Women accounted for 55.6% of the sample (of which 2% were pregnant). Regarding education, the sample was dominated by respondents with secondary (high school) education (53.3%), 35.6% had primary education and 11.1% had higher (university) education. 45.6% of respondents were of working age and employed, 22.2% were retired, and 11.2% comprised housewives. The independent predictors of sensitivity to the disturbing elements of the interior of the object under study were 14.4% of respondents were smokers, 5.6% wore contact lenses, 47.8% took medication regularly, and 24.4% had diagnosed chronic health problems or allergies.

Table 2 Independent predictors of respondents' sensitivity to indoor air quality

		%
How far do you live from this space?	Less than 1 km	52.2
	6-10 km	42.2
	More than 20 km	5.6
What is the main mode of transportation to this space?	On foot	36.7
	Bicycle	20.0
	Personal car	12.2
	Public transport (bus, train)	3.3
	By car, motorcycle	27.8
On average, how long does the trip take one way to this space?	Less than 15 minutes	64.4
	31-60 minutes	35.6
On the way, pass through the zones which could affect air quality?	Heavy vehicle traffic	4.4
	Sites under construction	1.1
	Agricultural areas	32.2
	None of the abovementioned	62.2
What is the main reason for the exposure to potential air quality risks?	Work	21.1
	Educational	6.7
	Recreational activities	8.9
	Home	63.3

		%
How often do you experience poor air quality during your commute?	Never	17.8
	Rarely	44.4
	Sometimes	34.4
	Often	3.3
Which of the following best describes the area you live in?	City centre	1.1
	Rural	95.6
	Mixed	3.3
In your daily life outside this space, how often are you exposed to polluting chemical products?	Never	33.3
	Rarely (less than once a month)	37.8
	Occasionally (1-3 times a month)	23.3
	Frequently (1-3 times a week)	4.4
	Daily	1.1
How often are you exposed to extreme temperatures in your daily activities?	Never	12.2
	Rarely (less than once a month)	41.1
	Occasionally (1-3 times a month)	37.8
	Frequently (1-3 times a week)	8.9
What is the level of exposure to noise during your daily activity?	Low (quiet environment)	36.7
	Low (occasionally)	30.0
	Moderate (ordinary urban noise)	31.1
	High (high intensity noise)	2.2
Which of the following health risks are you most frequently exposed to in your daily life?	Chemical products	18.9
	Extreme temperatures	13.3
	Loud noise	2.2
	Work at night	1.1
	Alternative changes	24.4
	Repetitive work	40.0
How would you rate your overall daily exposure to health risks outside of this space?	Very small	16.7
	Small	33.3
	Moderate	48.9
	Great	1.1

Relevant to the objectives of the study, the following hypotheses were statistically tested in the second phase of the research:

$H1_0$: There is no association between participants' individual characteristics and the number of bothering environmental factors reported within the space.

$H1_1$: There is a significant association between one or more of the participants' individual characteristics and the number of bothering environmental factors reported.

$H2_0$: There is no association between participants' characteristics and the number of symptoms experienced inside the church.

$H2_1$: There is a statistically significant association between one or more of the participants' characteristics and the number of symptoms experienced.

To test the above hypotheses, we used generalized linear regression analysis, and RStudio software (R version 4.3.1) was used to create the regression model. Independent predictors of bothering factors and symptom counts were identified through backward stepwise multivariable generalized linear modelling. A significance level of $p < 0.05$ was used for all statistical tests.

RESULTS AND DISCUSSION

Indoor microclimate and its influence on the protected wooden church

For optimal preservation of the historical monument and the comfort of the people working or using the monument, the parameters of the indoor microclimate should not fluctuate greatly. They should be maintained according to the international ASHRAE standard (ASHRAE Handbook–HVAC Applications, 2011), at an average temperature of 20°C (±1°C –2°C), and for a relative humidity of 50% (±3%).

Because the wooden church did not have a heating and ventilation system, and some windows were damaged, the internal microclimate was closely conditioned by the external climate. The average temperature value during the study period was 11.67°C and did not correspond with the international ASHRAE standard. The thermal amplitude of the internal climate was large, with a value of 35.4°C. The maximum temperature value of 29°C was recorded on July 14, 2024, at 18:49, and the minimum value of –6.4°C was recorded on two days in different months. The first recording was on January 16, 2025 at 07:21 and the second recording was on February 11, 2025 at 08:21.

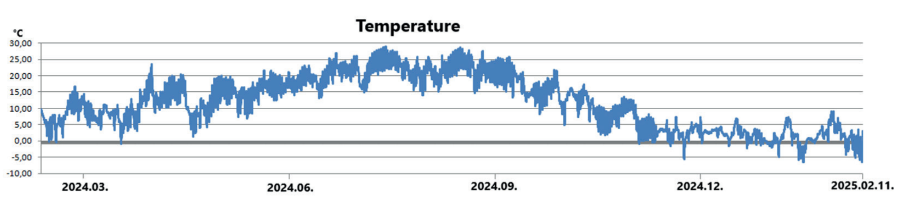

Fig. 4 Indoor temperature fluctuations (°C) from February 12, 2024 to February 11, 2025

The relative humidity inside the church had high values and presented an average value, during the study period, of 70.83%, with a maximum value of 89.20% recorded on December 10, 2024 at 2:52 PM and a minimum value of 30.10% recorded on September 8, 2024, at 7:19 PM.

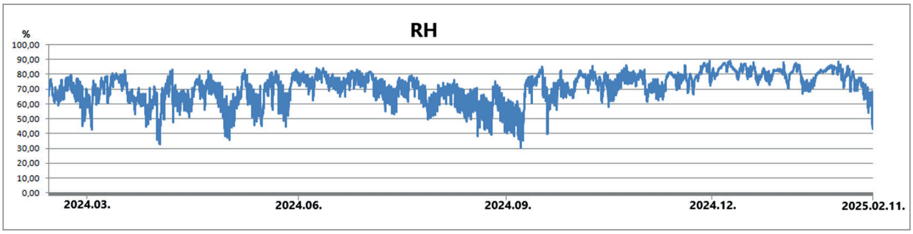

Fig. 5 Indoor humidity fluctuations (%) from February 12, 2024 to February 11, 2025

The temperature and relative humidity values were not within the optimal values and hence the microclimate inside the church was not optimal for human health and for the preservation of the objects inside; in fact, the high humidity favoured the appearance of fungal colonies (Dannemiller et al., 2018), which will be detailed in a future study. Preliminary results regarding the load of cultivable fungi, obtained by the Koch sedimentation method, indicated the indoor air contamination values ranged from medium (157.18 ± 1 colony-forming units CFU/m^3) to very high (1047.89 ± 13.33 CFU/m^3). The most frequently isolated genera were *Alternaria, Actinomucor, Penicillium, Epicoccum, Coniochaeta, Aureobasisdium, Didymella, Aspergillus* and *Cladosporium*. Except for the genus *Actinomucor*, all others have been mentioned in other studies on wooden churches or are known to degrade wood and plant cell walls (Lopez et al., 2007; Isola et al., 2024; Radu et al., 2020; Horvath et al., 1976). *Actinomucor* can usually be found in soil, with soil-dwelling genera often reported in indoor air due to their relocation from the external environment (Khan & Karuppayil, 2012).

The interior microclimate of the church was conditioned by the exterior microclimate. The periods with the maximum and minimum values of the interior temperature align with the periods of the exterior climate, and the closeness between the average temperature values during the study period can be noted—interior 11.67° and exterior 11.8°C. In terms of the relative humidity, the average value inside the wooden church (70.83%) was influenced by the exterior climate (72.44%), and the close average values of the relative humidity are notable. During the study period, the average value of the CO2 concentration was 429.18 ppm, with a maximum value of 1103 ppm recorded on August 8, 2024, at 8:00 PM and corresponding to the time of the religious service for the church's patron saint. The minimum value was 384 recorded on November 22, 2024, at 10:53 AM. The CO2 concentration values mostly varied between 400-500 ppm, while periods with values higher than 1100 ppm were recorded during religious services, due to the large number of parishioners and the oppressive air. The access path (door) remained open, influencing the value of the CO2 concentration, and contributing to the reduction of the values.

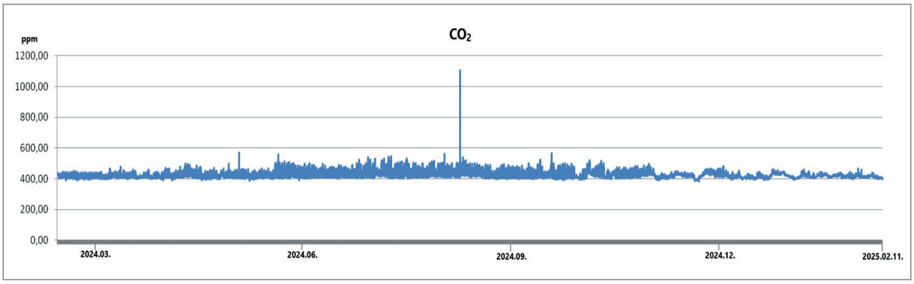

Fig. 6 Indoor CO_2 fluctuations (ppm) from February 12, 2024 to February 11, 2025

The analysis of the CO_2 concentration in the monitored wooden church fell within the standards of the ASHRAE position document on indoor carbon dioxide, American Society of Heating and ANSI/ASHRAE Standard 62.1-2010, Ventilation for acceptable indoor air quality, which provides for a concentration < 1000 ppm.

The PM2.5 concentration values fluctuated inside the church, ranging from the lowest at 0.00 μg/m^3, with the maximum reaching as high as 24.00 μg/m^3. The higher values occurred in the more closed spaces. During various activities in the church, the PM2.5 level increased due to the existing carpets and textiles, as well as the presence of dust that accumulated inside and penetrated from the outside through the damaged and degraded windows. As can be seen in Figure 7a, in the spatial distribution of the average PM2.5 values, higher values were found in the narthex (at the entrance to the church) and in the altar, and the lowest values were in the nave.

For PM10, the values fluctuated within the church, ranging from lows of 0.00 μg/m^3 to highs of 29.00 μg/m^3. The spatial distribution of PM10 followed the PM2.5 pattern, with higher values in the narthex and altar, and lower values in the nave. PM10 concentration values were influenced by textiles, damaged windows and reduced dust removal.

VOC concentrations fluctuated within the church between a minimum value of 0.47 mg/m^3 and a maximum value of 3.20 mg/m^3. The spatial distribution of VOC, as seen in Figure 7c, had higher values in the narthex and altar, and lower in the nave. TVOC are a group of critical pollutants. According to the World Health Organization and Directive 2000/39/EC, optimal values are at the threshold of < 1 mg/m^3.

Inside the church when there is no activity, the values remained constant at 0.01 mg/m^3, both in the narthex, nave and altar. During services, the HCHO concentration value reached the threshold of 0.05 mg/m^3. According to the United States Environmental Protection Agency, the optimal level of formaldehyde HCHO is < 0.004 mg/m^3.

The British Standards Institution dictates brightness values for both natural and artificial light of between 50-200 lux. Inside the church, natural light is influenced by the distribution of windows, as seen in Figure 7d, where we find average values of between 2 and 320 lux, with lower values in the narthex and at the joints of the structure. The extreme values of natural light were between 0 and 490 lux, influenced by the external environment, where natural light values on sunny days reached a maximum of approximately 147,000 lux. Artificial light was closely linked to the lighting fixtures, and inside the church, there were 3 lighting sources—the first in the narthex, the second in the nave (candelabra) and the last in the altar. The values of artificial light fluctuated between 20.2 and 145 lux. The highest values of artificial light were in the area close to the coverage of the lighting fixtures, as seen in Figure 7e.

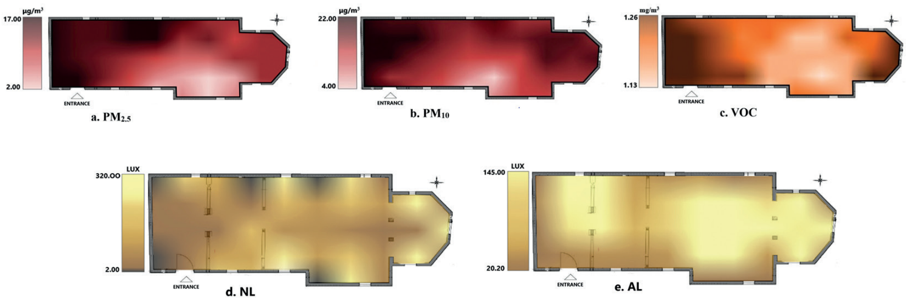

Fig. 7 Indoor average values of PM2.5, PM10, HCHO, VOC, NL and AL for each monitoring point - (a) Particulate matter PM2.5, (b) Particulate matter PM10, (c) Volatile organic compounds VOC, (d) Natural light, (e) Artificial light

The two main indicators of indoor microclimate, temperature and relative humidity, influence PM concentrations and human health (Jo et al., 2017; Zuo et al., 2021). Simultaneously, temperature and relative humidity increase the amount of PM2.5 and PM10, which increase the risk of respiratory and cardiovascular problems in the human body (Hernandez et al., 2017). Some studies associate the occurrence of lung cancer and cardiovascular diseases with long-term exposure to PM10 (Saini et al., 2021). High values of relative humidity can increase the risk of mould development, which poses a risk to human health (Freitas et al., 2010; Caciora et al., 2024).

The level of acoustic intensity is important because as the decibel level increases, the noise is more difficult to tolerate and exposure to high sound intensity can have negative consequences on the human body such as sound fatigue, headaches, increased pulse, anxiety, stress attacks, hypertension and digestive diseases (Mureşan, 2022; Roșca, 2023). Within the church, the levels of acoustic intensity had acceptable thresholds when religious services were not being held with average values between 35-40 dBA, but during religious services, the level of acoustic intensity increased. During the service on 08.08.2024, between 19:02:19 and 20:14:04, the acoustic intensity values had an average value of 67.44 dBA, and the values fluctuated as seen in Figure 8, with a minimum value of 35.7 dBA recorded at

19:02:19 at the beginning of the service and a maximum value of 91.4 dBA recorded at 20:07:25. Higher values may cause discomfort to the human body.

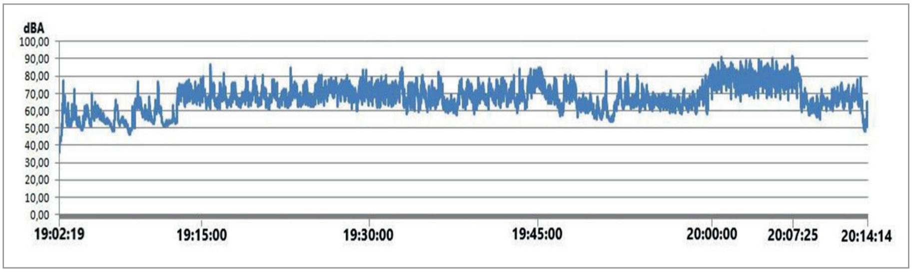

Fig. 8 Acoustic intensity level during the religious service on 08.08.2024, in the time interval 19:02:19 - 20:14:14

Visitors' perceptions of indoor air quality and its health effects

In the evaluation of factors that participants found bothersome within the space, the top three issues reported "often" or "very often" were dry air (45.5%), closed or unventilated air (36.7%), and dust (35.6%). These factors were the most frequently cited as causes of discomfort in the space. Conversely, the least reported issues included visible mould or apparent moisture (3.3%), odours from outside (6.7%), and indoor air temperatures that were too low (7.8%), indicating minimal concern regarding these factors among participants (Figure 9).

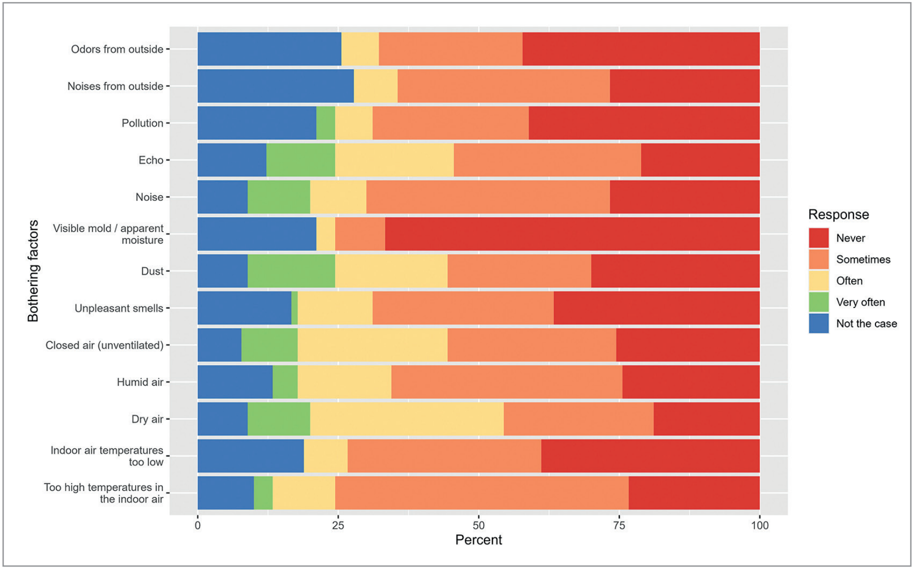

Fig. 9 The identified bothering factors in the church interior

The most frequently reported symptoms experienced "often" or "very often" were dry throat (21.1%), repeated sneezing (16.7%), and congestion of the nasal passages (14.4%). Conversely, the least reported symptoms were nausea or vomiting, dizziness or fainting, and headache and migraine.

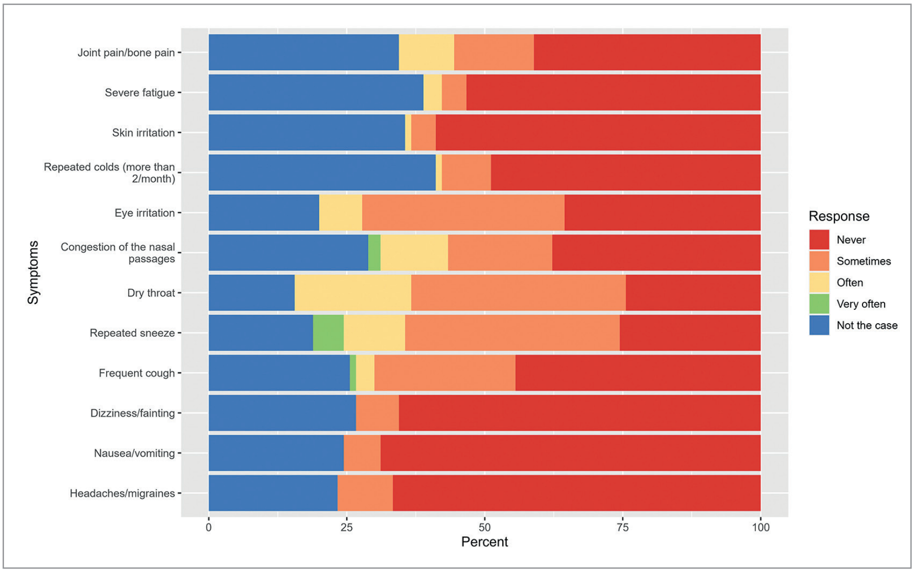

Fig. 10 The most frequently reported symptoms occurring in respondents during a visit to a church interior

Participants reported spending an average of 1.2 hours per day in the space, with religious activities being the primary reason for visitation (63.3%). The majority rated the air quality within the space as "Good" (64.4%), while a small portion rated it as "Low" (13.3%, see Figure 3). In cases where air quality issues were observed, 22.2% noted that they were most prominent at the end of activities. Most participants (72.2%) indicated that symptoms related to air quality resolved within 1-2 hours after leaving the space, and only 4.4% were aware of any complaints about the space's air quality. Among participants aware of complaints related to the space (n=4), reports of inconvenience were equally attributed to occasional visitors or users (50.0%) and individuals from the neighbourhood (50.0%). When describing the ideal environment, participants emphasized emotional and spiritual benefits, with equal mentions (25.0% each) of finding peace through prayer, experiencing a beautiful and recommended location, achieving personal peace in a relationship with God, and feeling an intensified divine presence that strengthens religious convictions (see Table 3).

Table 3 Respondents' perception of the monument space

		Smokers (%)	Taking medication regularly (%)	With chronic illness or allergies (%)	Total (%)
What is the main motive of your visit?	Religion	92.3	83.7	68.3	63.30
	Tourism and religion	0.0	7.0	9.0	25.60
	Tourism	0.0	0.0	0.0	2.20
	Rituals and traditions	0.0	4.7	13.7	4.40
	Festivals and religious holidays	7.7	2.3	4.5	2.30
	Charitable activities	0.0	2.3	4.5	1.10
	Research	0.0	0.0	0.0	1.10
In general, how do you rate the air quality in this space?	Very low	0.0	0.0	0.0	0.0
	Low	30.8	11.6	18.2	13.3
	Good	38.5	62.8	50.0	64.4
	Very good	23.1	20.9	22.7	12.2
	I don't answer	7.7	4.7	9.1	10.0
If you have noticed air quality problems in this space, when do you think they are most pronounced?	At the beginning of the activity	0.0	0.0	0.0	0.0
	During the activity	30.8	9.3	4.5	12.2
	At the end of the activity	30.8	7.0	27.3	22.2
	All the time	0.0	7.0	13.6	5.6
	Not applicable	38.5	67.4	50.0	51.1
	I don't answer	0.0	9.3	4.5	8.9
Do most of the mentioned symptoms disappear within a maximum of 1-2 hours after leaving this space?	Yes	76.9	76.7	68.2	72.2
	No	0.0	0.0	0.0	0.0
	Not the case	23.1	23.3	31.8	27.8
Are you aware of any complaints about inconvenience caused by the use of this space?	Yes, I am aware of many complaints	0.0	0.0	0.0	0.0
	Yes, I have heard of some complaints	0.0	0.0	4.5	4.4
	No, I have not heard of complaints	53.8	76.7	68.2	48.9
	I don't know	46.2	23.3	27.3	46.7
If you are aware of complaints, which group(s) reported inconvenience?	Occasional visitors/users	50.0	50.0	100.0	50.0
	Neighborhood	50.0	50.0	0.0	50.0

		Smokers (%)	Taking medication regularly (%)	With chronic illness or allergies (%)	Total (%)
The ideal environment. Can you describe this location?	A place with a great emotional charge, here you find the peace you need in your conversation with God, through the voice of prayer	0.0	33.3	33.3	25.0
	It is a beautiful location and I recommend visiting it	0.0	0.0	0.0	25.0
	It is the ideal place that gives you peace of mind in your personal relationship with God	0.0	33.3	33.3	25.0
	It is the ideal place where you feel the divine presence everywhere, your religious convictions are accentuated more strongly	100.0	33.3	33.3	25.0

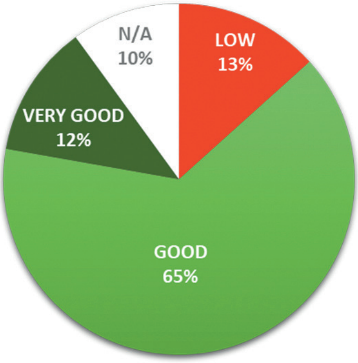

Fig. 11 Perceived indoor air quality according to respondents

Individuals without diagnosed health problems were more likely to report increased bothering factors in the space (beta = 3.54, 95% CI, 1.11 to 5.97, p = 0.005). Commute times of 31-60 minutes were also associated with increased bothering factors (beta = 3.19, 95% CI, 1.05 to 5.33, p = 0.004). Additionally, participants exposed to extreme temperatures rarely (beta = 5.22, 95% CI, 1.92 to 8.52, p = 0.003), occasionally (beta = 3.99, 95% CI, 0.66 to 7.32, p = 0.021), or frequently (beta = 6.71, 95% CI, 2.26 to 11.2, p = 0.004) in their daily activities were significantly more likely to report increased bothering factors (Table 4).

Table 4 Independent predictors of reporting increased bothering factors in the space

		Beta	95% CI	p-value
Diagnosed with health problems (chronic diseases, allergies)	Yes	Reference	Reference	
	No	3.54	1.11, 5.97	0.005
On average, how long does the trip take one way to this space?	Less than 15 minutes	Reference	Reference	
	31-60 minutes	3.19	1.05, 5.33	0.004
How often are you exposed to extreme temperatures in your daily activities?	Never	Reference	Reference	
	Rarely (less than once a month)	5.22	1.92, 8.52	0.003
	Occasionally (1-3 times a month)	3.99	0.66, 7.32	0.021
	Frequent (1-3 times a week)	6.71	2.26, 11.2	0.004

CI = Confidence Interval;
Results are based on a backward step-wise, multivariable generalized linear model

Participants not currently receiving medication reported fewer symptoms (beta = -1.70, 95% CI, -2.92 to -0.48, $p = 0.008$). Experiencing poor air quality during commutes was significantly associated with increased symptoms, particularly among those who experienced it rarely (beta = 2.58, 95% CI, 0.87 to 4.28, $p = 0.004$), sometimes (beta = 3.49, 95% CI, 1.72 to 5.26, $p < 0.001$), or often (beta = 5.36, 95% CI, 1.73 to 8.99, $p = 0.005$, Table 5). Our analysis shows that the number of symptoms reported by respondents was related to different variables. Based on the above results, the null hypothesis ($H2_0$) was rejected.

Table 5 Perceptions of air quality in relation to independent predictors of the symptoms described

		Beta	95% CI	p-value
Currently receive medication (daily/weekly/monthly)	Yes	Reference	Reference	
	No	-1.70	-2.92, -0.48	0.008
How often do you experience poor air quality during your commute?	Never	Reference	Reference	
	Rarely	2.58	0.87, 4.28	0.004
	Sometimes	3.49	1.72, 5.26	<0.001
	Often	5.36	1.73, 8.99	0.005

CI = Confidence Interval;
Results are based on a backward step-wise, multivariable generalized linear model

CONCLUSIONS

The conservation of heritage objects, including valuable wooden churches, is important because over the years, they are prone to deterioration (Ilies et al., 2018), and their physical protection is essential, due to the historical, and artistic values and artefacts in their space (Uring et al., 2020; Ginting et al., 2024). Within historical monuments, the indoor microclimate is an important factor that affects buildings and exhibits and has an influence on people's health (Horgos et al., 2023; Zaha et. al., 2023). On the other hand, parishioners or visitors to historical monuments can themselves be a source of influence on the indoor microclimate (Ferdyn-Grygierek, 2016).

The construction material plays an important role, as wood facilitates the presence of microbial loads (Stenson et al., 2019). An important role that can facilitate the appearance of pollutants is represented by the defective construction of buildings (Bungau et al., 2023). Studies have confirmed that both suspended particles and dust are extremely dangerous to human health (Kim et al., 2015; Nonthapot et al., 2024). High concentrations of formaldehyde, total volatile organic compounds, can pose a risk to people by causing nausea, and dizziness, with the potential to cause asthma and in some cases even cancer (Baroja et al., 2005).

The above conclusions were confirmed by the research presented in this study. According to the data obtained, it is concluded that the air inside the church represents a risk factor not only for the objects inside but also for human health. The temperature range recorded inside the church did not meet international standards over the one-year monitoring period, with an average of 11.69°C, having large fluctuations between a minimum of -6.4°C and a maximum of 29°C. The relative humidity in a one-year period had high values with an average of 70.83%, which poses a risk to the degradation of bio-materials in the building (including the constructional wooden parts, carpets, and textiles), and for human health. High levels of PM2.5, PM10, and VOC have occasionally been noted in different periods, influencing the indoor microclimate, which can cause respiratory and olfactory problems, irritation, fatigue and headaches. The results of the survey conducted on a sample of 90 visitors reveal that the respondents' main negative perceptions were dry air (45%), closed, unventilated air (36.7%) and dust (35.6%). The most common health symptoms exhibited in the space were dry throat (21.1%), repeated sneezing (16.7%) and nasal congestion (14.4%). Two hypotheses were tested using multivariate generalized linear models. The null hypotheses were both rejected, indicating that the characteristics of individuals influenced the perceptions of bothering factors and the experienced symptoms. This highlights the fact that the microclimatic conditions inside the church did impact the health and comfort of visitors.

Primary on-site research identified obvious significant damage to some of the interior features. The wooden church has some damaged windows, a result of the internal microclimate parameters which are influenced by the external climate. The devices needed to be connected to the power supply at all times and during periods of power outages, external batteries were used. To reduce airborne particulate matter and the degradability of the interior wood elements, as well as to reduce the risk of health damage and increase the comfort of visitors, we recommend the installation of an HVAC system and the use of air filters throughout the interior of the protected building. Cleaning is recommended to eliminate dust, which supports the development of microorganisms together with high humidity. For cold weather, the installation of a heating system is advisable. The removal of carpets, textiles, and rugs, which harbour dust, will assist in reducing this factor.

Future studies are required to complete the research with further monitoring of other pollutants such as O_2, O_3, SO_2, CH_4, NO, NO_2, H_2S, CO, microbiological investigations and their influence on the inside artefacts and human health. The respondents also reported the sound system inside the church as problematic, which they described as an element that reduced the quality of the experience. Our measurements confirmed these claims. It showed that the recorded values fluctuated significantly during events and services, varying from 35.7 dBA to a maximum of 91.4 dBA. Higher values can cause discomfort to the human body. For this reason, we recommend tuning the loudspeakers so that the acoustics do not cause discomfort and disturbance to the human body and do not reduce the quality of the experience for visitors.

To prevent the degradation of historical monuments, preventive conservation is needed, therefore the conditions of the indoor environment must be monitored and evaluated, and they must be maintained at the requisite level of standards. Temperature and humidity are two air variables with an important impact on the deterioration of the inside artefacts, and the health of visitors and parishioners (Ilies et al., 2019). In addition to these two air variables, less or more light has consequences for the building and the artefacts and must be carefully monitored (Ferdyn-Grygierek, 2016), this being one of the greatest threats to the integrity of the exhibits.

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