RIGA TECHNICAL
UNIVERSITY

Mārtiņš Metāls

METHODOLOGY TO PROVIDE A CONSERVATION MICROCLIMATE IN THE HISTORICAL RELIGIOUS BUILDINGS

Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
Faculty of Civil and Mechanical Engineering
Institute of Sustainable Building and Engineering Systems

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METODOLOGY TO PROVIDE A CONSERVATION MICROCLIMATE IN THE HISTORICAL RELIGIOUS BUILDINGS

Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (PhD), the present Doctoral Thesis has been submitted for public defence on 15 June 2026, at 13:00, at the Faculty of Civil and Mechanical Engineering of Riga Technical University, Ķīpsalas ielā 6A, Room 546.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (PhD) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Mārtiņš Metāls……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in English as a collection of scientific publications. It consists of an Introduction, seven chapters, Conclusions, 39 figures, Bibliography, and five appendices; the total number of pages is 111, including appendices. The Bibliography contains 25 titles.

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23.04.2025.

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Nacionālā kultūras mantojuma pārvalde atzinīgi novērtē Mārtiņa Metāla veikto promocijas darbu, kas izstrādāts Rīgas Tehniskās universitātes, Būvniecības un mašīnzinību fakultātes Ilgtspējīgo būvmateriālu un inženiersistēmu institūtā, par konservējoša mikroklimata nodrošināšanu vēsturiskās ēkās.

Pētījuma rezultāti sniedz visaptverošu, praksē pielietojamu rīcības plānu vēsturisko ēku lietotājiem un uzturētājiem, palīdzot nodrošināt konservējošu mikroklimatu Latvijas klimatiskajos apstākļos. Šis pētījums būtiski veicina kultūras mantojuma saglabāšanu, piedāvājot risinājumus, kas ļauj vēsturiskajām vērtībām tikt saglabātām ilgtermiņā un nodotām nākamajām paaudzēm.

Vadītāja Ināra Bula

Translation:
To: Mārtiņš Metāls
From: National Heritage Board of Latvia

The National Heritage Board highly values the Doctoral Thesis of Mārtiņš Metāls, carried out in the Institute of Sustainable Building Materials and Engineering Systems of the Faculty of Civil and Mechanical Engineering of Riga Technical University, on the conservation of cultural heritage and the provision of indoor microclimate. The research results offer a comprehensive theoretical foundation, practical applicability, and tools for analysing the indoor environment of historic buildings. We consider this a significant contribution to the field of cultural heritage preservation, with enduring value for both present and future generations.

Ināra Bula
Director, National Heritage Board of Latvia
23.04.2025

Īpaši aizsargājamais kultūras piemineklis -
Turaidas muzejrezervāts

24.04.2025. Nr.1-18/77

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Atsauksme

Īpaši aizsargājamais kultūras -piemineklis - Turaidas muzejrezervāts atzinīgi novērtē Mārtiņa Metāla veikto promocijas darba pētījumu Rīgas Tehniskās Universitātes, Būvniecības un mašīnzinību fakultātes, Ilgtspējīgo būvmateriālu un inženiersistēmu institūtā par konservējoša mikroklimata nodrošināšanu vēsturiskās ēkās. Šī pētījuma rezultāti sniedz visaptverošu un skaidru rīcības plānu vēsturisko ēku lietotājiem un uzturētājiem, kā Latvijas klimatiskajos apstākļos nodrošināt konservējošu mikroklimatu vēsturiskās ēkās.

Mārtiņa Metāla pētījums dod iespēju arī Turaidas muzejrezervāta vēsturiskās ēkas kā vērtību saglabāt un nodot nākamajām paaudzēm.

Pieminekļu nodaļas vadītājs Jānis Spila

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Translation:
To: Mārtiņš Metāls
From: The specially protected cultural monument – Turaida Museum Reserve

The specially protected cultural monument – Turaida Museum Reserve – highly appreciates Mārtiņš Metāls's Doctoral Thesis developed at the Institute of Sustainable Building Materials and Engineering Systems of the Faculty of Civil and Mechanical Engineering of Riga Technical University on the conservation of cultural heritage and the provision of indoor microclimate in buildings. The Thesis provides an in-depth and comprehensive overview of the theoretical aspects of indoor climate and includes practical microclimate research. We consider the research results to be valuable not only for specialists in the field but also for the historical buildings of the museum reserve, as a value to be preserved and passed on to future generations.

Jānis Spila
Head of the Monument Department,
The Specially Protected Cultural Monument – Turaida Museum Reserve
24.04.2025

CONTENTS

GENERAL DESCRIPTION OF THE THESIS

Relevance of the research

Historical churches are integral to Europe's cultural heritage, housing valuable liturgical and art objects. In Latvia, 226 churches are recognised as national monuments, and approximately 2378 movable and immovable national monuments are located in these and other churches [1]. In the Baltic region, the main risk to these heritage assets is uncontrolled indoor air humidity, which leads to condensation and biodeterioration, especially due to fungi. Although standards like EN 15759-1 define general goals for conservation heating [2], no concrete threshold values for air parameters in conservation microclimates have been established, especially in unheated or intermittently heated historic churches.

Hypothesis

Despite the great diversity of cultural and historical religious buildings, it is possible to develop a methodology for ensuring a conservation microclimate that maintains optimal air parameters (within the thresholds of temperature and humidity).

Goal of the study

To determine the threshold values of air parameters for a conservation microclimate in historical religious buildings (churches, chapels and places of worship) and to develop guidelines for their maintenance.

Novelty and Practical Application

This is the first study conducted in a transitional climate zone between maritime and continental climates, characterised by elevated absolute air moisture content [3], which, based on empirical data and simulations, establishes precise conservation microclimate threshold values (for temperature and absolute humidity) for different types of historical religious buildings. In Latvia, the absolute humidity typically ranges from 3–6 g/kg in winter to 10–14 g/kg in summer, significantly influencing condensation risks and preservation conditions. The outcome of the study is a methodology that can be applied by cultural heritage managers, architects, and engineers to ensure a conservation microclimate in various types of historical churches.

Description of the main chapters and methodology

The Doctoral Thesis is structured as a thematically unified collection of scientific publications. It includes five scientific publications.

Paper I, "Control of Indoor Climate of Historical Cult Buildings", published in E3S Web of Conferences, Vol. 246: Cold Climate HVAC & Energy 2021. The doctoral candidate's contribution to the preparation of the publication is 90 %, including the planning and execution of experiments, sample collection, processing and analysis, compilation and analysis of results, drafting of the main text, as well as revision and editing. This paper addresses the methods and technologies used to control the indoor climate of historical religious buildings. Paper I identifies the main issues of the indoor microclimate and determines the need for further in-depth research and its structure. The study focuses on maintaining stable temperature and humidity levels to preserve cultural and historical artefacts within these buildings. It explores various HVAC (heating, ventilation, and air conditioning) solutions and their effectiveness in historical contexts, providing insights into best practices for achieving optimal conservation environments. The research also includes calculations of the surface temperatures of enclosing structures under different indoor and outdoor air temperatures, highlighting the importance of adaptive climate control systems that respond to the specific needs of each building.

Paper II, "Typology of Latvian Churches and Preliminary Study on Indoor Air Temperature and Moisture Behaviour", published in MDPI – Buildings in 2022. The doctoral candidate's contribution to the preparation of the publication is 90 %, including the planning and execution of experiments, sample collection, processing and analysis, compilation and analysis of results, drafting of the main text, as well as revision and editing. This Paper presents a comprehensive typology of Latvian churches, categorising them based on architectural features, construction materials, and historical context. It also provides a preliminary study on the indoor air temperature and moisture behaviour in these churches. The research identifies the specific microclimate challenges faced by different types of churches and lays the groundwork for future, more detailed studies. The findings highlight the significant variation in indoor climate conditions across different church types, emphasising the need for tailored conservation strategies to address these challenges effectively.

Paper III, "Preliminary Study on Indoor Air Temperature and Moisture Behaviour in 13th-Century Churches in Latvia", published in MDPI – Sustainability in 2023. The doctoral candidate's contribution to the preparation of the publication is 90 %, including the planning and execution of experiments, sample collection, processing and analysis, compilation and analysis of results, drafting of the main text, as well as revision and editing. This paper focuses on a detailed preliminary study of the indoor air temperature and moisture behaviour in 13th-century churches in Latvia. The study uses empirical data collected from various historical churches to analyse how these parameters fluctuate throughout the year and impact the preservation of cultural artefacts. Measurements of indoor air parameters were conducted in four types of churches over a year. The research includes indoor temperature measurements at various points within a single-nave church and compares these with the determined possible dew point. Additionally, moisture content calculations for all measurement points over the year were performed for four types of churches. The findings suggest that the age and construction methods of these churches contribute to unique microclimate challenges, necessitating specific preservation techniques

Paper IV, "Ventilation and Air Conditioning Design Approach Based on ASHRAE Psychrometric Chart and Mollier Diagram", published in Frontiers Media SA in 2024. The doctoral candidate's contribution to the preparation of the publication is 10 %, including the compilation of results, sample collection, as well as revision and editing. This paper discusses a design approach for ventilation and air conditioning systems using the ASHRAE Psychrometric Chart and Mollier Diagram. The research emphasises the application of these tools in optimising HVAC systems for historical buildings. It outlines the benefits of using these diagrams to achieve precise control over indoor climate conditions, ensuring both energy efficiency and the preservation of cultural heritage. The paper also includes case studies demonstrating the practical implementation of this approach in historical religious buildings.

Paper V, “Study on Indoor Air Temperature and Moisture Behaviour in Historical Churches”, published in Elsevier – Energy & Building in 2024. The doctoral candidate’s contribution to the preparation of the publication is 90 %, including the planning and execution of experiments, sample collection, processing and analysis, compilation and analysis of results, drafting of the main text, as well as revision and editing. This paper presents an extensive study on the indoor air temperature and moisture behaviour in historical churches. The research includes data collected from a variety of historical churches, analysing how internal and external factors influence the microclimate. Measurements of indoor air parameters were conducted in four types of churches over a year. The study emphasises the relationship between visitor numbers, building usage, and the resulting indoor climate conditions. It also includes moisture content calculations for all measurement points over the year for the four types of churches. The study concludes with recommendations for managing these variables to optimise the conservation environment, highlighting the need for dynamic control systems to maintain appropriate temperature and humidity levels. This research is crucial for developing effective strategies to preserve historical churches and their valuable contents.

1. THEORETICAL BACKGROUND

The theoretical explanation [3] of indoor air humidification and dehumidification processes, which is fundamental for understanding ventilation and air-conditioning system behaviour, is provided in Paper IV. This publication is a critical methodological pillar within the overall structure of this Doctoral Thesis, as it establishes the physical and analytical basis for interpreting indoor air parameter changes independently of specific building typologies or usage scenarios.

While the earlier publications in this Thesis (Papers I–III) focus primarily on empirical monitoring, classification of building types, and observed microclimate behaviour, Paper IV addresses a fundamental methodological gap: the need for a clear, physics-based interpretation of indoor air-state changes that can be directly translated into ventilation and air-conditioning design calculations. Without such a theoretical framework, measured air parameters remain descriptive rather than predictive, limiting their applicability for system design and conservation-oriented microclimate control.

Paper IV introduces a structured approach in which the processes occurring within a space are analysed prior to defining the air exchange rate. This is a crucial methodological shift. Instead of starting with assumed ventilation volumes, the publication proposes first identifying the dominant sensible and latent loads acting within the room. Based on this analysis, the direction of the indoor air-state change process is determined (the direction of air state change describes the trajectory of changes in air parameters, temperature and humidity ratio, determining the type of air treatment process) and expressed through an angular process coefficient ($\Delta h/\Delta x$). This coefficient defines the slope of the process line on both the ASHRAE psychrometric chart and the Mollier (h–x) diagram (The Mollier diagram is a graphical representation of the state of moist air per unit of dry air).

The diagrams presented in Paper IV (Figs. 1 and 2) illustrate how this process line represents the combined effect of internal heat gains, moisture loads, and air distribution effectiveness. Once the process direction is defined, the Mollier diagram becomes a powerful design and evaluation tool. It allows the designer to graphically determine the required supply air parameters for a given indoor target state, as well as to assess how changes in air exchange rate affect the distance between supply air and exhaust air conditions.

This approach is particularly relevant for buildings with sensitive indoor environments, such as historical churches and cultural heritage buildings investigated in this Thesis. In such buildings, ventilation rates are often restricted due to conservation requirements, energy limitations, or intermittent occupancy. Paper IV demonstrates that, by using the process line on the Mollier diagram, it is possible to quantitatively evaluate the consequences of reduced air exchange rates on indoor temperature and humidity conditions already at the design stage. This makes it possible to assess whether indoor air quality and conservation criteria can still be met under constrained ventilation scenarios.

Furthermore, Paper IV highlights the role of the air distribution system through the air distribution effectiveness coefficient (M_{ad}). The diagrams show how different air distribution strategies shift the effective indoor process line, thereby influencing the required supply air parameters. This provides a direct link between room air processes and system-level design decisions, such as diffuser selection and air supply strategy, without relying solely on empirical correction factors.

Within the overall framework of this Doctoral Thesis, Paper IV therefore serves as the theoretical and methodological bridge between empirical microclimate observations and simulation-based analyses. The process-based interpretation of air-state changes established in this publication underpins later steps of the research, including the definition of air parameter threshold values and the development of conservation-oriented microclimate methodologies for different church typologies. By grounding these subsequent analyses in a clearly defined psychrometric and Mollier-based framework, the research ensures consistency, transparency, and physical validity across measurement, calculation, and simulation stages.

In summary, Paper IV provides not only a theoretical explanation of indoor air humidification and dehumidification processes but also a practical design-oriented methodology. Defining the direction of air-state change processes on the Mollier diagram, it enables direct ventilation design calculations, supports informed decision-making under constrained air exchange conditions, and establishes a unified analytical language for researchers, designers, and building operators involved in indoor climate control.

2. PRESENT STUDY

2.1. Methods

Calculations

In Paper I, initial indoor climate measurements in various churches were compiled, and calculations of thermal resistance, heat accumulation, and condensation risks were conducted to determine the need for further in-depth research.

Based on the foregoing, the temperatures were calculated on the wall, the corner of the external wall, the ceilings, the corner between the ceiling and wall and the external wall forming a corner with the ceiling.

Calculations in Papers III and V applied a trimmed mean approach to reduce the influence of extreme values and potential measurement anomalies in the time series data. This method excludes a fixed proportion of the lowest and highest values from the dataset before calculating the average, providing a more robust measure of central tendency that is less sensitive to outliers.

Specifically, 10 % of values from both tails of the distribution were removed (i.e., the lowest and highest 10 %), and the mean was calculated from the remaining 80 %:

$$\bar{x}_{\text{trim}} = \frac{1}{n-2k} \sum_{i=k+1}^{n-k} x_{(i)}, \tag{3.1}$$

where n is the total number of observations, $x_{(i)}$ represents the i-th ordered value of the dataset, and $k = \lfloor 0.1n \rfloor$ is the number of values removed from each tail [4].

This method was used to calculate the average air temperature, relative humidity, and surface temperature values over defined periods, ensuring that the results were not unduly affected by transient anomalies or sensor errors.

Based on air temperature and relative humidity measurements, the partial pressure of water vapour in moist air, P_w (kPa), is calculated:

$$P_w = 6{,}112 \cdot e^{\left(\frac{17{,}67 \cdot T}{243{,}5+T}\right)} \cdot \frac{RH}{100}, \tag{3.2}$$

where T is air temperature (C°), e is Euler’s number [5], and RH is relative humidity (%). The air moisture ratio W (g/kg) is calculated from the partial pressure P_w:

$$W = 622 \frac{P_w}{P - P_w}, \tag{3.3}$$

where P is total pressure (Pa)[6].

By substituting the expression for the partial pressure of water vapour P_w, derived from air temperature and relative humidity, into Equation (3.3), a combined formula is obtained for directly calculating the air moisture content W, based solely on temperature and relative humidity Equation (3.4):

$$W = \frac{622 \cdot \left(611{,}2 \cdot e^{\left(\frac{17.67 \cdot T}{243.5+T}\right)} \cdot \frac{RH}{100}\right)}{P - \left(611.2 \cdot e^{\left(\frac{17.67 \cdot T}{243.5+T}\right)} \cdot \frac{RH}{100}\right)}. \tag{3.4}$$

Based on temperature and *RH* measurements, the difference between indoor and outdoor air absolute humidity v (g/m³) is determined by the following equation:

$$v = \frac{P_W \cdot M}{R \cdot T}, \tag{3.5}$$

where $M = 18.02$ is the molar mass of water vapour (g/mol), and $R = 0.08314$ is the universal gas constant (L·bar/mol·K) [7].

Equation (3.6) is derived by expressing the water vapour partial pressure in terms of temperature and relative humidity and substituting it into the general gas-law-based formulation of the absolute humidity Equation (3.5).

$$v = \frac{RH}{100} \cdot \frac{6{,}112 \cdot e^{\left(\frac{17{,}67 \cdot T}{243{,}5 \cdot T}\right)} \cdot 18{,}02}{(273{,}15 + T) \cdot 0{,}08314}, \tag{3.6}$$

where the excess moisture Δv (g/m³) is determined by the following equation:

$$\Delta v = v_i - v_e \tag{3.7}$$

where v_i is the humidity by volume of indoor air (g/m³), and v_e is the humidity by volume of outdoor air (g/m³) [8].

Measurements

Temp/RH/Light/Ext-Temp Kit (Fig. 1) at 30-minute intervals, with a measuring accuracy of ±2.5 % for relative humidity and ±0.2 °C for temperature. These measurements were part of the studies presented in Papers III and V.

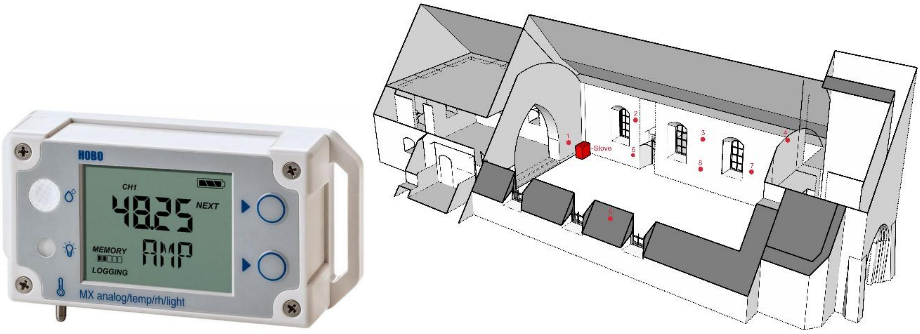

Fig. 1. Measuring instrument and location example in Krimulda church [9].

The locations and number of measuring instruments in churches are specified in Papers III and V.

2.2. Typology of religious buildings

In Paper II, a typological study of religious buildings is presented based on the thermal resistance types of their enclosing structures in relation to the age of the buildings and their spatial forms, which affect the potential warm air flow [6]. This typology provides an overview of the most common types of religious buildings by their quantity, which informs further research on the types of churches where additional studies should be conducted to encompass as wide a range of churches as possible.

In this section, based on Paper II [10], a typological study of the spatial and structural characteristics of Lutheran churches in Latvia is presented, aiming to identify their impact on potential airflow directions and condensation risks. A survey of 335 churches revealed that 276 of them are currently operational. These were classified according to their spatial layout and construction period, taking into account the thermal properties of wall and ceiling structures (Fig 2).

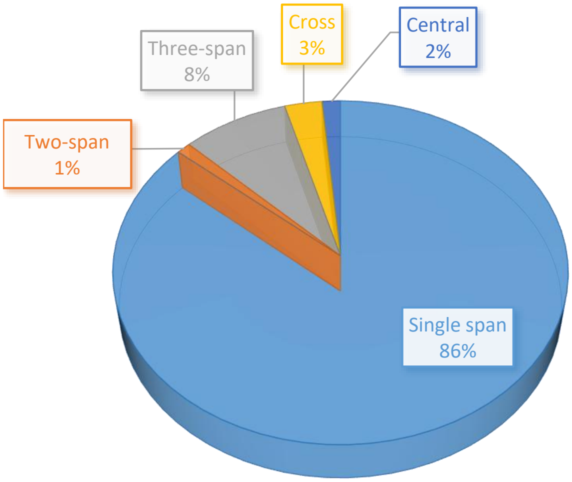

Fig. 2. Distribution of Latvian Lutheran churches by spatial layout (from Paper II).

The structural analysis of these churches revealed that wall thickness decreases with each subsequent century – from 1.5–2.0 m in the 13th–16th centuries to 0.8–1.0 m in the 19th century. The thermal conductivity coefficient (λ) of masonry walls remained around 0.87 W/m·K throughout this period, while ceiling materials varied, resulting in a λ range from 0.1 W/m·K to 0.8 W/m·K, depending on whether the material was a brick vault, wooden vault, or straight wooden construction (Fig. 3).

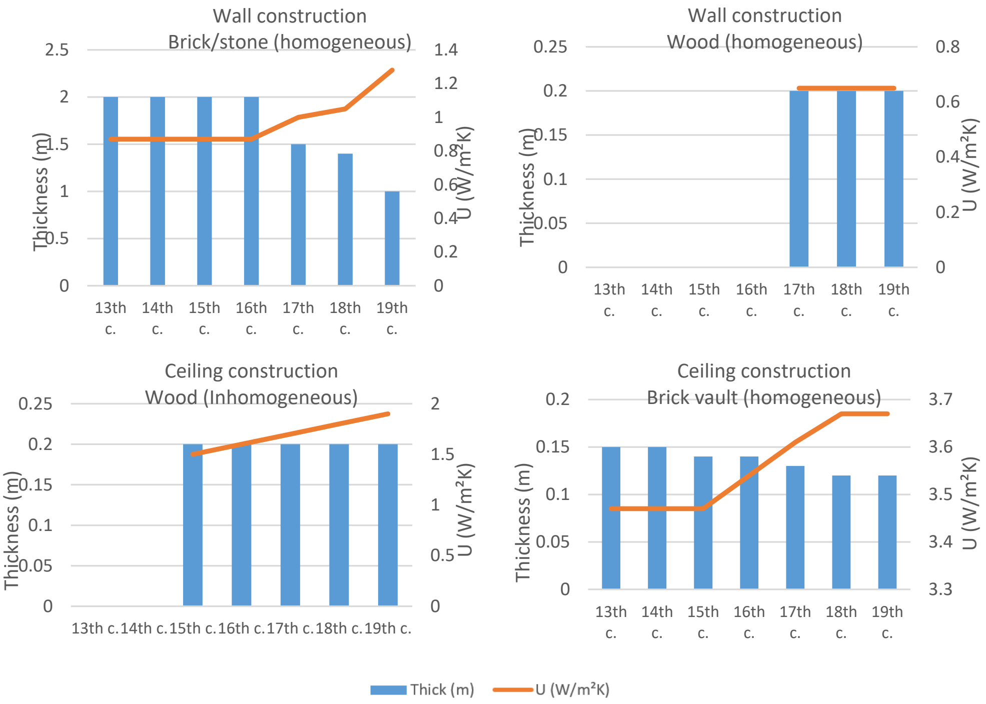

Fig. 3. Types, dimensions and thermal transmittance U of church constructions.

Special attention was given to churches where a partition wall with a wide arch separates the altar area from the main hall. This layout, found in 29 churches, may significantly affect air circulation and moisture distribution.

An important observation relates to the influence of spatial layout on the indoor microclimate: it is assumed that different spatial configurations (single-nave, three-nave, central, etc.) generate different airflow directions. These differences are crucial for analysing heating strategies and potential condensation conditions. The observations summarised in this section serve as a foundation for further airflow modelling studies presented in Paper II.

2.3. Measurement results

Temperature and moisture in the Krimulda Church

This section presents the results of detailed indoor temperature and humidity measurements in the Krimulda Church [9], focusing on the thermal behaviour during heating events and human occupancy.

For the heating strategy of a religious building, opting for a single heat source for the entire structure, as is the case with the Krimulda Church, can result in an uneven temperature distribution within the premises. Consequently, both the internal surface of its building envelope and the surfaces of various valuable items/interior details can reach the dew point temperature. We can conclude that irregular heating strategies cause significant temperature fluctuations in the indoor air and on the surfaces of the building (e.g., walls, ceiling, floor, interior items), leading to moisture condensation on various surfaces Fig. 4. Therefore, this heating strategy cannot be defined as a heating system providing a preserved microclimate.

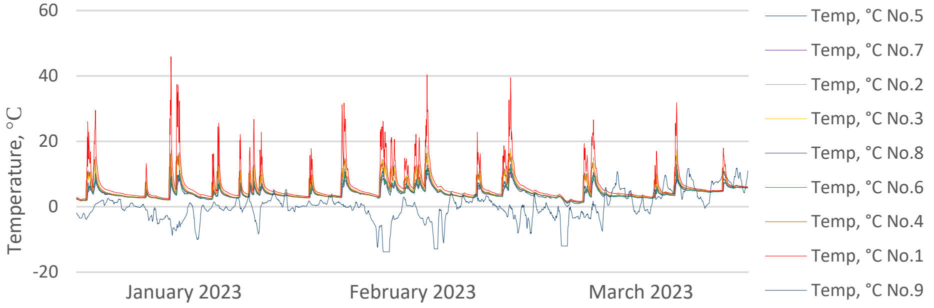

Fig. 4. Temperatures in the Krimulda Church

The results of indoor air parameter measurements and calculations in the Krimulda Church indicate that the moisture vapours from the building structures (including the building envelope and interior details) constitute up to 2 g/kg (Fig. 5).

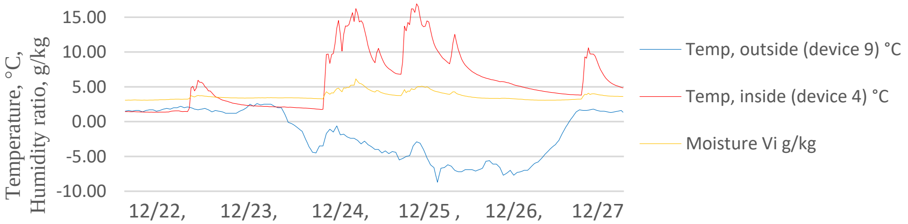

Fig. 5. Outdoor and indoor moisture and temperature in the Krimulda Church on the balcony between 12/22/2022 and 12/28/2022.

If one is using this type of building on a regular basis during the warm season when the indoor humidity ratio increases, it is necessary to monitor the air parameters and to install dehumidifiers to reduce the moisture concentration indoors from 14.33 g/kg at least to 10 g/kg (Fig. 6).

A significant influx of visitors during the heating season, along with the rapid increase in indoor temperatures resulting from a heating device, can lead to condensation risks. Potential condensation risks can be prevented either by ensuring a constant minimum indoor air temperature of 7 °C or by means of air-drying methods to reduce the indoor humidity level from 6.1 g/kg to 4.5 g/kg.

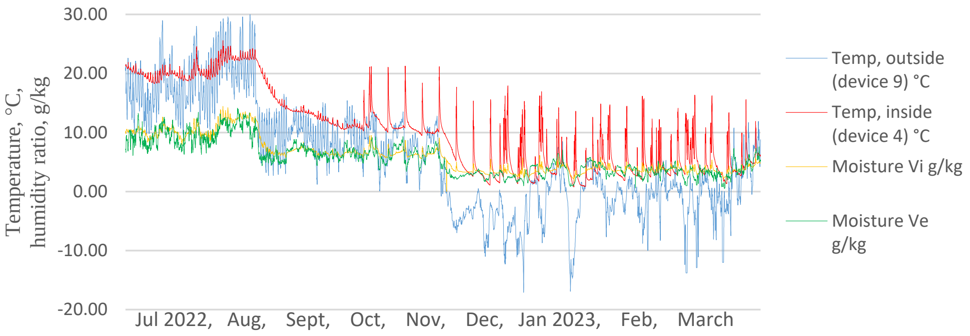

Fig. 6. Outdoor and indoor humidity and temperature in the Krimulda Church on the balcony.

These results complement the theoretical condensation risk calculations in Paper I with practical long-term measurements, confirming that even when surface temperatures approach the dew point, condensation does not occur due to the thermal inertia of the building envelope.

In the context of Paper II, the data help to validate the typological conclusions regarding single-nave churches, particularly confirming that heating effects are local, while the direction of warm-air convection is predictable, which is essential for typological modelling.

Moisture in the Turaida Church

The Turaida Church [11] lacks a permanent heating and ventilation system. During the cold season, it is heated once a week with electric heaters before services. When indoor relative humidity reaches 98–100 %, dehumidifiers are installed. Outdoor air parameters were approximated using the same measurement data as for the Krimulda Church due to similar geographical conditions.

From the air parameter measurements in the Turaida Church we can conclude that venting the church during the warm seasons at high outside temperatures creates huge infiltration of the outside air and air humidity that poses condensation risks, which is 13.52 g/kg, It is recommended to decrease such indoor air humidity (13.52 g/kg) to 10 g/kg in order to decrease potential condensation risks due to air temperature fluctuations.

Heating the indoor air and a large number of simultaneous visitors in the church (0.41 pers/m² or 0.14 pers/m³) during the cold season increases the air moisture content by 2.66 g/kg. In order to prevent condensation risks on the surfaces of indoor structures and interior details, the minimum permanent indoor air temperature during this period should be 6.5 °C, or the indoor air should be dried from 5.79 g/kg to 3.5 g/kg.

Moisture in Liepaja St. Trinity Cathedral

Liepaja St. Trinity Cathedral [11] has a permanent heating system connected to the district heating network, with a heat exchanger power of 250 kW. The heating system ensures that the indoor temperature stays between 5 °C and 7 °C during the heating season

It can be concluded that comparing the microclimate of Liepaja St. Trinity Cathedral to the Krimulda Church and Turaida Church, which do not have regular heating systems, the microclimate of Liepaja St. Trinity Cathedral is more stable (has fewer fluctuations). A heating strategy, which ensures a permanent indoor temperature at 6 °C with short-term fluctuations up to 12 °C can be defined as a heating strategy promoting maintenance of a preserving microclimate.

As 410 persons (0.46 pers/m² or 0.04 pers./m³) attend the cathedral during the cold season, it actually increases the indoor humidity by 1.49 g/kg and air temperature by 3.2 °C, which does not cause large microclimate fluctuations and does not create potential condensation risks.

Increasing the indoor temperature with a heating element by 3 °C (without visitors of the building), one can detect an increase in the indoor air humidity ratio by 1.1 g/kg (Fig. 7), which is explained by moisture vapours from the building's structures and interior items.

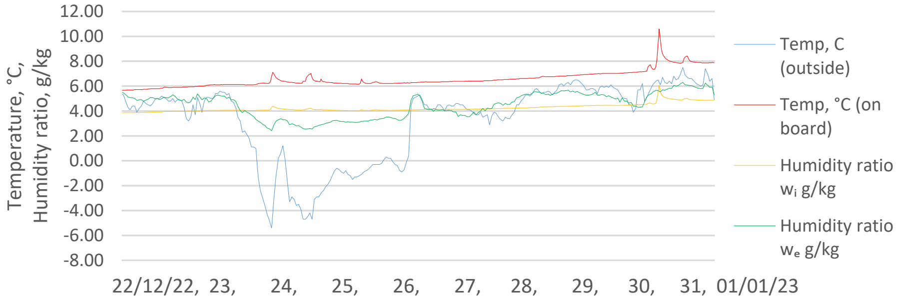

Fig. 7. Outdoor and indoor moisture and temperature in Liepaja St. Trinity Cathedral hall between 22.12.2022. and 02.01.2023

Moisture in Riga Jesus Church

Riga Jesus Church [11] has a permanent heating system connected to a local boiler house in the basement, where a 35 kW pellet heating boiler is used. The heating system maintains an indoor temperature between 12 °C and 17 °C during the heating season when the air is heated for religious and other activities.

The natural ventilation ensures that during the cold season or heating period, simultaneous 500 visitors (0.65 pers/m² or 0.087 pers/m³) do not create huge moisture fluctuations and the actual increase of indoor humidity is twice as low as the calculated one for the number of visitors. During the warm season periods, the microclimate of Riga Jesus Church is more stable than of the Turaida Church, because Riga Jesus Church is not visited by as many people daily. Meanwhile, during the cold season periods, the microclimate of Riga Jesus Church is more stable than that of the Turaida Church. In general, it can be concluded that during the cold season periods, the churches with a high number of visitors would have a more stable indoor climate if they had a steady and permanent indoor temperature between 5 °C and 10 °C, which allows for a higher air humidity up to 7 g/kg (Fig. 8).

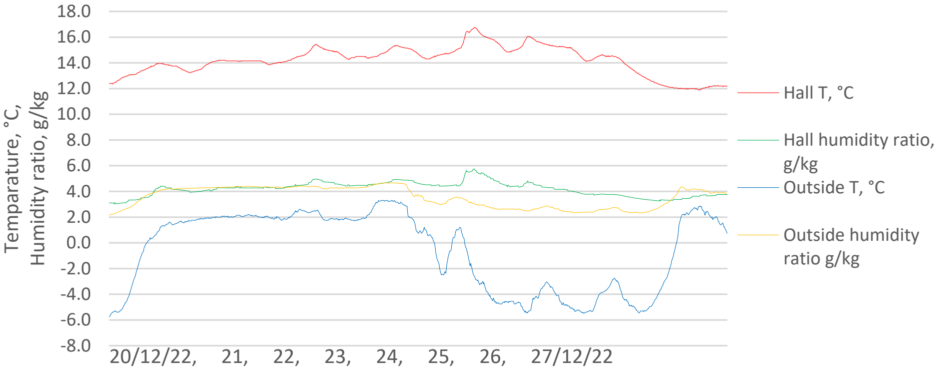

Fig. 8. Outdoor and indoor humidity ratio and temperature in Riga Jesus Church in the hall between 20/12/2022 and 28/12/2022.

As the wooden churches (the Turaida Church and Riga Jesus Church) increase their indoor temperature, one cannot detect an increase in indoor humidity concentration, which we detect in the masonry churches as moisture release from the structures and interior details.

The results show that the maximum allowable indoor air humidity ratio during the summer period is 10 g/kg, while during the winter period, when churches are in operation, either a constant minimum indoor air temperature of 6.5 °C or a maximum humidity ratio of 3.5 g/kg is maintained.

It can be generally concluded that churches with a high number of visitors would achieve a more stable indoor climate during the winter period if they maintained a steady indoor temperature between 5 °C and 10 °C, allowing for higher air humidity up to 7 g/kg. In wooden churches like Turaida and Riga Jesus Church, increasing the indoor temperature does not significantly increase indoor humidity concentration, unlike in masonry churches, where moisture release from structures and interior details is observed

A consistent pattern of excess moisture behaviour has been identified across all four studied churches – Krimulda, Turaida, Riga Jesus Church, and Liepaja St. Trinity Cathedral. In all cases, when the outdoor air temperature drops below 0 °C, excess moisture values remain above zero, indicating that indoor air holds more moisture than outdoor air during cold periods.

As the outdoor temperature rises above 0 °C, excess moisture values fluctuate both above and below zero, reflecting significant variability between indoor and outdoor absolute humidity. This variability becomes especially prominent during interseasonal periods when indoor air inertia and outdoor air infiltration interact.

The highest recorded excess moisture (Fig. 9) levels – reaching 6 g/m³ – were observed in Krimulda and Turaida churches at outdoor temperatures around +30 °C. In both cases, these peak values occurred during short-term periods in late summer, coinciding with open-door visitor access and increased infiltration of warm, humid outdoor air.

In Krimulda Church (Fig. 9 (A)), excess moisture peaks during unstable late-summer weather with rapid fluctuations in outdoor humidity and precipitation.

In Turaida Church (Fig. 9 (B)), similar values were observed, primarily due to open doors and lack of climate control.

In Liepaja St. Trinity Cathedral (Fig. 9 (C)), the highest excess moisture reached 4 g/m³ during the cold season (October to April), a period not directly comparable to Krimulda and Turaida measurements.

In Riga Jesus Church (Fig. 9 (D)), excess moisture reaches 5 g/m³ at an outdoor temperature of 5 °C. However, the indoor environment remains more stable, likely due to controlled intermittent heating and lower air infiltration. Like Turaida Church, Riga Jesus Church is also built from wood, and the minimum maintained indoor temperature during winter contributes to moisture retention in the indoor air.

These findings underscore the importance of temperature and the building envelope behaviour in shaping indoor air moisture dynamics. Particularly in unheated or partially heated historic churches, infiltration and thermal inertia are key factors influencing excess moisture and potential condensation risks.

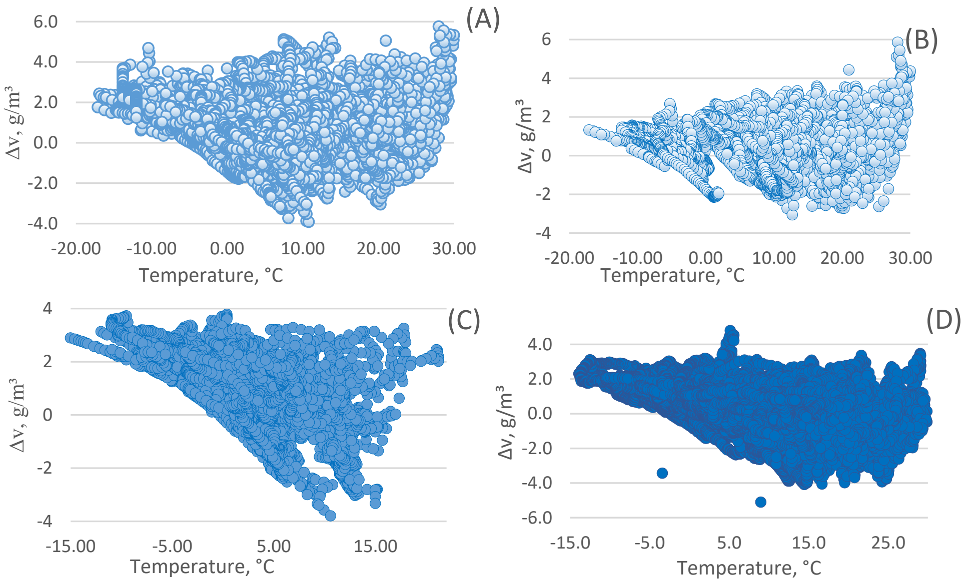

Fig. 9. Excess moisture: (A) in the Krimulda Church, on the balcony; (B) in the Turaida Church, on the lamp; (C) in Liepaja St. Trinity Cathedral, in the hall; (D) in Riga Jesus Church, in the hall.

It can be generally concluded that churches with a high number of visitors would achieve a more stable indoor climate during the winter period if they maintained a steady indoor temperature between 5 °C and 10 °C, allowing for higher air humidity up to 7 g/kg. In wooden churches like Turaida and Riga Jesus Church, increasing the indoor temperature does not significantly increase indoor humidity concentration, unlike in masonry churches, where moisture release from structures and interior details is observed.

3. SIMULATION

Simulation models developed using IDA ICE software for the Turaida Church, Krimulda Church, Riga Jesus Church, and Liepaja St. Trinity Cathedral (Fig. 10) aimed to analyse surface temperatures of envelope structures and determine the direction of indoor air state change (ε) during different seasonal and occupancy conditions.

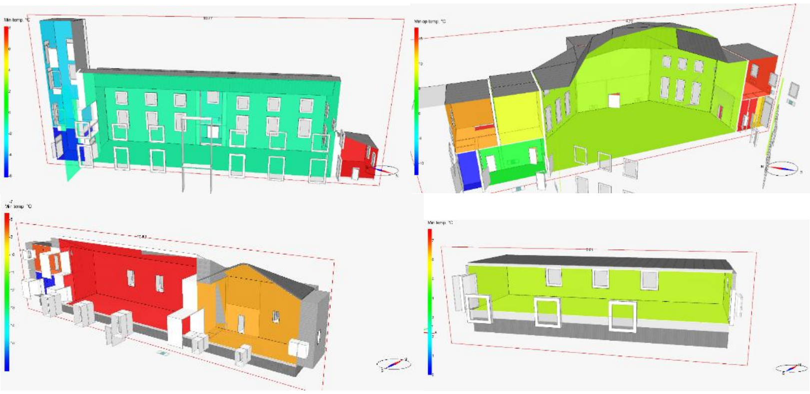

Fig. 10. Indoor surface temperatures in Liepaja Cathedral, Riga Jesus Church, and Krimulda and Turaida Churches.

In all four churches, the simulations were based on measured visitor load and heating schedules provided in Papers III and V. The goal was to understand the interaction between structural materials, heating operation, and moisture behaviour in historic spaces.

In Liepaja St. Trinity Cathedral, the IDA ICE model reflected the actual heating schedule. While measured air temperatures showed no condensation risk, the simulation indicated potential risk zones in less-heated areas, such as the tower room and the organ balcony, where surface temperatures dropped below 0 °C. The calculated direction of indoor air state change ($\varepsilon = 7.0$ kJ/kg) differed from the measured value (Fig. 11), suggesting additional moisture in the space originating from the building's structures. The warm air ductwork supplying the organ area from colder tower zones further increases this risk during winter.

In Riga Jesus Church, made of wood and heated intermittently, simulations showed surface temperatures remaining above 2 °C in the main hall throughout the year, even in unoccupied periods. However, surface temperatures around doors and windows dropped below freezing in winter. During high visitor loads, the air state change was $\varepsilon = 3.2$ kJ/kgw. The Mollier diagram revealed a deviation between simulated and measured data (Fig. 11), possibly caused by outdoor air infiltration or moisture retention due to the wooden envelope and warmer indoor baseline temperatures. Among the four churches, Riga Jesus Church displayed the most stable winter indoor conditions, despite short-term fluctuations.

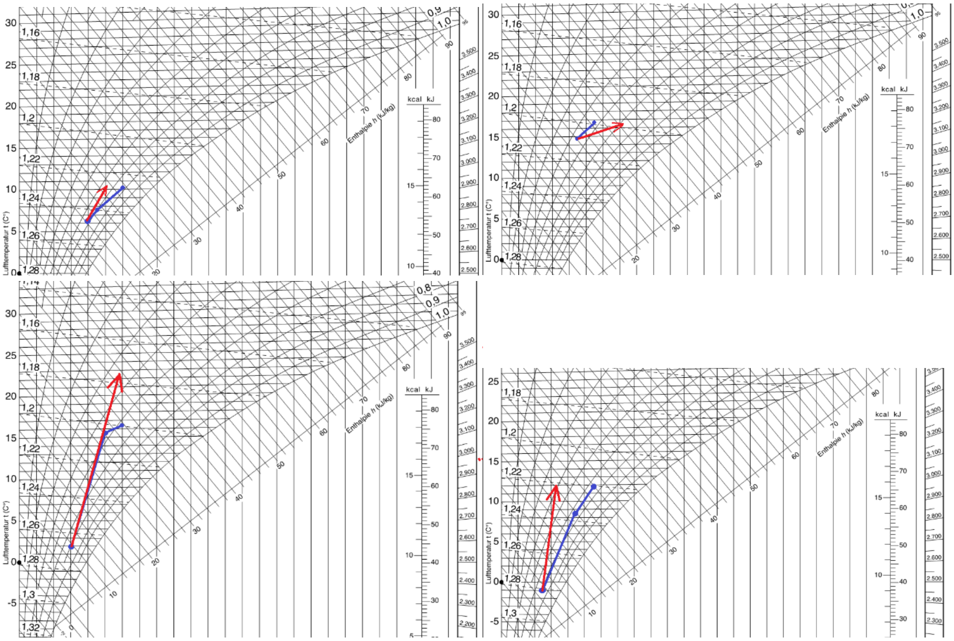

Fig. 11. Mollier diagram (red – ε, blue – measurement) data for Liepaja Cathedral, Rig Jesus Church, and Krimulda and Turaida Churches.

The simulation for Krimulda Church, a granite masonry structure with 1.6 m-thick walls, did not align well with measured values. The IDA ICE model underestimated surface temperatures, primarily because it failed to account for high thermal inertia and intermittent heating, which are characteristic of this church. Measurements showed that actual wall surface temperatures remained above 0 °C, while the simulation predicted freezing conditions. The calculated air state change (ε = 6.33 kJ/kgw) again differed from measured results, further confirming that moisture emissions from the structure play a significant role that is not captured by the model.

For Turaida Church, which is built of wood and also employs intermittent heating, the simulation indicated surface temperatures higher than those measured during unoccupied periods in winter. Like in Krimulda Church, the simulation overestimated thermal performance due to simplified assumptions that do not reflect the real behaviour of the structure under periodic heating. On 24 December 2022, when 70 visitors were present, the calculated direction of air state change reached ε = 17 kJ/kgw. The discrepancy from measured indoor air parameters highlighted how thermal accumulation and moisture retention in wooden elements distort the simulation under real conditions.

Overall, the simulations across all four churches show that simplified energy models like IDA ICE do not fully capture the moisture dynamics and thermal lag in historic structures, especially when intermittent heating and high-mass materials are involved. Although such models are useful for identifying critical risk zones and understanding general air behaviour, they tend to underestimate or overestimate surface temperatures and air moisture interactions, particularly in churches with non-continuous heating strategies and limited ventilation control. Therefore, while simulation is a valuable support tool, it must be used alongside empirical measurements and knowledge of building physics for accurate climate management in historical churches.

4. METODOLOGY FOR CONSERVATION MICROCLIMATE IN HISTORICAL RELIGIOUS BUILDINGS

This chapter presents a methodology for maintaining a conservation microclimate in historical religious buildings, developed through the synthesis of heating strategies, usage intensity, and building typology. Based on data from Paper III (Krimulda Church) and Paper V (Turaida, Riga Jesus Church, and Liepaja Cathedral), buildings are primarily classified by their heating strategy – no heating, intermittent heating, or continuous heating – aligned with EN 15759-1.

A secondary classification considers the intensity of use, and within each group, churches are further divided into two types based on their enclosing structures: wooden or masonry. These structural differences significantly affect thermal resistance, thermal mass, and moisture dynamics.

For unheated churches, represented by Turaida Church (wooden) and Krimulda Church (masonry), measurements show that visitor numbers and internal moisture load during events can lead to condensation risks. For wooden churches, humidity must be limited to 3.5 g/kg in winter and below 10 g/kg in summer, and visitor density must be kept below 0.14 persons/m³. For masonry churches, indoor temperature must not fall below 7 °C, or air must be dried below 6.1 g/kg to avoid condensation (Fig. 12).

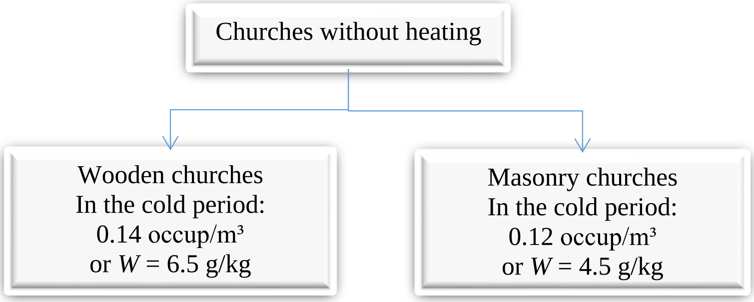

Fig. 12. Air parameter threshold values for churches without a heating strategy.

In churches with heating, two strategies are distinguished.

Continuous heating (Riga Jesus Church, Liepaja Cathedral): Simulations and measurements show that while drying of materials occurs in winter due to high thermal energy, summer periods may still require dehumidification above 10 g/kg, and winter may need humidification below 5 g/kg. A maximum short-term temperature increase of 4 °C is allowed (Fig. 13).

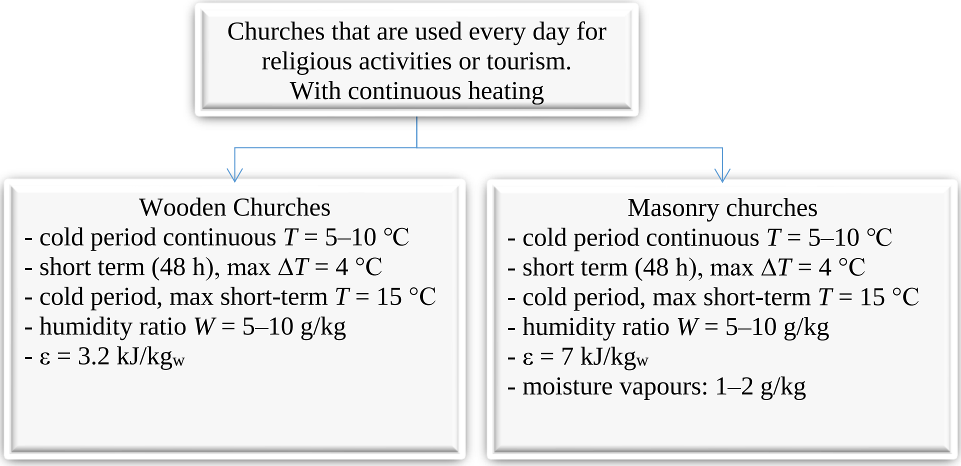

Fig. 13. Air parameter threshold values for churches with a continuous heating strategy.

Intermittent heating (in Turaida and Krimulda Churches): Sudden temperature increases raise air humidity rapidly due to moisture release from surfaces. Maintaining a minimum temperature around 6 °C and controlling humidity between 4.5 g/kg and 10 g/kg is crucial (Fig. 14).

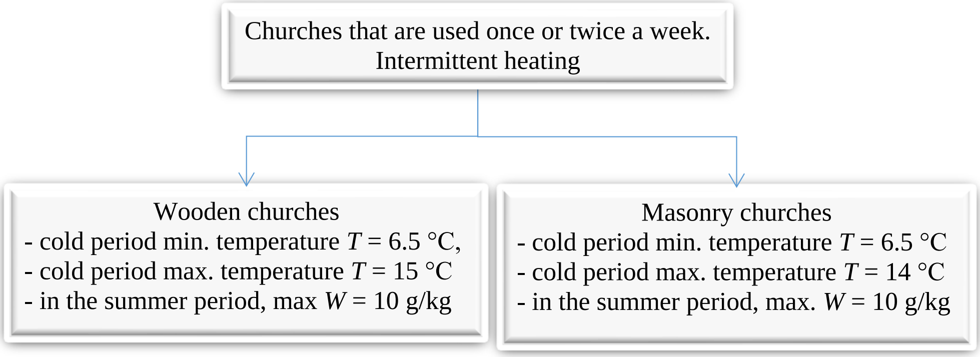

Fig. 14. Air parameter threshold values for churches with an intermittent heating strategy.

The final methodology (Fig. 15) combines these classifications and offers practical thresholds for managing temperature and humidity in historical churches, depending on their heating strategy, material composition, and usage pattern. This approach supports long-term preservation of structures and interiors by minimising condensation and material degradation risks.

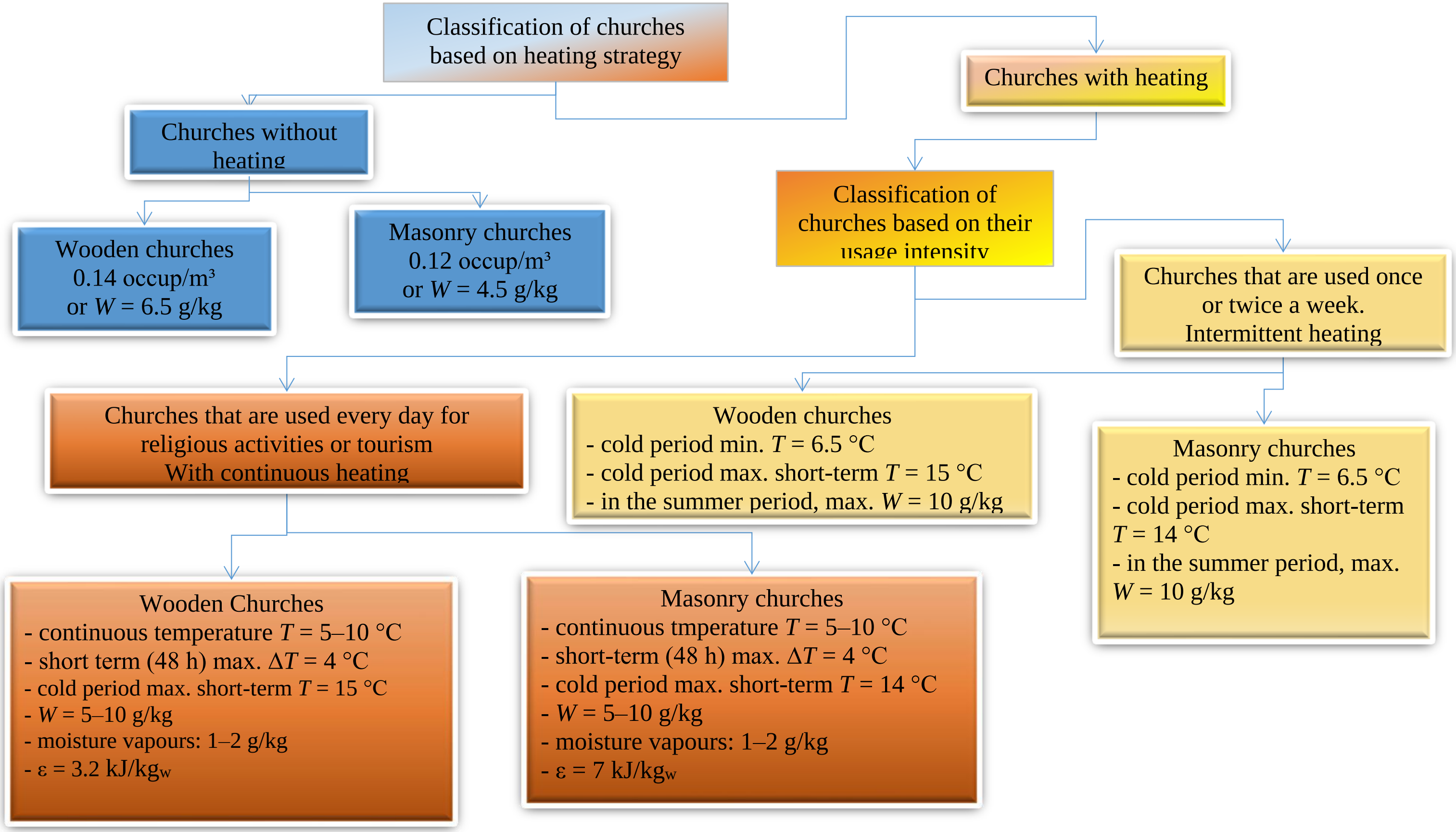

Fig. 15. Methodology for a conservation microclimate.

5. PRACTICAL RECOMMENDATIONS FOR HISTORICAL CHURCH USERS

1. Install air parameter measuring devices (temperature, relative humidity).
2. Record air parameter measurements in a logbook once per day, and at least twice per day during periods of more intensive building use.
3. In medieval masonry buildings without permanent heating or mechanical ventilation, install mobile dehumidifiers when relative humidity reaches 95 %.
4. If a short-term indoor air heating method is used during the winter period for the time the building is in use, it should be repeated at least every two days, even when the building is not in use, in order to maintain a minimum indoor air temperature of +4 °C to +6 °C. During such short-term heating events, the indoor air temperature should not exceed +14 °C in masonry buildings and +15 °C in wooden buildings, and the humidity ratio should not exceed 10 g/kg.
5. If a medieval church is used during the winter and no heating or dehumidification equipment is available, the number of visitors should be limited to 0.12–0.14 visitors per m^3.
6. During the summer period (July and August), ventilation is not recommended if the church is not equipped with an air dehumidification system.
7. When designing and installing mechanical ventilation systems and/or permanent heating systems, it is necessary to comply with the threshold values of air parameters for a conservation microclimate as defined in this study.
   - **For wooden churches**
     Cold period continuous indoor temperature: 5–10 °C.
     Short-term (48 h) fluctuations: maximum $\Delta T = 4$ ° C.
     Maximum short-term air temperature during the winter period: 15 °C.
     Humidity ratio: 5–10 g/kg.
     Moisture vapour emissions: 1–2 g/kg.
     Direction of air state change: $\varepsilon = 3.2$ kJ/kgw.
   - **For masonry churches**
     Cold period continuous indoor temperature: 5–10 °C.
     Short-term (48h) fluctuations: maximum $\Delta T = 4$ °C
     Maximum short-term air temperature during the winter period: 14 °C.
     Humidity ratio: 5–10 g/kg.
     Moisture vapour emissions: 1–2 g/kg.
     Direction of air state change: $\varepsilon = 7$ kJ/kgw.

CONCLUSIONS

As a result of the study, the initially proposed hypothesis is confirmed, based on comparative measurement, calculation, and simulation data.

In addition to confirming the proposed hypothesis, the study provides several significant scientific findings based on the analyses presented in Papers II–V and Chapters 5 and 6 of this Thesis.

Paper II demonstrates that in churches with different enclosing structures, excess indoor air humidity reaches up to +6.0 g/m³ (90 % curve), while during the cold period it ranges between 1–2 g/m³.

Paper III, based on measurements in Krimulda Church, shows that moisture emissions from building structures can reach up to 2 g/kg. In addition, a survey of 264 churches was conducted, forming the basis for the development of a church typology.

Paper IV demonstrates that the analysis of air processes using psychrometric charts and Mollier diagrams is essential for determining air treatment processes and for developing sustainable HVAC system design solutions.

Paper V establishes critical microclimate thresholds, showing that indoor humidity can reach up to 13.52 g/kg, creating condensation risks. It was determined that during the warm period, safe indoor humidity should not exceed 10 g/kg, while during the cold period either a minimum indoor temperature of 6–7 °C should be maintained or the humidity ratio should be reduced to 3.5–4.5 g/kg.

The simulation analysis presented in Chapter 5 shows that the IDA ICE software does not fully account for the thermal accumulation effects of massive masonry structures, resulting in discrepancies between simulated and measured data, particularly under intermittent heating conditions.

Finally, Chapter 6 presents, for the first time, a systematic determination of indoor air parameter threshold values for ensuring a conservation microclimate in historical religious buildings, along with a methodology for its implementation.

The developed methodology for ensuring a conservation microclimate in historical religious buildings offers valuable insights for building users and HVAC system designers.

Guidance for building users

- Optimised heating strategies: Users can implement optimised heating strategies based on the classification – buildings without heating, with intermittent heating, and with continuous heating. This allows them to maintain suitable indoor conditions while minimising energy consumption and environmental impact.
- Mitigation of condensation risks: Clear guidelines are provided for mitigating condensation risks during both cold and warm seasons, ensuring the preservation of building materials and interiors.

Benefits for HVAC system designers

- Tailored system design: HVAC system designers can tailor systems to meet the specific heating needs identified for each type of religious building (wooden or masonry) and its heating strategy (intermittent or continuous). This includes

recommendations for temperature and humidity control that align with conservation principles.
- Integration of conservation goals: The methodology integrates conservation goals with HVAC system design, promoting sustainable practices that balance environmental responsibility with the preservation of cultural heritage.

Advantages of long-term building preservation

- Enhanced preservation efforts: By following the methodology, building users and designers can contribute to the long-term preservation of historical religious buildings. This includes minimising the deterioration of structural materials due to excessive moisture or temperature fluctuations.
- Sustainable management: Sustainable management practices, such as controlled heating and humidity levels, ensure that these buildings remain structurally sound and culturally significant for future generations.

In summary, the methodology provides practical guidelines that empower building users and HVAC system designers to collaborate effectively in preserving historical religious buildings. By implementing these strategies, stakeholders can enhance the longevity and cultural value of these architectural treasures while promoting sustainable building management practices.

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- "The Best Building of the Year", 1st and 3rd place (2022) and 1st place (2023) in the category "Restoration";
- "The Most Energy Efficient Renewable Building", 2nd place (2020) and 1st place in the category "The most energy-efficient renovated apartment building" (2021).

In December 2024, a patent application was submitted for a timber frame building solution developed by "Akords U" Ltd.