

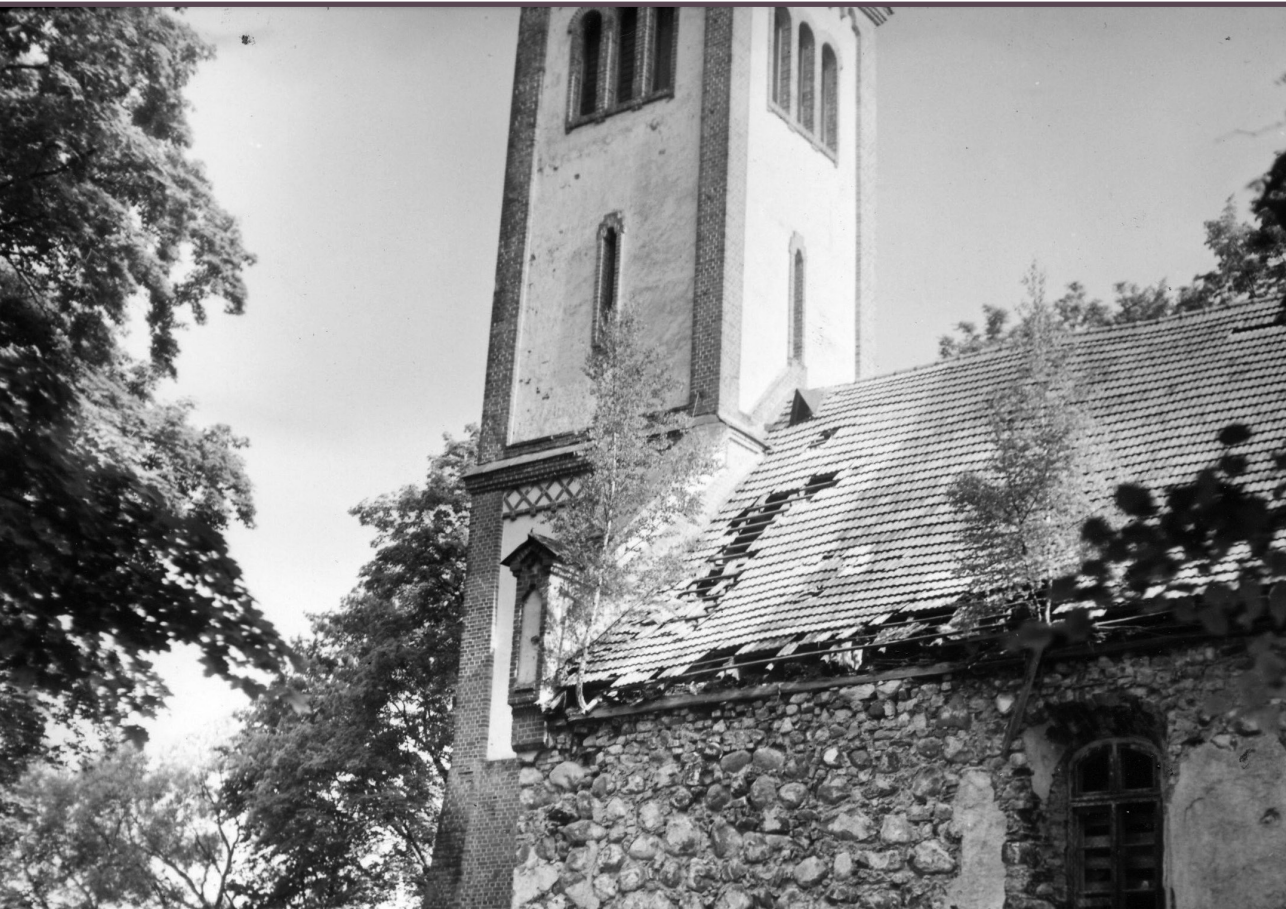


RIGA TECHNICAL  
UNIVERSITY

**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 Materials and Engineering Systems

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**METODOLOGY TO PROVIDE  
A CONSERVATION MICROCLIMATE  
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BUILDINGS**

**Doctoral Thesis**

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ANATOLIJS BORODIŅECS

Riga 2026

## ANOTĀCIJA

Latvijā ir 226 kulta ēkas ar valsts nozīmes pieminekļa statusu, kā arī aptuveni 2378 kustami un nekustami valsts nozīmes pieminekļi, kas atrodas šajās un citās kulta ēkās. Šie objekti ir svarīgi Latvijas kultūras mantojuma elementi, kas prasa īpašu pieeju saglabāšanai. Viena no galvenajām problēmām kultūras pieminekļu saglabāšanā ir mikroklimats, kas ietekmē to stāvokli un konservāciju. Tomēr Latvijā, Eiropā un citūr pasaulē nav izstrādāti normatīvi, kas regulētu konservējoša mikroklimata gaisa parametrus, piemēram, temperatūru un relatīvo mitrumu, un to pieļaujamās robežas. Atšķirībā no Eiropas, Baltijas valstīs ir būtiskas atšķirības mikroklimatos, kas jāņem vērā, izstrādājot piemērotas konservācijas metodes. Šī darba mērķis ir noteikt vēsturisko kulta ēku konservējoša mikroklimata gaisa parametru robežvērtības un nodrošinašanas vadlīnijas.

Pētījums balstās uz sākotnējiem mikroklimata mērījumiem astoņās baznīcās, kas veikti, izstrādātu darba uzdevumus un struktūru. Pamatojoties uz izstrādāto pētījuma struktūru apkopoti 361 Latvijas baznīcu dati, kuri tika analizēti, lai izveidotu baznīcu tipoloģiju pēc to norobežojošo konstrukciju veidiem un telpiskās struktūras. Pētījums parādījis, ka visizplatītākais baznīcu veids Latvijā ir vienjoma baznīcas, kuras raksturo 238 no 261 baznīcas. Šīs baznīcas tiek definētas kā ēkas ar vienu galveno telpu un apjomu, kas veido vienotu, bieži vien augstu telpu, kurā mitruma un temperatūras izmaiņas ir salīdzinoši vienmērīgas. Turpmākie padziļinātie mērījumi tika veikti četrās baznīcās vienjoma Krimuldas mūra un Turaidas koka baznīcās, kā arī centriskā tipa baznīcā - Rīgas Jēzus koka baznīcā, un trīsjomas baznīcā – Liepājas Svētās Trīsvienības mūra katedrālē.

Krimuldas baznīcā veiktie mērījumi ietvēra astoņus dažādus punktus, kuros tika mērītas gaisa temperatūras un virsmu temperatūras izmaiņas dažādos laika periodos, iegūstot svarīgu informāciju par siltuma izplatību izstarojuma un konvekcijas ceļā. Datalizēti temperatūras mērījumu rezultāti arī parādīja viduslaiku mūra ēkās lielu akumulācijas ietekmi. Temperatūras un relatīvā mitruma mērījumu rezultāti ļāva aprēķināt gaisa mitruma koncentrāciju un absolūto mitrumu, un uz tā pamata ir izanalizēta ēkas iekšējo un ārējo gaisu mijiedarbība un noeiktas maksimālās pieļaujamās gaisa temperatūras un mitruma koncentrācijas. Kā arī aprēķini atklāj mitruma iztvaikojumu 1 – 2 kg/g no ēkas konstrukcijām, ko svarīgi ir ņemt vērā projektējot AVK (apkures, ventilācijas, kondicionēšanas) sistēmas.

Tika izpētīts, ka ventilācijas un gaisa kondicionēšanas projektēšana jāusāk ar tehnoloģisko un cilvēku aktivitāšu analīzi telpā, kā arī ārējo klimatu ietekmes izvērtēšanu. Tomēr šiem faktoriem nevajadzētu būt saistītiem tikai ar ventilācijas plūsmu vai kondicionētā gaisa apriti telpā. Ventilācijas un gaisa kondicionēšanas procesu analīze psihrometriskajās diagrammās vai Molljē diagrammās ir izšķiroša ilgtspējīgu sistēmu projektu izstrādē un gaisa apstrādes iekārtu veida, dzesēšanas un apkures jaudu noteikšanā.

Pētāmām baznīcām tika izstrādāti IDA ICE (IDA Indoor Climate and Energy) programmas modeļi un no iegūtajiem rezultātiem tika aprēķināts gaisa izmaiņu procesu virzieni, kas tiek modelēti, izmantojot Molljē diagrammu. Tika arī veikta IDA ICE programmas salīdzināšana ar iegūtajiem mērījumiem, secinot, ka programma neņem vērā mūra ēku lielo siltuma akumulāciju, kas būtiski ietekmē rezultātus, it īpaši viduslaiku baznīcās.

Pamatojoties uz iegūtajiem datiem, tika izstrādāta metodoloģija kā nodrošināt vēsturiskās baznīcās konservējošu mikroklimatu, šī metodoloģija balstās uz pētījumos iegūtajiem rezultātiem. Pamatojoties uz iegūtajiem rezultātiem, tika izstrādāta arī vadlīnijas ēku lietotājiem

un restauratoriem, kas sniedz praktiskus norādījumus par mikroklimatu kontroli un pielāgošanu dažādos klimatiskajos apstākļos, lai nodrošinātu ilgtermiņa saglabāšanu. Šīs vadlīnijas ietver ieteikumus par piemērotākajiem vērtību diapazoniem dažādiem baznīcu tipiem un sniedz praktisku instrumentu ēku konservēšanai, izmantojot mūsdienīgas tehnoloģijas un pētījumus iegūtos datus.

Iegūtā konservējos mikroklimata nodrošināšana metodoloģija un norādījumi lietotājiem ir izmantotjami arī viduslaiku pilīs, kurās ir ierīkoti muzeji.

## ABSTRACT

In Latvia, there are 226 religious buildings with national monument status, as well as approximately 2378 movable and immovable national monuments located in these and other religious buildings. These objects are important elements of Latvia's cultural heritage that require special approaches for preservation. One of the main challenges in cultural heritage preservation is the microclimate, which affects the condition and conservation of these buildings. However, there are no regulations in Latvia or Europe that define the air parameters for a conservation microclimate, such as temperature and relative humidity, and their acceptable limits. Unlike Europe, the Baltic States have significant differences in microclimates that must be considered when developing suitable conservation methods. The aim of this study is 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 through detailed measurements and analysis of different church typologies.

The study is based on initial microclimate measurements taken in five churches to develop the tasks and structure of the dissertation. Based on the developed research structure, data from 361 Latvian churches were collected and analysed to create a typology of churches based on the types of their enclosing structures and spatial characteristics. The research showed that the most common type of church in Latvia is the single-nave church, represented by 238 out of 261 churches. These churches are defined as buildings with a single main space and volume, forming a unified, often high space in which moisture and temperature variations are relatively uniform. Further detailed measurements were conducted in four churches: the single-nave Krimulda masonry Church, Turaida wooden Church, the central-plan Church of Jesus in Riga, and the three-nave Holy Trinity Cathedral in Liepāja.

In Krimulda Church, measurements were taken at eight different points where air and surface temperature variations were recorded over different time periods, providing valuable information about heat distribution through radiation and convection. Detailed temperature measurements also revealed the significant thermal mass impact in medieval masonry buildings. Temperature and relative humidity measurements allowed for the calculation of air humidity concentration and absolute humidity, and based on this, the interaction between the building's indoor and outdoor air was analysed, determining the maximum permissible air temperature and humidity concentrations. The calculations also revealed moisture evaporation of 1–2 kg/g from the building's structures, which is crucial when designing HVAC systems.

It was found that the design of ventilation and air conditioning systems should begin with analysing both technological and human activities within the space, as well as evaluating the impact of external climates. However, these factors should not be solely tied to ventilation flow or conditioned air circulation within the room. Analysing ventilation and air conditioning processes on psychrometric charts or Mollier diagrams is crucial for developing sustainable system projects and determining the type, cooling, and heating capacities of air handling units.

The models of the studied churches were developed using the IDA ICE program, and based on the results obtained, the directions of air change processes were calculated and modelled using the Mollier diagram. A comparison of the IDA ICE program with the obtained measurements showed that the program does not account for the significant thermal mass of masonry buildings, which substantially affects the results, particularly in medieval churches.

Based on the obtained data, a methodology was developed to ensure a conservation microclimate in historical churches, and this methodology is based on the findings from the study. Additionally, guidelines for building users and restorers were developed, providing practical instructions for controlling and adjusting the microclimate in various climatic conditions to ensure long-term preservation. These guidelines include recommendations for optimal value ranges for different types of churches and provide a practical tool for building conservation using modern technologies and data obtained from the research.

The methodology for ensuring the conservation microclimate and the guidelines for users can also be applied in medieval castles, where museums are established.

## LIST OF PAPERS

### **Paper I**

Metals, M., Lesinskis, A., Turauskis, K., Martin. Control of Indoor Climate of Historical Cult Buildings, E3S Web of Conferences. Vol.246: Cold Climate HVAC & Energy 2021, [10.1051/e3sconf/202124601005](https://doi.org/10.1051/e3sconf/202124601005)

### **Paper II**

Metals, M., Palcikovskis, A., Borodinecs, A., Lesinskis, A. Typology of Latvian Churches and Preliminary Study on Indoor Air Temperature and Moisture Behavior, MDPI – Buildings 2022, 12(9), 1396, [10.3390/buildings12091396](https://doi.org/10.3390/buildings12091396).

### **Paper III**

Metals, M., Lesinskis, A., Borodinecs, A., Turauskis, K. Preliminary Study on Indoor Air Temperature and Moisture Behaviour in 13th-Century Churches in Latvia MDPI – Sustainability, 2023, 12(9), 1396, [10.3390/su151813965](https://doi.org/10.3390/su151813965)

### **Paper IV**

Lesinskis, A., Strauts, U., Metals, M., Afonicevs, V., Millers, R. Ventilation and Air Conditioning Design Approach based on ASHRAE Psychrometric Chart and Mollier Diagram, Frontiers Media SA, [10.3389/fbuil.2024.1372288](https://doi.org/10.3389/fbuil.2024.1372288)

### **Paper V**

Metals, M., Lesinskis, A., Borodinecs, A., Turauskis, K. Study on indoor air temperature and moisture behaviour in historical churches, Elsevier – Energy & Building, 2024, 310, [10.1016/j.enbuild.2024.114083](https://doi.org/10.1016/j.enbuild.2024.114083)



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23.04.2025.

Mārtiņam Metālam

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

The National Heritage Board highly values the doctoral dissertation by Mārtiņš Metāls, carried out in the Institute of Sustainable Building Materials and Engineering Systems of Riga Technical University's Faculty of Civil and Mechanical Engineering, 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



24.04.2025. Nr.1-18/77

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#### Atsauksme

Ipaši 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 mikroklimate drošināšanu vēsturiskās ēkās. Šī pētījuma rezultāti sniedz visaptverošu un skaidru rīcības plānu vēsturisko ēku lietotājiem un uzturētājiem, kā Latvijas klimatiskajos apstākļos nodrošināt konservējošu mikroklimate vēsturiskās ēkās.

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

Pieminekļu nodaļas vadītājs

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The specially protected cultural monument – Turaida Museum Reserve – highly appreciates Mārtiņš Metāls’s doctoral dissertation in the Institute of Sustainable Building Materials and Engineering Systems of Riga Technical University’s Faculty of Civil and Mechanical Engineering on the conservation of cultural heritage and the provision of indoor microclimate in buildings. The dissertation 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

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# 1. INTRODUCTION

Historical churches are an essential part of Europe's cultural heritage. The buildings and their interiors, including liturgical and art objects, are documents of our cultural heritage that must be preserved for future generations. In the region of Latvia (Baltic states), the most significant microclimate issue in cultural and historical religious buildings is associated with uncontrolled indoor air humidity [1]. Uncontrolled elevated indoor air humidity either condenses on various cultural and historical values (paintings, equipment, structures) or infiltrates them, which in turn creates a favourable environment for the spread of various fungi, leading to the erosion of these cultural and historical values [1]–[3].

According to the data of the National Heritage Board of Latvia [4], there are:

- 226 religious buildings with the status of National Cultural Monuments (including churches, cathedrals, synagogues, prayer houses);
- 1385 movable art and cultural monuments of national significance (including paintings, dishes, etc.) located in religious buildings;
- 993 immovable art and cultural monuments of national significance (including altars, organs, benches, pulpits, interior and exterior details, etc.) located in religious buildings.

The European standard LVS EN15759-1:2012, adapted in Latvia, specifies “Indoor climate specification for conservation” [5] and emphasises that the humidity and temperature parameters of such a microclimate are aimed at preserving the objects in the space. The standard defines: "Conservation heating: Conservation heating uses heat to improve the indoor climate for conservation. The primary aim is to keep RH at a stable and appropriate level throughout the year in order to minimise damage due to RH variations and to prevent dampness and biodeterioration." Currently existing regulations and/or standards do not specify the threshold values for the parameters of a conservative microclimate.

The indoor air microclimate factors affecting such buildings are:

- I. User comfort requirements
- II. Thermal resistance of building envelope structures
- III. Influence of external and internal humidity
- IV. Number of visitors
- V. Warm air flows

I. User comfort requirements, according to the aforementioned standard, the parameters of a conservative microclimate are aimed at the preservation of the building and objects, not comfort requirements. The guidelines specified in standards and regulations do not negate the visitors' desire to stay in a religious building where comfort is also ensured. Therefore, we will consider the possible application of comfort level requirements in historical religious buildings. According to Latvian construction legislation [6], the indoor air temperature in different types of buildings should be between 16 °C and 22 °C, depending on the type of building and room usage. At the same time, Latvian legislation does not regulate or specify the desired air temperature in religious buildings. In residential and office buildings, Latvian construction legislation specifies indoor air temperatures from 20 °C to 22 °C, which is considered a comfort temperature for humans with a clothing insulation value of 1 clo and activity level of 1.2 met

for sedentary work. For religious buildings, we can apply the activity level of 1.2 met for sedentary activities, but the clothing insulation value of 1 clo cannot be applied during the heating season, as users of historical religious buildings visit in winter clothing, equivalent to 2 clo. However, standards and regulations do not foresee comfort temperatures with clothing insulation of 2 clo. In the San Vito Church in L'Aquila, Italy [7], the comfort level of indoor air temperature during the heating season with clothing insulation of 2 clo was studied, and it was concluded that if the indoor air temperature is maintained at 11.97 °C and the relative humidity at 63.5 %, the comfort level is essentially ensured.

II. The thermal resistance of the building envelope structures forms the building's insulation during the heating period, directly affecting the required amount of heating energy resources. Depending on the various thermal resistances of the building's envelope structures, different internal surface temperatures of these structures form, often creating so-called thermal bridges [8]. Frequently, due to the low internal surface temperatures of the envelope structures, condensation forms on them, which in turn creates a favourable environment for the spread of various fungi.

III. The influence of external and internal humidity directly increases or decreases the indoor air humidity if the building envelope structures have high infiltration. During the heating period, when the outdoor air is the driest, with high infiltration, the building air will be excessively dried, while the opposite can be true in summer periods [9].

IV. The number of visitors increases both the indoor air humidity and the indoor air temperature. One visitor releases 30–n70 grams of moisture and 15 watts of heat per hour, depending on the clothing insulation (clo) and the intensity of activity (met) [10].

V. Warm air flows, considering the large volumes of historical religious buildings, including ceiling height, during the heating period, can create significantly different surface temperatures of the building envelope structures and various objects depending on their location [11].

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).

Research goal: 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.

Research tasks:

- setting goals and hypothesis,
- critical analysis of existing research,
- development of religious building typology,
- measurement and analysis of microclimate in different building types,
- development of IDA models for different types of religious buildings and data analysis,
- determination of conservative microclimate threshold values for different types of religious buildings and development of methodology.

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.

**Paper I, "Control of Indoor Climate of Historical Cult Buildings"**, published in E3S Web of Conferences, Vol. 246: Cold Climate HVAC & Energy 2021. The contribution of the doctoral candidate 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. Addresses the methods and technologies used to control the indoor climate of historical religious buildings. 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 contribution of the doctoral candidate 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. 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 contribution of the doctoral candidate 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. 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 contribution of the doctoral candidate to the preparation of the publication is 10%, including the compilation of results, sample collection, as well as revision and editing. 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 by Elsevier in Energy & Building in 2024. The contribution of the doctoral candidate 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.

## 2. LITERATURE REVIEW

A comprehensive and critical review of the scientific literature was conducted within the framework of this Doctoral Thesis. The analysis is based on the introductory sections of Papers I, II, III, and V, as well as on the dedicated Literature Review sections of Papers II and III. These publications collectively examine existing research on indoor microclimate conditions in historic churches, with particular emphasis on temperature, humidity, heating strategies, and conservation requirements.

Types of literature and research approaches

The reviewed literature can be broadly classified into four main groups according to their research focus and methodological approach.

First, a substantial body of research addresses indoor climate monitoring in historic churches and other heritage buildings, primarily through long-term measurements of air temperature and relative humidity. These studies provide valuable descriptive insights into seasonal microclimate fluctuations and the influence of outdoor climate, building geometry, and heating operation. However, most of these works remain observational in nature and do not progress towards defining quantitative threshold values for a conservation microclimate. This limitation is consistently identified in the literature reviewed in Papers I, II, III, and V.

Second, several studies focus on heating systems and thermal comfort in churches, particularly aiming to identify energy-efficient or visitor-comfort-oriented heating solutions. A representative example is the study conducted in the Church of the Holy Cross in Harju-Risti, Estonia [12], which evaluates different heating strategies under cold climate conditions. While such research contributes to understanding energy use and comfort requirements, it does not address the preservation-oriented indoor climate criteria nor define allowable limits for temperature and humidity from a conservation perspective.

Third, a number of studies carried out in Southern and Central Europe investigate microclimate risks in historic churches during the warm season, when overheating and excessive humidity are the dominant concerns. These studies often examine cooling needs, ventilation strategies, and summer moisture risks. However, their results are strongly climate-dependent and cannot be directly transferred to the Baltic climate zone, where the most critical microclimate challenges occur during the cold season due to heating-induced drying or condensation risks. This geographical and climatic mismatch is highlighted across all reviewed publications.

Fourth, studies from Scandinavian countries [13] could be expected to provide closer climatic comparability. Nevertheless, as identified in the literature review sections of Papers II and III, these studies typically focus on relative humidity and temperature trends without analysing the humidity ratio or absolute moisture content of air. As a result, they do not capture the full moisture balance of indoor air and are unable to describe the direction and mechanisms of air parameter changes.

Limitations of existing standards and guidelines

The European standard LVS EN 15759-1:2012 “Conservation of cultural property – Indoor climate – Part 1: Guidelines for heating churches, chapels and places of worship”, which is referenced already in the introduction of this Doctoral Thesis, provides a conceptual framework for conservation heating. The standard emphasizes the importance of stable relative humidity and temperature to minimize material damage and biological deterioration.

However, as confirmed by the critical analysis conducted in Papers I – V, this standard does not define specific numerical threshold values for indoor air temperature, relative humidity, or humidity ratio that would ensure a conservation microclimate. Instead, it offers general principles and qualitative guidance, leaving the determination of acceptable air parameter limits to case-specific interpretation. This gap between normative guidance and practical design requirements represents a key unresolved issue in both standards and scientific literature.

#### Importance of humidity ratio analysis

A central methodological limitation identified in the reviewed literature is the predominant reliance on relative humidity (RH) as the sole moisture indicator. While RH is useful for assessing surface condensation risk, it is highly temperature-dependent and does not fully describe the actual moisture content of indoor air.

As demonstrated and discussed in Papers I, III, and V, the humidity ratio (or absolute moisture content) is a critical parameter for understanding indoor air processes, especially in heated historic churches. Analysis of humidity ratio enables the identification of moisture sources, evaluation of moisture excess, and determination of the direction of air parameter changes during heating or occupancy periods. Without this parameter, it is not possible to establish robust threshold values for a conservation microclimate or to assess condensation and mould growth risks in a physically consistent manner.

#### Identified research gap

Based on the systematic review of existing literature, a fundamental research gap is clearly identified: to date, no scientific publication defines quantitative threshold values of indoor air parameters for a conservation microclimate in historic churches, particularly for the Baltic climate region. Existing studies either focus on different climatic zones, prioritize thermal comfort or energy efficiency, or rely on incomplete moisture analysis.

This unresolved gap directly motivates the research presented in this Doctoral Thesis, which aims to determine conservation-oriented indoor air parameter thresholds by combining detailed measurements, humidity ratio analysis, building typology classification, and simulation-based assessment. The literature review thus provides a clear justification for the originality and necessity of the present research.

### 3. THEORETICAL BACKGROUND

The theoretical explanation [14] 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 forms 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 (Figures 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 historic 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 ( $Mad$ ). 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. By 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.

## 4. PRESENT STUDY

Before the start of the study, the research methodology and structure were developed, as shown in Fig. 3.1. This framework served as the basis for data collection, analysis, and interpretation throughout the research process. As the first step of the study, the hypothesis, aim, and tasks are defined, based on the theoretical justification of air parameter changes presented in Paper IV and the initial research results obtained in Paper I. In the next step, a critical analysis of existing studies is carried out, reflected in Papers I, II, III, and V. The following step involves a survey of churches and the development of different typologies according to the types of enclosing structures and spatial layouts, as presented in Paper II.

Based on the initial measurements (pre-study) presented in Paper I, decisions are made regarding the selection of appropriate measurement instruments and optimal measurement intervals. The pre-study results, obtained using different measurement intervals, indicate that in churches with a large air volume relative to floor area, as well as with a relatively low and variable number of occupants, fluctuations in air parameters exhibit a pronounced cumulative character. This behavior is further influenced by the thermal and moisture storage capacity of the building structures, resulting in slow dynamics of microclimate parameter changes and consequently justifying the use of longer measurement intervals.

At the same time, the possibilities for remote data acquisition were evaluated. However, considering that the main study object is Krimulda Church—the oldest functioning church in Latvia—located in a rural area within the valley of the Runtīņa River, a small tributary of the Gauja River basin, where mobile network coverage is limited, and where the massive masonry walls (up to 2 m thick) significantly attenuate signal transmission, stable long-term remote data transmission could not be ensured. Therefore, a methodological decision was made to use local data logging with periodic data retrieval, ensuring continuity of measurements and data reliability.

At the same time, the pre-study results were used to evaluate the necessity of performing in-situ measurements of wall thermal transmittance (U-value) and wall moisture content. The findings indicate that the massive masonry structures of historic churches are characterized by significant thermal mass, leading to strongly non-stationary heat transfer processes. It should be emphasized that the absence of in-situ U-value measurements does not affect the validity of the research results, as the selected methodology is based on the analysis of indoor air parameters, which directly characterize the microclimate and its impact on the conservation of cultural heritage. In addition, the influence of capillary moisture was observed, further affecting the thermal behavior of the structures. Considering that such constructions are characterized by strongly non-stationary heat and moisture transfer processes, the U-value as a steady-state parameter is not sufficiently representative in this context. Moreover, medieval masonry walls are not homogeneous and do not have uniform thickness—they are often tapered (thinner in the upper parts), with heterogeneous material composition and internal structure, which makes it difficult to determine a representative U-value from a single measurement point. Similarly, point-based wall moisture measurements do not adequately capture the spatial distribution and dynamic behavior of moisture in such massive and heterogeneous constructions. Therefore, these measurements were not included in the scope of this study.

In the next stage of the research, in-depth microclimate measurements, air parameter calculations, and data analysis are conducted for the identified church types, as reflected in

Papers III and V. The subsequent step involves the development of simulation models for these same church types in the IDA ICE (IDA Indoor Climate and Energy) software, where building use scenarios identical to actual conditions are simulated and compared with measurement and calculation data, as presented in Chapter 5 of this Thesis.

IDA ICE software is used for the development of simulation models in this study, and its applicability was evaluated during the methodological design phase. IDA ICE is widely applied in the design of building engineering systems, particularly for the analysis of ventilation and heating systems, including the determination of building heat losses.[15] The use of this software ensures the comparability of the research results with methods applied in engineering practice. IDA ICE is a dynamic multi-zone building performance simulation tool for analyzing indoor climate, energy use, and air quality, and its models have been validated against experimental data in several studies. [16] The simulation results obtained in IDA ICE are compared with measurement and calculation data in order to evaluate their consistency, which is a commonly applied approach in building performance and indoor climate studies. In addition, simulations are used to theoretically determine the direction of air parameter change processes. IDA ICE enables dynamic analysis of heat, air, and moisture (HAM) processes, including airflow and thermal behavior, allowing for a detailed assessment of indoor climate conditions. [16] The applicability of IDA ICE for indoor climate and energy analysis has been demonstrated in multiple studies, including investigations of building energy performance, indoor environmental quality, and comparisons of simulation tools.[17] By comparing simulation results with experimental data, it is possible to assess the accuracy and suitability of the software for microclimate analysis in historic churches.

In the next step, based on the comparison data obtained in the previous stage, air parameter threshold values are determined for the different church types with varying levels of occupancy. Finally, a methodology for ensuring a conservation microclimate in churches of different types and usage intensities is developed, as presented in Chapter 6 of this Thesis.

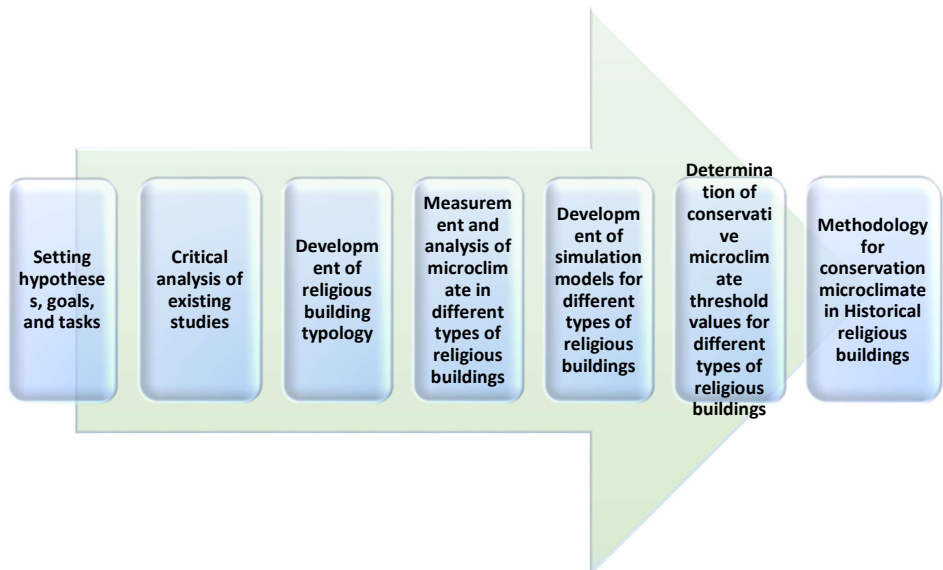


Fig. 3.1. Research structure.

## 4.1. Research 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, corners of external wall, ceilings, corners 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, a trimmed mean approach was applied. 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 %:

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

where  $n$  is the total number of observations,  $x_{(i)}$  represents the  $i$ -th ordered value of the dataset, and  $k = [0.1n]$  is the number of values removed from each tail [18].

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:

$$p_w = 6.112 \cdot e^{\left(\frac{17.67 \cdot T}{243.5 + T}\right)} \cdot \frac{RH}{100}, \quad (3.2)$$

where  $T$  is air temperature ( $^{\circ}\text{C}$ ),  $e$  is Euler's number [19], and  $RH$  is relative humidity (%). The air moisture ratio  $W$  (g/kg) is calculated from the partial pressure  $P_w$ :

$$W = 622 \frac{P_w}{P - P_w}, \quad (3.3)$$

where  $P$  is total pressure (Pa) [1], [20].

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):

$$W = \frac{622 \cdot \left(6.112 \cdot e^{\left(\frac{17.67 \cdot T}{243.5 + T}\right)} \cdot \frac{RH}{100}\right)}{P - \left(6.112 \cdot e^{\left(\frac{17.67 \cdot T}{243.5 + T}\right)} \cdot \frac{RH}{100}\right)}. \quad (3.4)$$

Based on temperature and  $RH$  measurements, the difference between indoor and outdoor air absolute humidity is calculated –  $v$  ( $\text{g}/\text{m}^3$ ), which is determined by the following equation:

$$v = \frac{P_w \cdot M}{R \cdot T}, \quad (3.5)$$

where  $M = 18.02$  is the molar mass of water vapour (g/mol), and  $R = 0.08314$  is universal gas constant (L·bar/mol·K) [21].

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).

$$v = \frac{RH}{100} \cdot \frac{6.112 \cdot e^{\left(\frac{17.67 \cdot T}{243.5 + T}\right)} \cdot 18.02}{(273.15 + T) \cdot 0.08314}, \quad (3.6)$$

where the excess moisture  $\Delta v$  ( $\text{g/m}^3$ ) is determined by the following equation:

$$\Delta v = v_i - v_e, \quad (3.7)$$

where  $v_i$  is the humidity by volume of indoor air ( $\text{g/m}^3$ ), and  $v_e$  is the humidity by volume of outdoor air ( $\text{g/m}^3$ ) [22].

## Measurements

Temp/RH/Light/Ext-Temp Kit (Fig. 3.2) at 30-minute intervals, with a measuring accuracy of  $\pm 2.5\%$  for relative humidity and  $\pm 0.2\text{ }^\circ\text{C}$  for temperature. These measurements were part of the studies presented in Papers III and V.

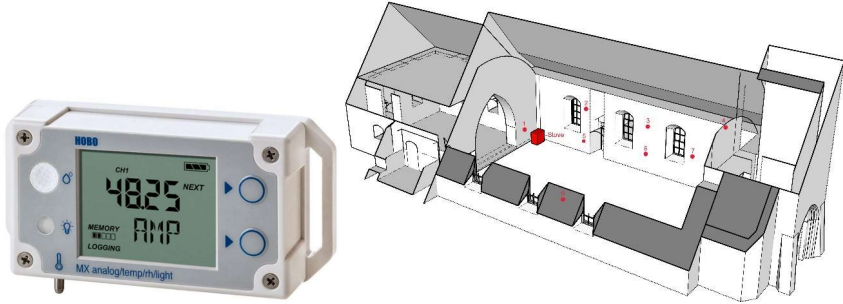


Fig. 3.2. Measuring instrument and location example in Krimulda Church [23].

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

## 4.2. 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 flows [24]. 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 chapter, based on Paper II, 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. 3.3).

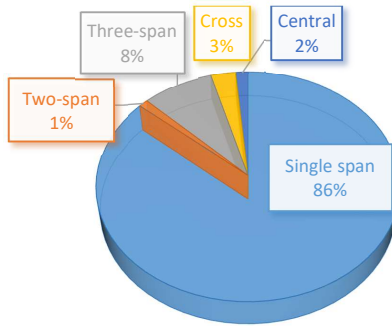


Fig. 3.3. Distribution of Latvian Lutheran churches by spatial layout (from Paper II).

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 ( $\lambda$ ) of masonry walls remained around 0.87 W/m·K throughout this period, while ceiling materials varied, resulting in a  $\lambda$  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. 3.4).

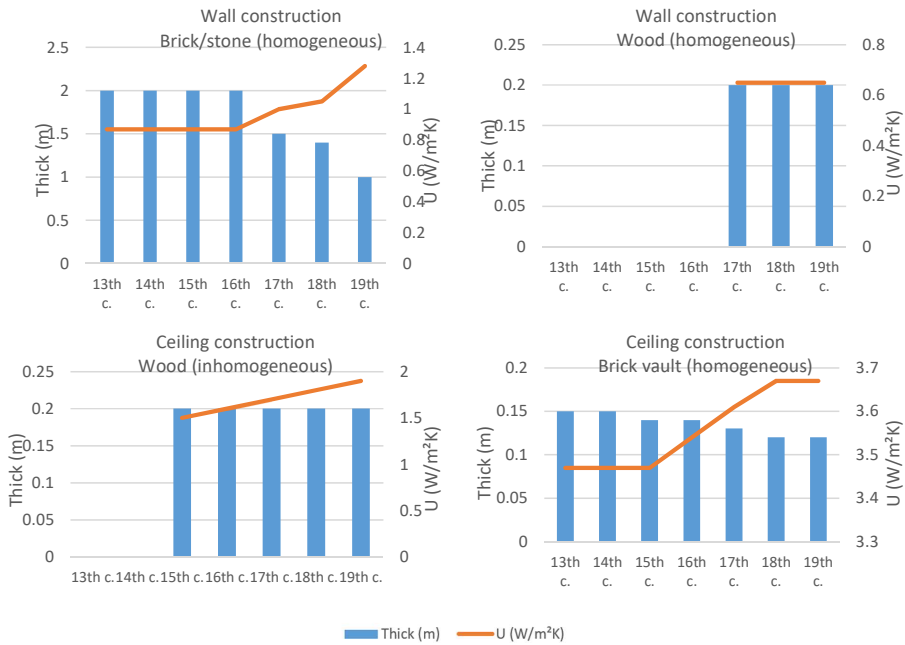


Fig. 3.4. Types, dimensions and thermal transmittance U of church constructions.

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 chapter serve as a foundation for further airflow modelling studies presented in Paper II.

### 4.3. Measurement results

#### 4.3.1 INITIAL THEORETICAL ASSESSMENT OF CONDENSATION RISKS

In Paper I, theoretical calculations were conducted to assess potential condensation risks on the surfaces of envelope structures in historic religious buildings with brick and wooden construction [4]. Measurements and calculations were conducted using three indoor air temperatures (6 °C, 12 °C, 18 °C) and three levels of relative humidity (40 %, 60 %, 80 %). Condensation temperatures were determined using the Mollier diagram, and building thermography was used to assess airflow characteristics.

Due to the significant thermal differences between brick and wooden buildings, they were evaluated separately. For brick churches with 1.6 m thick walls and 0.14 m brick vaults, the calculated thermal resistance was  $R_o = 1.06 \text{ m}^2\text{K/W}$  for walls and  $R_o = 0.29 \text{ m}^2\text{K/W}$  for ceilings. For wooden churches with 0.2 m thick walls and ceiling slabs filled with sand,  $R_o$  was  $2.73 \text{ m}^2\text{K/W}$  and  $1.04 \text{ m}^2\text{K/W}$ , respectively. These values were used to calculate surface temperatures at various points of the building envelope (walls, corners, ceilings) as shown in Fig. 3.5.

The results indicate that wooden churches generally pose a lower risk of condensation, especially when the RH stays below 60 %. However, elevated RH levels (e.g., 82 % in Turaida Church) significantly increase the risk.

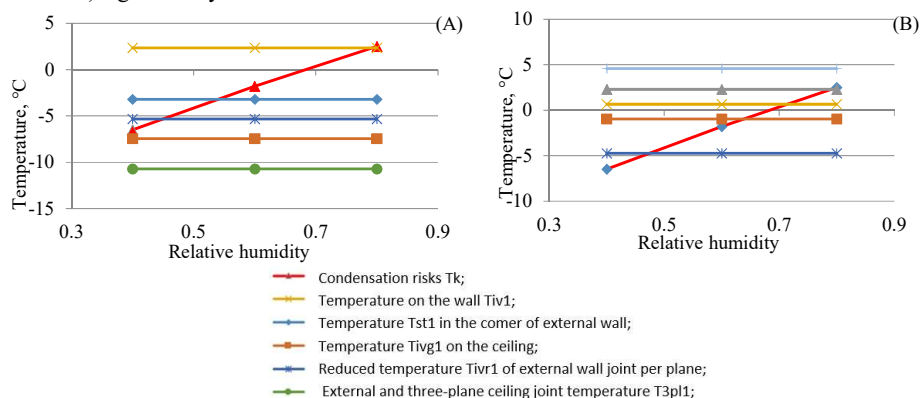


Fig. 3.5. Calculated wall and ceiling surface temperatures with indoor air temperature 6 °C: A – in brick churches, B – in wooden churches.

#### 4.3.2 IN-DEPTH TEMPERATURE AND HUMIDITY 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 [25], 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 (see Fig. 3.6). Therefore, this heating strategy cannot be defined as a heating system providing a preserving microclimate.

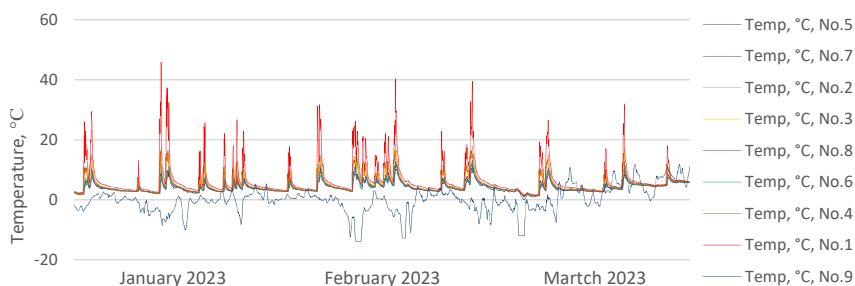


Fig. 3.6. Temperatures in the Krimulda Church.

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. 3.7).

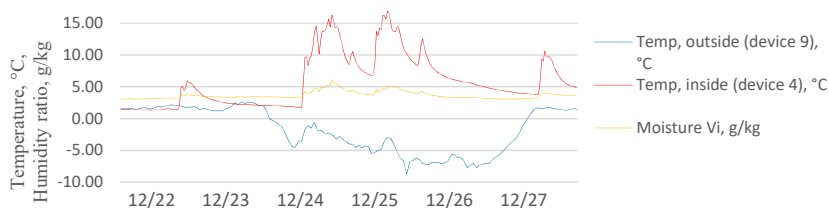


Fig. 3.7. Outdoor and inside moisture and temperature in the Krimulda Church on the balcony between 12/22/2022 and 12/28/2022.

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. 3.8).

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.

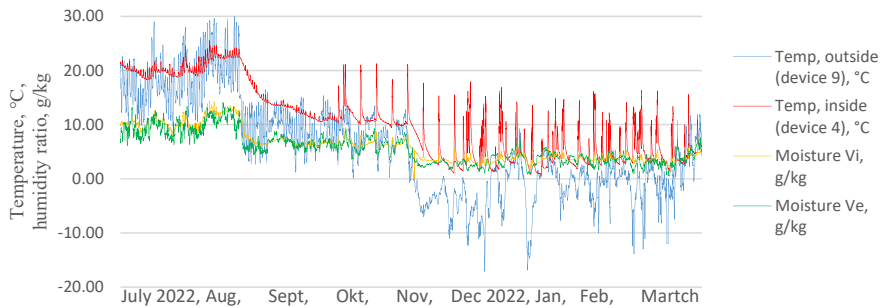


Fig. 3.8. Outdoor and inside humidity and temperature in the Krimulda Church on the balcony.

These results complement the theoretical condensation risk calculations from 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 to decrease potential condensation risks due to air temperature fluctuations.

Heating up the indoor air and a large number of simultaneous visitors in the church (0.41 pers/m<sup>2</sup> or 0.14 pers/m<sup>3</sup>) during the cold season increases the air moisture content by 2.66 g/kg. 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 [23] 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, if comparing the microclimate of Liepaja St. Trinity Cathedral to the Krimulda Church and Turaida Church, which do not have regular heating systems, that 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./m<sup>2</sup> or 0.04 pers./m<sup>3</sup>) 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 as well as 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 indoor air humidity ratio by 1.1 g/kg (Fig. 3.9), which is explained by moisture vapours from the building's structures and interior items.

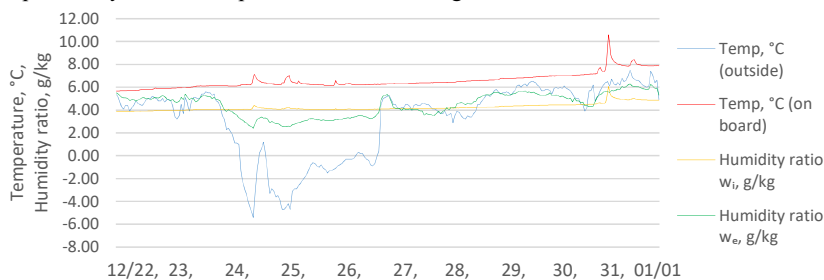


Fig. 3.9. Outdoor and inside moisture and temperature in Liepaja St. Trinity Cathedral on the board between 12/22/2022 and 01/02/2023.

### 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./m<sup>2</sup> or 0.087 pers./m<sup>3</sup>) do not create huge moisture fluctuations and the actual increase of indoor humidity is twice as less as the calculated one for the number of visitors. During the warm season periods, the microclimate of Riga Jesus Church is more stable than in 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. 3.10).

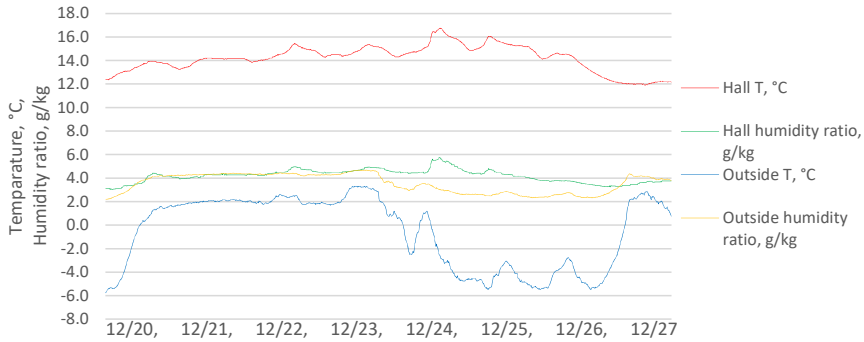


Fig. 3.10. Outdoor and inside humidity ratio and temperature in Riga Jesus Church in the hall between 12/20/2022 and 12/28/2022.

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 Church, Turaida Church, 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 levels – reaching 6 g/m<sup>3</sup> – 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. 3.11 (A)), excess moisture peaks during unstable late-summer weather with rapid fluctuations in outdoor humidity and precipitation.

In Turaida Church (Fig. 3.11 (B)), similar values were observed, primarily due to open doors and lack of climate control.

In Liepaja St. Trinity Cathedral (Fig. 3.11 ©), the highest excess moisture reached 4 g/m<sup>3</sup> during the cold season (October to April), a period not directly comparable to Krimulda and Turaida measurements.

In Riga Jesus Church (Fig. 3.11 (D)), excess moisture reaches 5 g/m<sup>3</sup> 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 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.

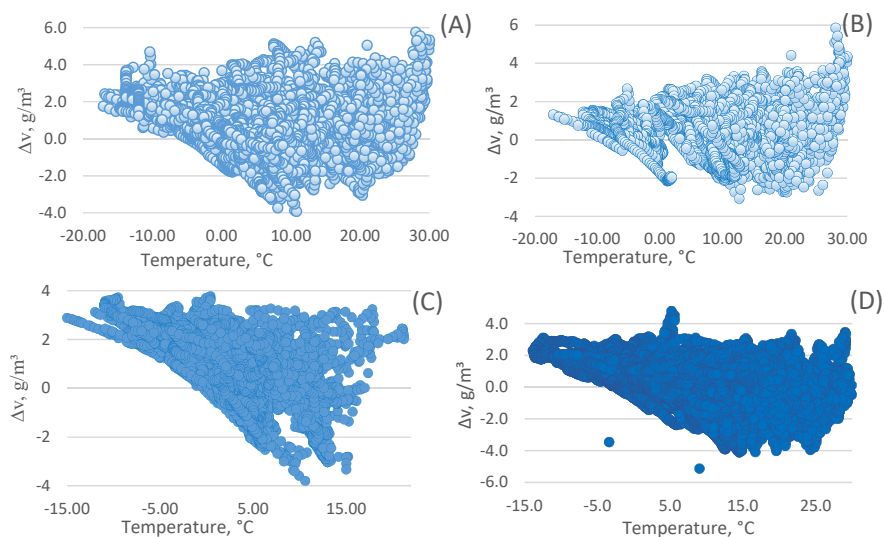


Fig. 3.11. Excess moisture: A) in the Krimulda Church on the balcony; B) in the Turaida Church on the lamp; C) in Liepaja St. Trinity Cathedral on the board; D) in Riga Jesus Church in the hall.

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.

## 5. SIMULATION

To determine the surface temperatures of the building's enclosing structures and the direction of air condition changes in the space for the four objects studied in Papers III and V – Turaida Church (Fig. 4.4), Krimulda Church (Fig. 4.1), Riga Jesus Church (Fig. 4.3), and Liepāja Holy Trinity Cathedral (Fig. 4.2) – simulation models are created using the IDA ICE

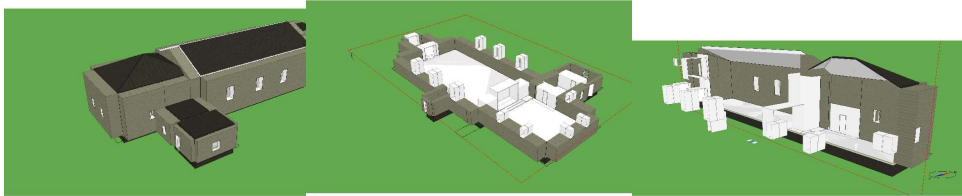


Fig. 4.1. IDA model of Krimulda Church.

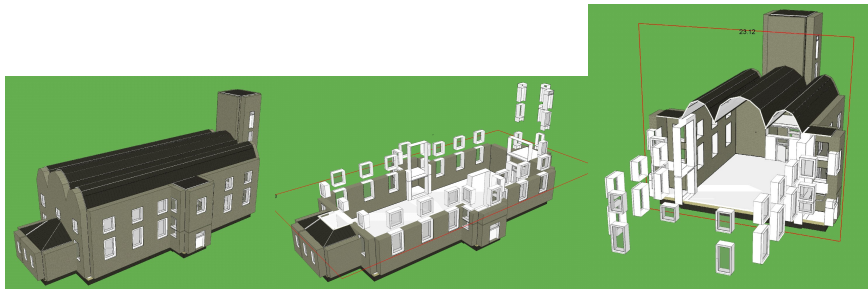


Fig. 4.2. IDA model of Liepāja St. Trinity Cathedral.

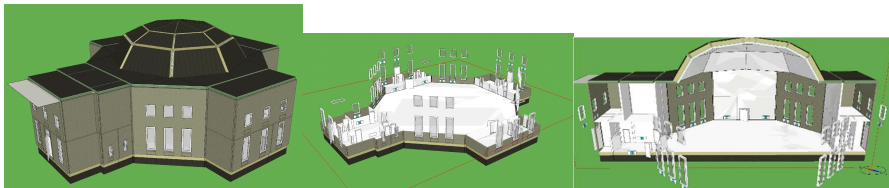


Fig. 4.3. IDA model of Riga Jesus Church .

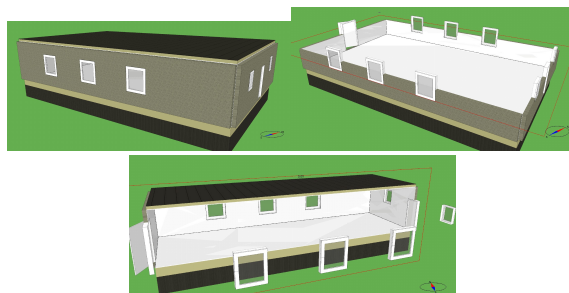


Fig. 4.4. IDA model of Turaida Church.

## 5.1. Masonry Liepāja St.Trinity Cathedral

The IDA ICE model of the Liepāja St. Trinity Cathedral was created considering the actual occupancy and heating system schedule, as reflected in Paper V, Table 1, and Section 3.2 [11]. The visualisation of the surface temperatures of the simulation model is shown in Fig. 4.5. Examining the measured temperatures in Liepāja St. Trinity Cathedral in Paper V and the dew point shown in Fig. 4.6, we see that there are no condensation risks at the measured points. However, examining the internal surface temperatures of the simulation model throughout the church (Fig. 4.5), we see that there is indeed a risk in the tower room where the temperature is below  $-2\text{ }^{\circ}\text{C}$ . In the cathedral's main hall, on the balcony (gallery), there is a Baroque-period organ, where the surface temperature of the outer walls is shown to be below  $0\text{ }^{\circ}\text{C}$ .



Fig. 4.5. Temperatures of inside surfaces.

If we look at the individual hall ceiling surface temperatures near the organs throughout the year (Fig. 4.7), we can see that the lowest surface temperatures are reached in January ( $-2\text{ }^{\circ}\text{C}$ ) and February ( $-4\text{ }^{\circ}\text{C}$ ). Comparing the measured temperature with the simulated model of the ceiling surface temperatures (Fig. 4.7) seen in the dew point (Fig. 4.6), we observe that there is a risk of condensation during this cold period of the year. Considering also that the air supplied to these historic organs comes from the tower room through the second-floor duct, where the air temperature is even lower.

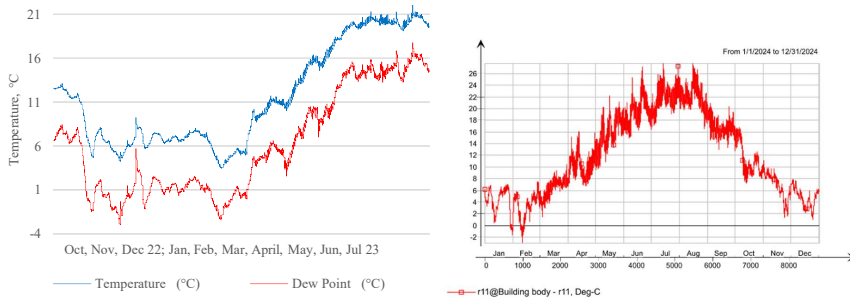


Fig. 4.6. Temperature and dew point measurements.

Fig. 4.7. Ceiling temperature.

According to the IDA ICE simulation data, the room unit heat for the large hall is either 39.932 kW or 38.65 kW. Additionally, the maximum occupancy of the large hall is approximately 499 occupants. Given that each visitor emits about 30–50 g/h of moisture depending on clothing and physical activity intensity, we can determine the direction of the air state change process in the room, denoted as  $\epsilon$ . The calculated direction of the air state change process in the large hall is 7.0 kJ/kg (Fig. 4.8), which slightly differs from the measured value.

The theoretical calculation of the air state change direction, differing from the measured value, indicates that there is indeed a higher increase in moisture content in the room, confirming moisture condensation from the building's structures.

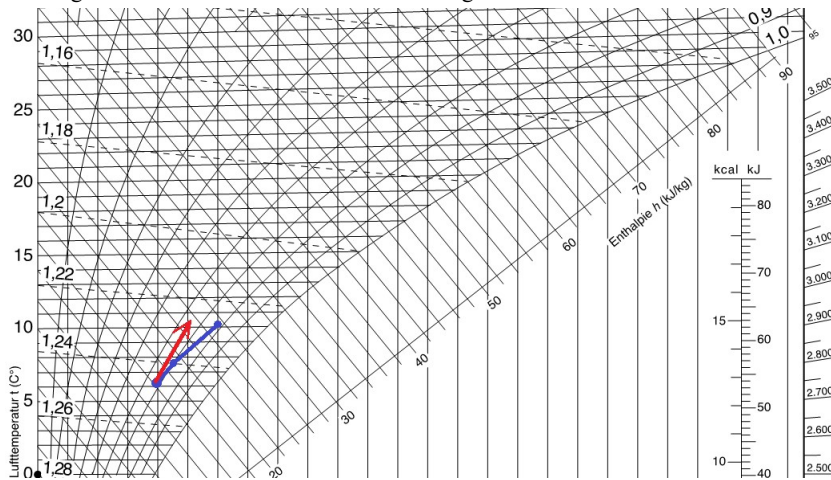


Fig. 4.8. Angular coefficient of process changes of air parameters on Molier diagram (red –  $\epsilon$ , blue – measurement) in the Liepaja St.Trinity Chatedral

## 5.2. Wooden Riga Jesus Church

Developing the IDA ICE model for Riga Jesus Church, visitor and heating system operation schedules were used as the basis, referenced from Paper V, Table 1 and Section 3.3 [11]. Reviewing the visualisation of internal surface temperatures of the church's enclosing structures in Fig. 4.9, various temperatures across different rooms of the building are evident, showing temperature differences of several degrees. Therefore, let us delve deeper into the large hall, which accommodates a significant number of people as discussed in Paper V.

From Fig. 4.9, it is observed that the internal surface temperatures of the enclosing structures in the large hall are above 0 °C. To assess potential risks, critical load moments are examined by reviewing surface temperatures over a one-year period (Fig. 4.10).

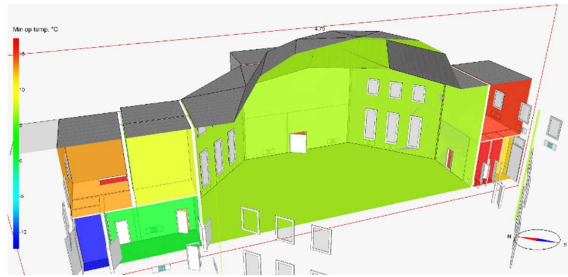


Fig. 4.9. Temperatures of Riga Jesus Church's inside surfaces.

In Fig. 4.10, it is evident that during the cold period of the year, the internal surface temperatures of certain enclosing structures are below 0 °C. Upon closer inspection of each of these surfaces, it is noted that the exterior door and window structures (Fig. 4.11) within rooms with lower air temperatures exhibit temperatures below 0 °C. Conversely, the lowest internal surface temperature of all enclosing structures in the large hall throughout the year is above 2 °C. This surface temperature is reached during the midweek period when there are no visitors in the building and indoor air temperatures are less heated, around 6 °C, contributing to these significant fluctuations.

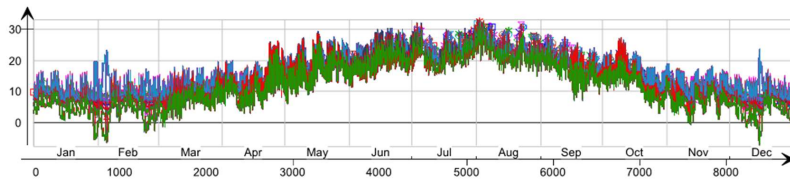


Fig. 4.10. Temperatures of Riga Jesus Church's inside surfaces.

In the simulation model, the room unit heat for the large hall is 10.802 kW. According to the analysis in Paper V, on 24 December 2022, between 5 PM and 6 PM, there were approximately 500 visitors present. It is noted that the direction of air state changes in the room was calculated as  $\epsilon = 3.2 \text{ kJ/kg}_w$ . The calculated direction of air state changes and the measured data from 24 December are depicted on the Mollier diagram (Fig. 4.11).

From the diagram, it is observed that there is a discrepancy between the calculated and measured values, suggesting either a higher actual heat input or lower air moisture content, possibly due to significant outdoor air infiltration. Comparing the measured data from this church with measurements from four other churches, it is evident that this church exhibits the highest temperature during the cold period. This higher internal and external air temperature fluctuation increases the rate of outdoor air infiltration, as confirmed by the excess moisture calculations detailed in Paper V.

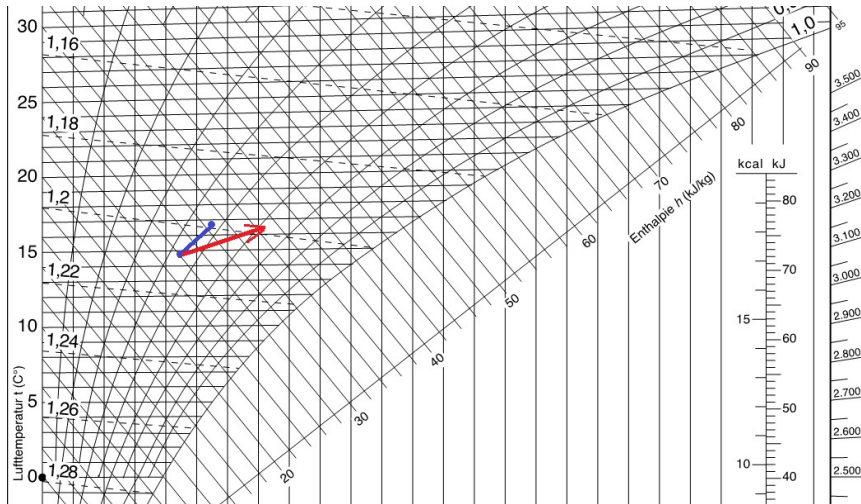


Fig. 4.11. Angular coefficient of process changes of air parameters on Mollier diagram (red –  $\epsilon$ , blue – measurement) in the Riga Jesus Church.

### 5.3. Masonry Krimulda Church

Developing an IDA ICE model for Krimulda Church, heating and visitor intensity data are reflected in Paper III and Table 1 of Paper V. The simulation model's minimum surface temperatures of the enclosing structures are depicted in Fig. 4.12. Comparing these simulated minimum surface temperatures with the actual measurements detailed in Paper III, it can be concluded that the IDA ICE simulation model does not provide accurate data, primarily due to the intermittent heating strategy employed in the building.

The intermittent heating strategy means that during the cold period of the year, the building is heated only once a day or once a week, while it remains unheated the rest of the time. Additionally, the church's enclosing structures consist of granite masonry exterior walls with a thickness of 1.6 meters, which have significant thermal mass. This indicates that the IDA ICE simulation model does not account for the thermal accumulation in the walls.

Comparing the IDA ICE model's surface temperatures over the year (Fig. 4.13) with the actual measured temperatures in Paper III, particularly at measurement point No. 6 on the wall surface (Fig. 3.6), it is evident that the actual surface temperature does not drop below 0 °C. This confirms that for buildings with significant thermal mass in their enclosing structures and employing intermittent heating strategies, the IDA ICE simulation may not provide comprehensive data.

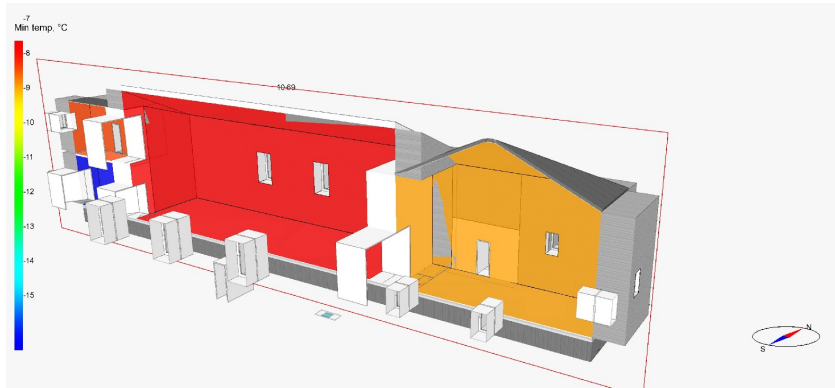


Fig. 4.12. Temperature of Krimulda Churh’s surfaces.

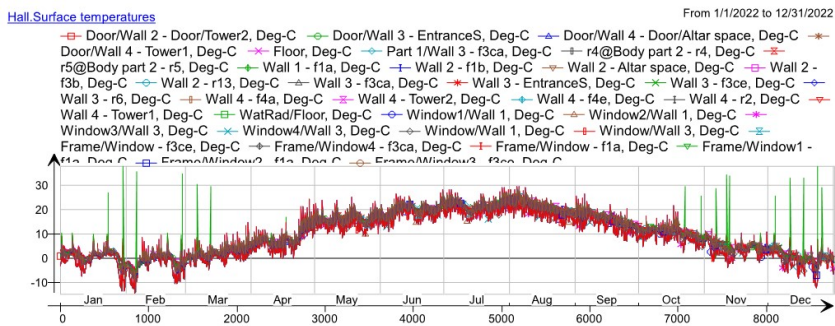


Fig. 4.13. Temperatures of Krimulda Church’s inside surfaces.

From the calculated heat consumption for the hall at 44.788 kW and the maximum simultaneous visitors reached on 24 December 2022 (as per Paper III), being 456 persons, the direction of air state change process  $\epsilon = 6.33$  kJ/kgw is determined (as shown in Fig. 4.14). This value differs from the measured data. Similar to the case with Liepaja Cathedral, this discrepancy is attributed to the fact that the calculation does not account for moisture evaporation from the building's structures, which has been identified and described in Paper III.

In buildings like Krimulda Church and Liepaja Cathedral, where significant thermal mass in the construction is employed, moisture evaporation from the building materials can significantly affect the indoor air conditions. This moisture evaporation process is not typically accounted for in simplified energy simulation models like IDA ICE, leading to discrepancies between simulated and measured data, especially in terms of humidity-related parameters. Therefore, when analysing such buildings, it is crucial to consider the actual physical properties and behaviours of the building materials and their interaction with the indoor environment.

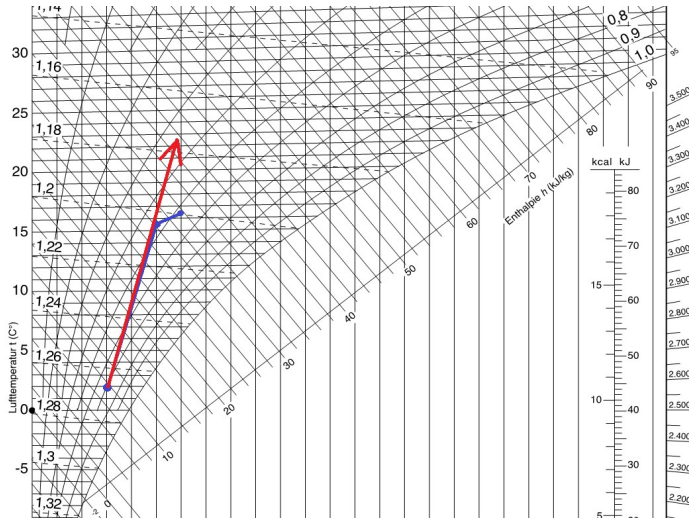


Fig. 4.14. Angular coefficient of process changes of air parameters on Molier diagram (red –  $\epsilon$ , blue – measurement) in the Krimulda Church.

### 5.4. Wooden Turaida Church

Based on the graphs of heat consumption and visitor count developed for Turaida Church in the IDA ICE model, as reflected in Paper V, the visualisation of minimum surface temperatures of the enclosing structures from the simulation model is shown in Fig. 4.15. To assess potential risks, critical load moments are examined by reviewing surface temperatures over a one-year period, depicted in Fig. 4.16.

Figure 4.16 provides insights into the variations in surface temperatures throughout the year, highlighting critical periods where temperatures approach or drop below certain thresholds. This analysis helps in identifying potential risks such as condensation or discomfort due to low surface temperatures, especially in historical buildings like Turaida Church, where maintaining optimal indoor conditions is crucial for preservation and comfort.

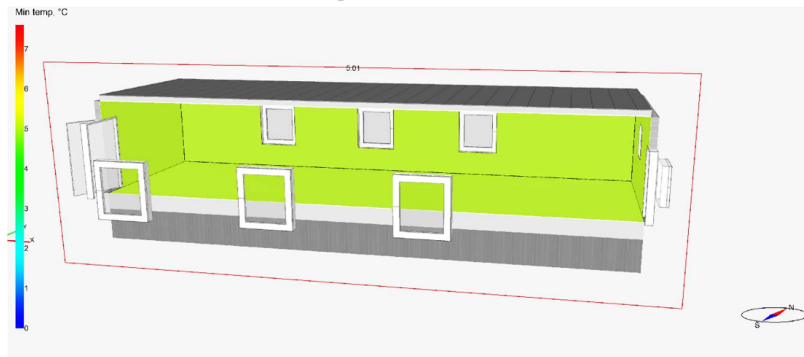


Fig. 4.15. Temperature of Turaida Church’s inside surfaces.

Comparing the minimum surface temperatures from the IDA ICE simulation model with the indoor air temperatures in Fig. 11 in Paper V, it is evident that the IDA ICE model shows

higher surface temperatures during the cold period compared to the measured air temperature during midweek periods when the room is not heated. Similar to the case of Krimulda Church's IDA ICE model, here too, the simulation model does not provide precise information when intermittent heating strategies are employed.

Intermittent heating strategies result in varying temperatures within the building's structure and objects, either accumulating higher or lower thermal masses. This variability is not adequately captured by simplified energy simulation models like IDA ICE, which assume steady-state conditions or do not account for the thermal mass dynamics and moisture evaporation accurately. As a result, the simulation may overestimate or underestimate surface temperatures, especially in periods when heating is intermittent.

For accurate assessments and risk evaluations in historical buildings like Turaida Church, where preserving optimal indoor conditions is critical, it is essential to consider detailed building physics and dynamic thermal behaviours in simulations. This includes proper modelling of intermittent heating effects, thermal mass interactions, and moisture dynamics within the building's structure.

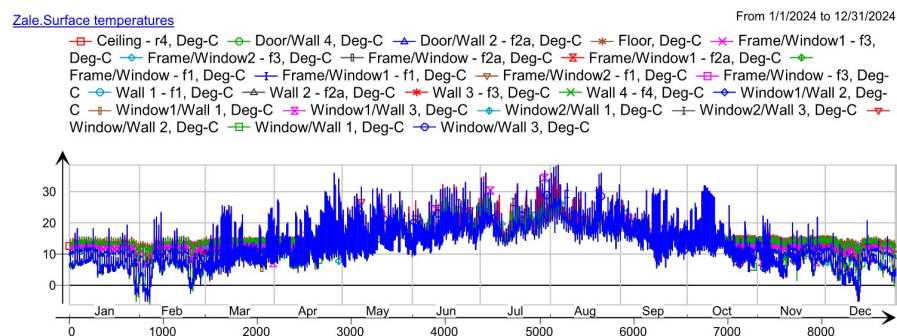


Fig. 4.16. Temperature of Turaida Church's inside surfaces.

Based on the IDA ICE model data for Turaida Church, the heat supplied is 13.385 kW. According to the data from 24 December 2022, with 70 simultaneous visitors (from Paper V), the direction of air state change process  $\varepsilon = 17 \text{ kJ/kgw}$  is determined, as depicted in Fig. 4.17. The actual measured change in indoor air state differs from the calculated value, which could be attributed to adjustments from the building's structure under periodic heating strategies, as observed between measured points No. 1 and No. 2 in Fig. 4.17.

Periodic heating strategies in historical buildings like Turaida Church lead to variations in thermal responses from the building's construction. These variations influence how heat is absorbed and released by the building's materials, affecting both the indoor air temperature and humidity levels differently than what might be simulated in a static model like IDA ICE.

Measured discrepancies between calculated and actual indoor air state changes highlight the complexity of maintaining consistent environmental conditions in historical buildings, where thermal mass and moisture dynamics play crucial roles. Accurate modelling requires considering these dynamic interactions to better predict and manage indoor climate variations effectively.

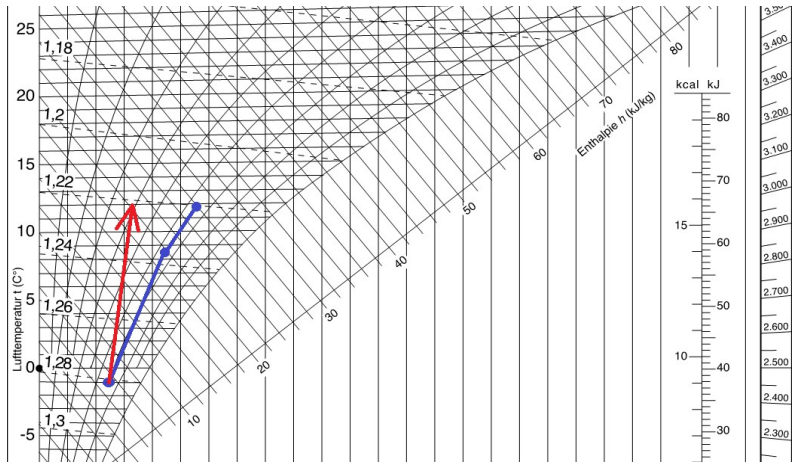


Fig. 4.17. Angular coefficient of process changes of air parameters on Molier diagram (red –  $\epsilon$ , blue – measurement) in the Turaida Church.

## 6. METODOLOGY FOR CONSERVATION MICROCLIMATE IN HISTORICAL RELIGIOUS BUILDINGS

The indoor climate of historical churches is primarily influenced by heating the air during cold periods. Therefore, the church heating will be considered as the primary classification going forward. Additionally, taking into account standard EN 15759-1, which categorises buildings as without heating, with intermittent heating, and with continuous heating. Based on indoor microclimate measurements and calculations from Paper III (Krimulda Church) and Paper V (Turaida, Riga Jesus Church, and Liepaja Cathedral), building usage intensity and the primary classification of "with heating" and "without heating" will be considered.

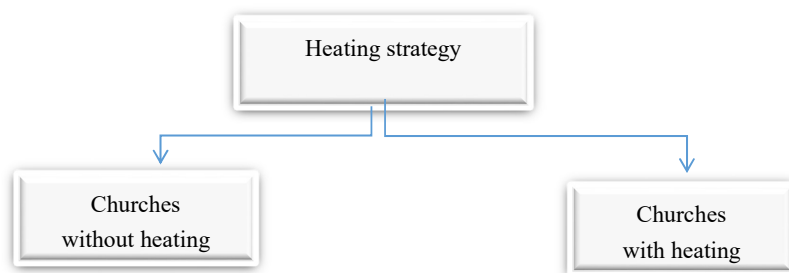


Fig. 5.1. Primary heating strategy.



Fig. 5.2. Construction types of churches.

Considering the typology of religious buildings (from Paper II), the primary distinction is made based on the types of enclosing structures, as their thermal resistance and thermal mass values vary significantly between buildings with wooden walls and those with masonry walls. Therefore, going forward, within each classification based on heating strategy or usage intensity, two subsections will be delineated based on the types of enclosing structures: churches with wooden walls and churches with masonry walls.

### 6.1. Historical religious buildings without heating

In this study, the examined Krimulda Church (masonry) and Turaida Church (wooden) are used continuously every day throughout the year, but heating is provided only once a week during the winter period for religious activities. Therefore, the microclimate data of these churches on weekdays correspond to churches without heating.

In Paper V, Turaida Church is categorised as a wooden single-nave church, for which air parameter measurements and humidity concentration calculations were conducted. This means that, based on this church's data, air parameters can be determined for wooden churches without heating. In Section 3.1 "Moisture in the Turaida Church" of Paper V, a detailed analysis is provided for the hottest summer day with the highest indoor air humidity on 27 August 2022,

depicted in Fig. 1. Conversely, during the winter period, the analysis focuses on 24 December 2022, the day with the highest simultaneous visitor count, resulting in the highest indoor air heating and humidity content during this period, illustrated in Fig. 5.3 B.

In the conclusions of Paper V, Section 5.1 "Turaida," it is concluded that to avoid condensation risks during the winter period, either the minimum indoor air temperature should be maintained at 6.5 °C or the air should be dried to 3.5 g/kg, or visitor numbers should be restricted. Furthermore, it is concluded that there is a high risk of condensation during the summer period if the indoor air humidity ratio exceeds 10 g/kg, as shown in Fig. 5.3 A. If the air temperature rapidly decreases to 15 °C at measurement points No. 1 or No. 2, there is a risk of condensation. Consequently, it is determined that during the winter period, for wooden churches without heating, the visitor count should be restricted to 0.14 occupants per cubic meter, or indoor air drying should be ensured to a maximum of 2.66 g/kg.

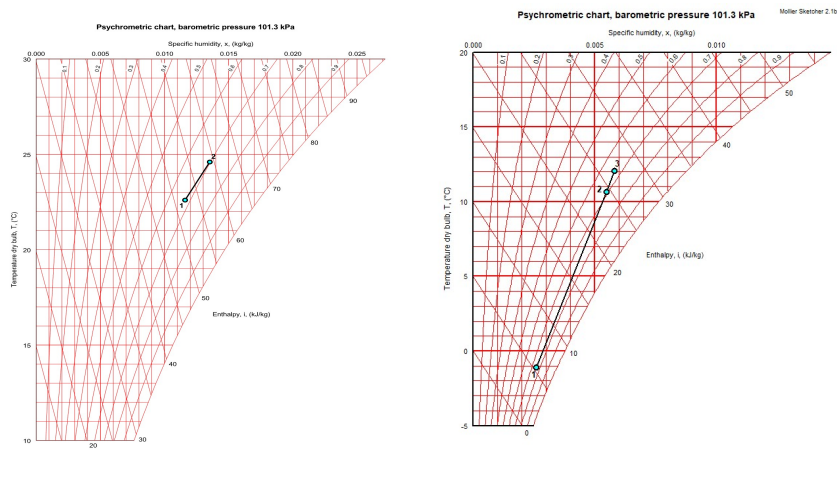


Fig. 5.3. Turaida Church – h-x diagram: A – 27 August 2022; B – 12 December 2022 (1 – 21/12/2022 14:00; 2 – 24/12/2022 15:00; 3 – 24/12/2022 16:00).

In Paper III, the Krimulda single-nave masonry church is examined, with air parameter measurements, humidity concentration calculations, and condensation risk assessments conducted. This allows for the determination of air parameters for masonry churches without heating based on this church's data. In Section 4.2 "Moisture in the Krimulda Church" of Paper III, detailed microclimate data are analysed for the hottest summer day with the highest indoor air humidity content on 22 August 2022, depicted in Fig. 5.4 A.

In Paper V, it is concluded that during the summer period, there is a significant risk of condensation if the indoor air humidity ratio exceeds 12 g/kg, as seen in Fig. 4.4 A. If any of the construction or object surfaces at points No. 1 or No. 2 accumulate 17 °C, there is a risk of condensation. Conversely, during the winter period, the analysis focuses on 24 December 2022, the day with the highest simultaneous visitor count (70 occup/h), resulting in the highest indoor air heating and humidity content during this period, depicted in Fig. 5.4.

In the conclusions of Paper V, it is determined that to avoid condensation risks during the winter period, either the minimum indoor air temperature should be maintained at 7.0 °C, or the air should be dried to 6.1 g/kg, or visitor numbers should be restricted. Consequently, it is specified that during the winter period, for wooden churches without heating, the visitor count

should be restricted to 0.12 occupants per cubic meter, or indoor air drying should be ensured to a maximum of 4.5 g/kg.

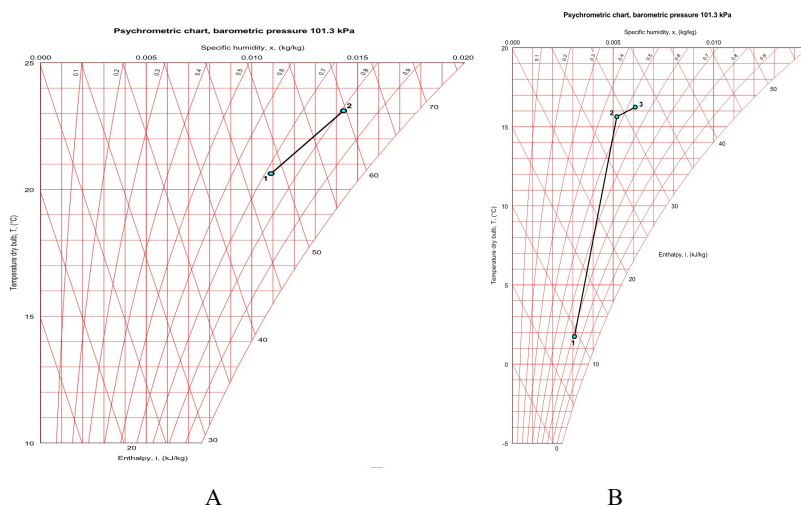


Fig. 5.4. Krimulda Church – h-x diagram: A – 22.08.2022; B – 24.12.2022.

Based on the categorisation of churches without heating into wooden and masonry churches, in order to maintain a conservation microclimate during the cold period without heating, it is necessary to restrict the simultaneous visitor count or ensure air drying. Figure 5.5 indicates the threshold values of parameters or the limits on simultaneous visitor intensity for churches categorised by their enclosing structures.

This approach allows for the preservation of suitable indoor conditions conducive to conservation efforts within these historical buildings, accounting for their specific structural characteristics and environmental challenges.

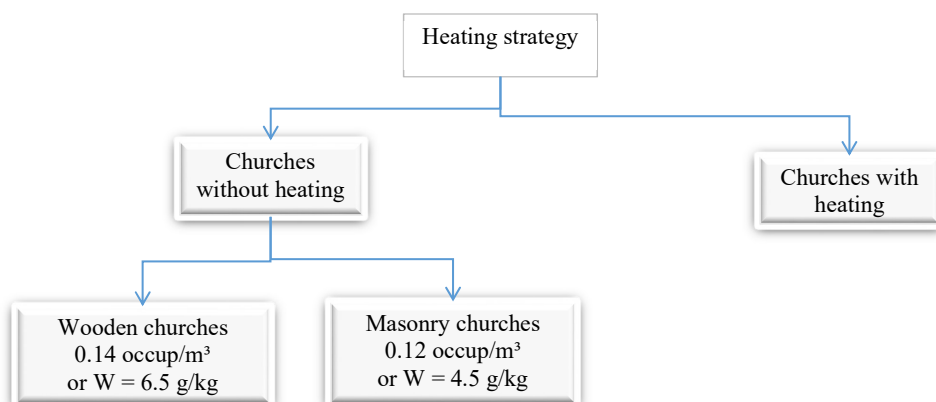


Fig. 5.5. Air parameter threshold values for churches with and without heating strategy.

## 6.2. Historical religious buildings with heating

Historical churches equipped with heating systems are further categorised based on their intensity of use, aligning with classifications of heating strategies: intermittent heating (Turaida and Krimulda Churches) and continuous heating (Riga Jesus Church and Liepaja St. Trinity Cathedral). This categorisation reflects the different approaches to maintaining indoor climate conditions in these historical structures, where intermittent heating involves periodic heating sessions while continuous heating ensures a consistently heated environment throughout the year. Each strategy is tailored to the specific needs and preservation requirements of the respective buildings.

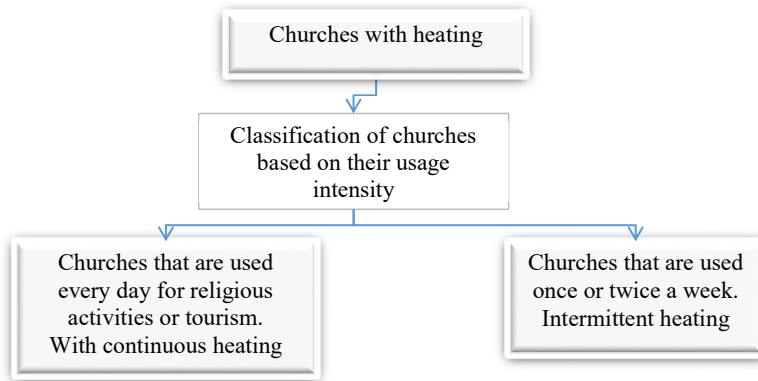


Fig. 5.6. Classification of heating strategies in heated churches according to usage intensity.

### Religious buildings with continuous heating

Historical churches with continuous heating, similar to those without heating, are classified into two types based on their enclosing structures: wooden and masonry walls. This heating strategy applies to Riga Jesus Church and Liepaja St. Trinity Cathedral, with their respective measurements detailed in Paper V.

#### Analysis of wooden church – Riga Jesus Church

In Section 3.3 of Paper V, the analysis focuses on 24 December 2022, which represents the day with the highest building load (500 occup./h) during the heating season for Riga Jesus Church. By plotting the parameters of this day on the h-x diagram (Fig. 5.7 A), it is observed that there are no condensation risks.

In Section 3.3 of Paper V, it is noted that the indoor air humidity concentration of the building exhibits seasonal symmetry with the outdoor air humidity concentration. This implies effective infiltration of outdoor air into the indoor spaces, resulting in indoor air humidity content during the cold period being close to outdoor air humidity content, ranging from 2 to 5 g/kg. This phenomenon enhances the drying process of the building's wooden structures.

Furthermore, increasing the indoor air temperature accelerates the rate of moisture evaporation from the building's wooden walls and other wooden interior details. Therefore, raising the indoor air temperature continuously during the cold period also increases the drying effect on the building's wooden structures. From this observation, it is determined that raising indoor air temperature above 15 °C without forced air drying and humidification is not recommended.

In the graph presented in Section 3.3 of Paper V, it is shown that the indoor humidity ratio fluctuates seasonally from 3.5 g/kg during the cold period to 12.14 g/kg during the warm period (Fig. 5.7 B). These fluctuations create unfavourable moisture variations for the building's wooden enclosing structures and interior details.

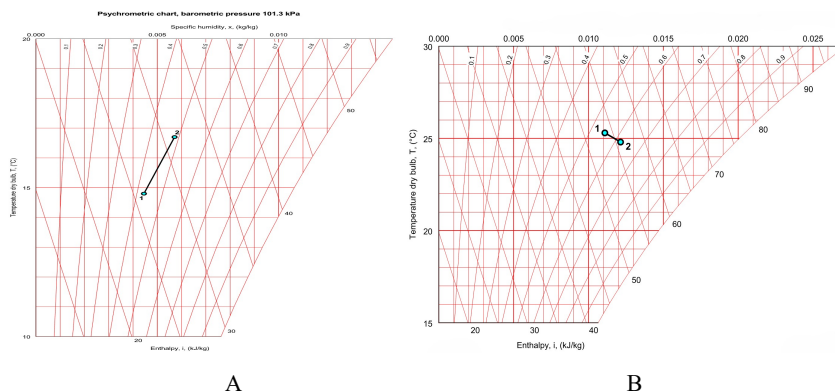


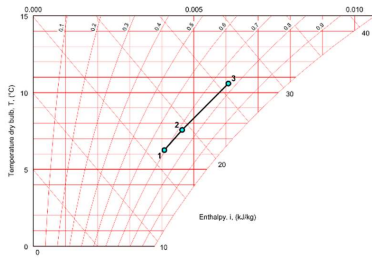
Fig. 5.7. Riga Jesus Church – h-x diagram: A – 24.12.2022 (1 – 00:40 PM; 2 – 7:00 PM); B – 28.08.2022 (1 – 12:00 AM; 2 – 9:00 PM).

#### Analysis of masonry church – Liepaja St. Trinity Cathedral

In Section 3.2 of Paper V, detailed analysis is provided for indoor air parameters of Liepaja St. Trinity Cathedral, particularly focusing on the day with the highest visitor intensity during the cold period (410 occup./h) on 31 December 2022, at 10 PM. In Fig. 5.8 A, between points 1 and 2 indicated in the church space, indoor air temperature is increased while maintaining a constant visitor count of 4 occupants. It is observed that this leads to an increase in humidity content, thereby intensifying the rate of moisture evaporation from the building's structures and interior details in proportion to the temperature changes.

In Section 5.2 of Paper V, it is concluded that the volume of moisture evaporation from the building's structures and interior details amounts to 1.1 g/kg. Furthermore, in Fig. 5.8 A, at point 3 reached, the short-term indoor air temperature and humidity ratio indicate a potential risk of condensation if any of the building's structures and/or interior details accumulate the temperature observed at point 1. Consequently, it is inferred that such rapid fluctuations in indoor air temperature may lead to condensation risks.

It can be concluded that during the cold period, with an increase in heating capacity, a permissible short-term fluctuation of indoor air temperature,  $\Delta T = 4$  °C, is acceptable to manage the risks associated with rapid temperature variations



A

B

Fig. 5.8. Molier diagram for Liepaja St.Trinity Cathedral: A – 31.12.2022 (1 – 27.12. 8:00 AM; 2 – 31.12. 8:00 PM; 3 – 31.12. 11:00 PM); B – 20.08.2023 (1 – 19.08. 6:30 PM; 2 – 20.08. 6:30 PM).

When increasing short-term indoor air temperature by more than 4 °C, it is recommended, after indoor activities, to gradually decrease indoor air temperature using heating capacity over more than 48 hours to reduce the potential accumulation of low temperatures in building structures and interior details. Under continuous heating conditions, it is advisable to implement forced indoor air ventilation systems with air dehumidification during the summer period if the indoor air humidity content exceeds 10 g/kg, and humidification during the winter period if the indoor air humidity content is less than 5 g/kg. By utilising indoor air ventilation systems, the direction of indoor air state change is determined to be  $\varepsilon = 7$  kJ/kg<sub>w</sub> for masonry churches and  $\varepsilon = 3.2$  kJ/kg<sub>w</sub> for wooden churches under maximum load conditions. Summarising these indoor air parameter threshold values for historical churches with continuous heating, they are reflected in Fig. 5.9.

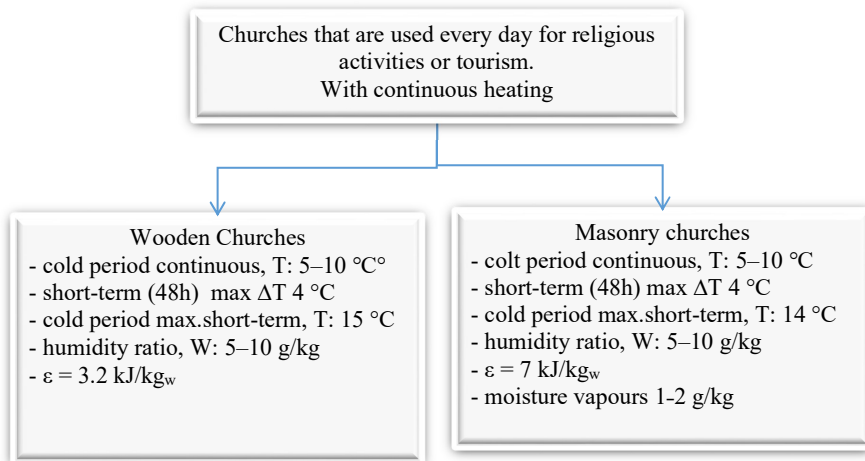


Fig. 5.9. Air parameter threshold values for churches with a continuous heating strategy.

**Religious buildings with intermittent heating**

Historical churches with intermittent heating, similar to other heating strategies, are classified into two types based on their enclosing structures: wooden and masonry walls. This heating strategy corresponds to Krimulda Church, with its measurements and calculations described in Paper III, and Turaida Church, detailed in Paper V.

Masonry Krimulda Church: The study in Paper III establishes the indoor air parameter threshold values by analysing the largest short-term fluctuations and days with the highest loads. These fluctuations are illustrated in Fig. 5.4. In Fig. 5.4 B, it is observed that during the cold period, maintaining a constant minimum air temperature of 6 °C or dehumidifying the air to 4.5 g/kg can prevent potential accumulation of lower temperatures on any of the building's surfaces or interior details. In the warm period, as shown in Fig. 5.4 A, dehumidification to 10 g/kg is necessary.

In Paper III, it is concluded that during the cold period, increasing heating capacity and raising indoor air temperature by 2 °C also increases indoor air humidity content by 2 g/kg. This is due to the fact that higher air temperature accelerates moisture evaporation from the building's structures and interior details. Summarising these indoor air parameter threshold values for historical churches with intermittent heating, they are reflected in Fig. 5.10.

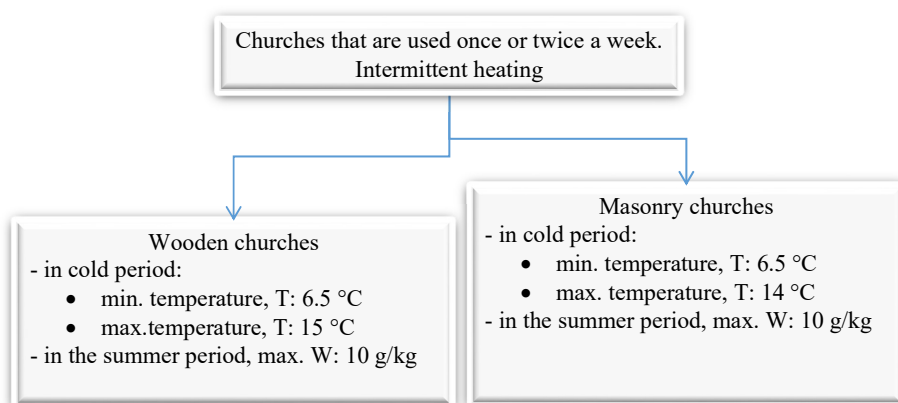


Fig. 5.10. Air parameter threshold values for churches with an intermittent heating strategy.

#### Methodology for providing conservation microclimate in historical religious buildings

The methodology for ensuring a conservation microclimate in historical religious buildings is developed by synthesising all previous classifications into a unified scheme (Fig. 5.11). The primary classification of buildings is based on heating strategies, which partially coincide with the intensity of building use. As a secondary classification, buildings are categorised based on intensity of use and according to the typology of religious buildings, distinguishing between two types based on their enclosing structures.

*Primary classification* is based on heating strategies:

- Without heating: Buildings that do not have a dedicated heating system and rely solely on intermittent or natural heating conditions.
- Intermittent heating: Buildings where heating is provided periodically, typically during religious activities or specific events.

- Continuous heating: Buildings equipped with a heating system that operates continuously or during extended periods to maintain stable indoor conditions.

In the *secondary classification* based on intensity of use, buildings are further categorised based on the frequency and intensity of use, which affects the operational heating strategy chosen.

In *typological classification* based on enclosing structures, religious buildings are categorised into two types:

- Wooden structures: Buildings with wooden walls and structures.
- Masonry structures: Buildings with masonry (brick or stone) walls.

By integrating these classifications into a unified scheme (Fig. 5.11), the methodology aims to provide tailored guidelines for achieving and maintaining a conservation microclimate suitable for the preservation of historical religious buildings. This approach considers both the architectural typology and the specific heating and usage patterns unique to each building type

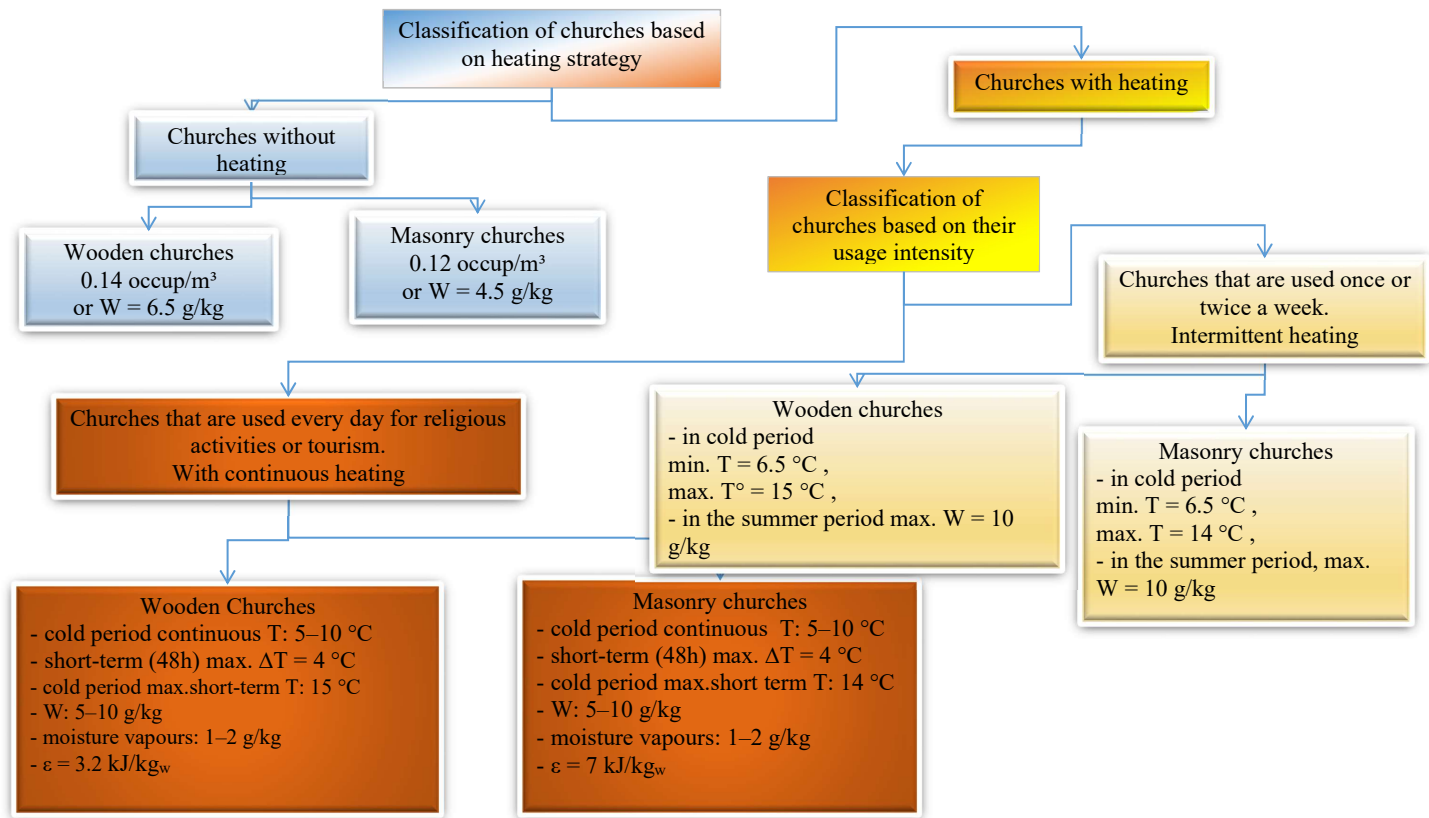


Fig. 5.11. Methodology for ensuring the conservation microclimate.

## 7. PRACTICAL RECOMMENDATIONS FOR HISTORIC 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<sup>3</sup>.
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 (48h) 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  $+6.0 \text{ g/m}^3$  (90% curve), while during the cold period it ranges between  $1\text{--}2 \text{ g/m}^3$ .

Paper III, based on measurements in Krimulda Church, shows that moisture emissions from building structures can reach up to  $2 \text{ g/kg}$ . 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 the development of sustainable HVAC system design solutions.

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

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 into 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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# Control of Indoor climate of Historical cult buildings

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**Abstract.** There are 320 historical cult buildings as cultural monuments of national significance in Latvia. Cultural and historical art monuments and artifacts (paintings, organs, chairs, altars, pulpits) must be preserved and protected in these cultural buildings. Specific indoor climate is necessary to maintain in historical cult buildings to pass on to future generations, but those specific requirements often are complete opposite of the actual microclimate and what the user wants.

Indoor climate measurements have been carried out in five brick wall and two wooden churches with and without heating systems. Potential condensation risks are determined using calculations. Typical air flow has been formed using building's thermography measurements. Heating systems and making use of buildings influence historical buildings and this has been determined. The main aim of the article is to determine potential indoor climate type of control in historical cult buildings avoiding humidification and dehumidification, and it is similar in the coastal climate of the Baltic Sea.

Results show that: great humidity fluctuations have been observed in buildings which have been used during winter, outdoor air has a great impact to buildings, less humidity fluctuations have been observed in buildings with controlled heating systems.

## 1 Introduction

Historic churches constitute an important part of European cultural heritage. Buildings and their interiors, including liturgical objects and artefacts, attest to our cultural heritage and must be preserved for future generations. Microclimate is a crucial factor in allowing the preservation of buildings and the artefacts in them. An unsuitable interior microclimate may cause irreversible loss.

According to data provided by the National Culture Heritage Administration (NKMP, until 2020 the former State Inspectorate for Heritage Protection) in Latvia:

- There are 226 cult buildings with the status of monument of national significance (incl. churches, cathedrals, synagogues, prayer houses);
- There are 1,385 movable art monuments of national significance (incl. paintings, tableware etc.) located in the cult buildings;
- There are 993 immovable art monuments of national significance (incl. altars, various benches, organs, pulpits, interior and "exterior" details) located in cult buildings [1].

The discussion resolution of a seminar organized by the State Inspectorate for Heritage Protection on 29 July 2008 states: "To ensure the comfort of church visitors, more and more often church building managers wish to install heating in churches. The choice of heating system is often not based on its impact on the monument, but rather following the recommendations of construction companies and forceful advertisements for heating systems which aim at a quick profit instead of the preservation of the building. [2]"

Initially, historic churches more than 300 hundred years old were not heated. Back then, requirements of church visitors were much lower than today [2]. Visitors would put on cloth caps, felt boots, mittens, and other warm clothing, and vessels used for the Blessed Sacrament were made of silver so that they could be used in cold temperatures. In other words, the church visitors initially took care of their own microclimate.

Since then, the growing needs of church visitors have required a more favorable environment inside church

buildings. At the same time, the economic possibilities and activities of church owners and managers have increased. The market offers versatile indoor climate control products. However, sufficient information about their suitability for solving a particular problem is often not available. Selected solutions do not always meet the building maintenance requirements i.e.:

- In such buildings, historic windows and doors are frequently not allowed to be replaced with new ones, and overhaul also is not permitted, which would reduce heat and air permeability because windows often have a separate status as cultural monuments of national significance [2].
- Buildings with the status of architectural monument of national significance may not be heat-insulated or undergo a change of façade [2].

According to data provided by the NKMP regarding movable and immovable art monuments in churches, one can see that church interiors constitute a considerable part of the cultural heritage in need of specific climate maintenance and control.

It must be noted that churches built 300 year ago and earlier were subject to very different construction techniques and principles of use, as compared to nowadays:

1. The foundations of a building were not waterproofed, and therefore its walls and columns were unprotected from the impact of capillary and atmospheric precipitation [3];
2. Parts of a building's brick structure were built with lime mortar, which ensured the exchange of various substances. Thus, they effectively drain away moisture absorbed through the foundations [3];
3. For many churches (especially urban ones) surrounding cultural layer has elevated the ground level (pedestrian paths, squares etc.) by several meters, which originally had been close to the ground floor level of the church [3].

So far, the requisite building microclimate has not been defined, and the most suitable types of microclimate control have also not been identified.

The standard AVOK (ABOK) – 2 – 2004 „Orthodox churches. Heating, ventilation and air conditioning” elaborated by the Russian Federation determines:

- Heating and ventilation must be installed in churches that are used all year round,
- The microclimate parameters of these churches must be ensured according to the season and the classification of their premises based on their use,
- In cold and transitional periods (autumn, spring) RH (relative humidity) must be 30%-45% and air temperature 12° - 18°C.

Meanwhile, according to the Russian Federation Building Standard SNIIP (СНИП) 31-103-99 „Orthodox Church buildings, structures and complexes”, the calculation of air temperature in the hall must be 14°C, in the middle part of the church it must be 16°C, at the altar it must be 18°C and in the baptism room it must be 22°C. If the annual average air moisture in Liepaja (LV) 78.8% and Riga (LV) 75.2% is compared against the average air humidity in Volgograd (RUS) 58%, it can be concluded that Latvia's climate differs, and the Russian Federation Standard is not fully applicable to Latvia [5].

T. Brostrom and J. Hanson made measurements in nine churches of the Baltic Region: Lau, Gotland (S), Oja, Gotland (S), Vaskinde, Gotland (S), Kaarma, Saaremaa (EST), Poide, Saaremaa (EST), Valjala, Saaremaa (EST), Kandava (LV), Tukums (LV), Dzirciems (LV). According to the measurements taken, the study found that the best and most stable indoor climate was in Oja Church which was nevertheless one of the most expensive in operation. Oja Church has intermittent (periodic) heating where the RH fluctuation interval during a year varies between 55% - 75%, whereas air temperature fluctuates between 8°C - 23°C [4]. This study does not examine the heat accumulation properties of brick wall constructions and the risks of condensation. Considering the vast heat accumulation potential of brick structures, a church with intermittent heating may possibly use equivalent or even higher energy consumption than a church which has permanent conserved heating. Potential condensation risks can be reduced with permanent conserved heating.

During their research of three churches, D.O. Sovetnikov, D.V. Baranova, A. Borodinecs, and S.V. Korniyenko came to the conclusion that in these churches “The result of thermal analysis shows that 75 % of heat loss emerges through a flat element and 25 % through thermal bridges. The bigger part of supplementary heat loss was found through the horizontal linear element (17 %) and the smaller part — through the vertical linear element (8 %)” [5].

**Table 1.** Summary of architectural and civil engineering characteristics

Church	Age	Heating type	Zoning	Heating elements	Structural solution of walls	Structural solution of ceilings	Structural solution of floors
Limbazi	1680	Local heating	Altar room	none	Granite boulder masonry walls b=1.4m	Brick vaults b=140mm	Wood deck floor on ground
			Parish hall	infrared lamps	Granite boulder masonry walls b=1.0m	Wooden deck ceiling with lime plaster	Wooden deck floor on ground

It is often the case that condensate formation in churches is caused by a lack of heat insulation, and in order to prevent it one needs to improve heat insulation of the dome [6]. Public buildings have some experience showing that heat insulation of the building envelope, if not accompanied by a reconstruction of the ventilation system, gives rise to elevated CO<sub>2</sub> concentration [7]. Meanwhile, if we consider cult buildings on a par with public buildings, we can expect similar results. Therefore, we will not propose the total heat insulation of the building envelope, which would also contradict the regulations governing the conservation of these monuments [13]. Evaluating the possible ventilation systems, it is established that the cheapest ventilation systems provide the least automation and control, and also represent the worst indoor climate [8]. Since the cheapest ventilation systems might fail to provide the necessary microclimate in the cult buildings, and since the most expensive ventilation systems are often unaffordable due to financial restrictions, we will not consider forced ventilation systems in our research. Ventilation by virtue of automated opening of windows and doors can ensure better and more stable indoor air parameters, while opening the windows when indoor air is too humid and outside air is drier [9].

M. Napp and T. Kalmes performed measurements in the Church of the Holy Cross (EST) with three various climate control methods (adaptive ventilation, conservation heating and dehumidification) and concluded: “Conserved heating with a heat pump showed the lowest annual energy consumption of 29 kWh/(m<sup>2</sup>·a). The energy consumption also depends on the outdoor climate: dehumidification is most effective during cold periods and the conserved heating is most effective during warm periods. [10]” In view of other studies [5; 6; 7; 9] this type of building has massive outdoor air infiltration during the cold season, so that in the cold (winter) period the air should not be dried and kept at a constant minimum temperature (+6°) instead, thus ensuring that the air does not become too dry during the cold season.

When defining possible microclimate risks, the main goal is to identify the possible microclimate control type for a historic cult building by using only constant conserved heating without forced air humidification and drying or other types of mechanical ventilation.

## 2 Methods

### 2.1. Summary of church descriptions

						and sand insulation	
Krimulda	1204	Irregular heating	Altar room	none	Granite masonry walls b=1.8m	Brick vaults b=140mm	Brick-paved floor
			Parish hall	pig-iron stove	Granite masonry walls b=1.5m	Wooden deck ceiling with glass fleecce insulation	Brick-paved floor
Cesis	1282 - 1287	Permanent gas heating (VIESSMANN, VITODENS 300, N=60Kw. Thermal load for hot water heating 6.8kW)	Altar room	radiator heating for adjacent rooms 25.9kW	Dolomite masonry walls b=1.8m	Brick vaults b=140mm	Wooden deck floor
			Parish hall	heated floors 27.2 kW	Granite masonry walls b=1.5m	Wooden deck ceiling with glass fleecce insulation	Tile floor
Liepaja St. Trinity	1758.	Municipal heating networks (heat exchanger 250kW)	Common	Radiators	Brick wall b=0,67 – 1,29 m	Rib brick vaults b=140mm	Wooden deck floor
Kuldiga St. Anne	1904	Firewood heating (Kronbergs& Kronbergs) 120kW	Altar room	Warm air heating channels	Red brick wall	Rib brick vaults	Wooden deck floor
			Parish hall	Warm air heating channels	Red brick wall	Rib brick vaults	Wooden deck floor
Matthew	1902	Municipal heating networks (heat exchanger 181kW)	Parish hall	Heated floor	Yellow brick wall	Wooden slab	Tile floor
Turaida	1750	Locally	Common	None	Horizontal beam b=200mm	Wooden slab b=150mm	Wooden deck floor
Riga Jesus	1822	Municipal heating networks	Common	Pig-iron radiators	Horizontal beam b=200mm	Wooden slab b=150mm	Wooden deck floor

## 2.1. Condensation risks

3. Condensation risks are analyzed at three room air temperatures (6°; 12°; 18°C) and three RH (40%; 60%; 80%). A Mollier Diagram was used to determine condensation temperature at all previously mentioned parameters which were summarized in Table 2.

**Table 2.** Condensation Tc risks at room temperatures  $\Theta_i$  and relative air humidity  $\varphi$

Average room temperatures $\Theta_i$	RH $\varphi_1$	RH $\varphi_2$	RH $\varphi_3$
	40%	60%	80%
$\Theta_{i1}$ Average room temperature 6 °C;	-6.5	-1.8	2.5
$\Theta_{i2}$ Average room temperature 12 °C;	-1.8	4.5	8.5
$\Theta_{i3}$ Average room temperature 18 °C;	3.5	10.0	14.5

Since the stone and wooden buildings have completely different thermal properties, we divided churches into two types — wooden and brick wall — to assess the risks as scrupulously as possible.

### 2.1.1. Temperatures of brick wall church building envelopes

Since the research applies to historic cult buildings, it can be clearly asserted that brick building walls older than 500 years are thicker than 1 meter and ceiling vaults are kept to a thickness of a half-brick (late Medieval half-brick) Knowing that Cesis and Krimulda churches (Table 1) have 1.6m thick walls and a half-brick of the ceiling vaults is 0.14m, heat resistance  $R_o$  of walls and ceilings were calculated:

$$R_o = R_{St} + \delta_{i1} \lambda_{i1} + \dots + \delta_{in} \lambda_{in} + R_{SE}$$

$$R_o(\text{walls}) = 1.06 \text{ m}^2 \text{ K/W}$$

$$R_o(\text{ceilings}) = 0.29 \text{ m}^2 \text{ K/W}$$

Based on the foregoing, the temperatures were calculated on the wall, corner of external wall, ceilings, corner between the ceiling and wall and external wall forming a corner with the ceiling, see Table 3.

**Table 3.** Temperatures of the building envelope of the brick wall church at the coldest five-days external temperature in Priekuli minus 22.3°C [11].

T° of the building envelope surface at:			
Room air T 6°C	Room air T 12°C	Room air T 18°C	
<b>T° on the wall</b>			
$T_{iw} = \Theta_i - R_{si} / R_o (\Theta_i - \Theta_e) =$	2.35 °C	7.61 °C	12.88 °C
<b>T° in the corner of external wall</b>			
$T_{2plw} = T_{iw} - 5,55 =$	-3.2 °C	2.06 °C	7.33 °C
<b>T° on the ceiling</b>			
$T_{ic} = \Theta_i - R_{si} / R_o (\Theta_i - \Theta_e) =$	-7.46 °C	-4.17 °C	-0.88 °C
<b>Reduced T° of external wall joint per plane</b>			
$T_{irw} = (T_{2plw} + T_{ic}) / 2 =$	-5.33 °C	-1.05 °C	3.22 °C
<b>External and three-plane ceiling joint T°</b>			
$T_{3pl} = T_{irw} - T_{sv} =$	-10.73 °C	-6.45 °C	-2.18 °C

### 2.1.2. Temperatures of wooden church building envelopes

Since the thickness of walls of all historic trimmed horizontal beam cult buildings is ~200mm, not exceeding 250mm, which can be explained by parameters of timber (off- cut slab, spigot and length of log), the thickness of walls examined in this paper is 0.2m, and the ceiling slab is made of wide-edge wooden beams, cladding with sand and clay mixture filling above it. Knowing that the thickness of walls in Turaida and Riga Jesus Church (Table 1) is 0.2m and the ceiling slab has sand filling of 0.15m, heat resistance  $R_o$  of walls and ceilings were calculation:

$$Ro(walls) = 2.73 \text{ m}^2 \text{ K/W}$$

$$Ro(ceilings) = 1.04 \text{ m}^2 \text{ K/W}$$

Based on the foregoing, temperatures on the wall, corner of external wall, ceilings, corner between ceiling and wall and external wall forming a corner with the ceiling were calculated, see table 4.

**Table 4.** Temperatures of the building envelope of wooden church at the coldest five-days external temperature in Priekuli minus 22.3°C [11].

T° of the building envelope surface at:			
Room air T 6°C	Room air T 12°C	Room air T 18°C	
<b>T° on the wall</b>			
$T_{iw} = \Theta_i - R_{si} / R_o (\Theta_i - \Theta_e) =$	4.58 °C	10.3 °C	16.01 °C
<b>T° in the corner of external wall</b>			
$T_{2plw} = T_{iw} - 5,55 =$	-0.97 °C	4.75 °C	10.46 °C
<b>T° on the ceiling</b>			

$T_{ic} = \Theta_i - R_{si} / R_o (\Theta_i - \Theta_e) =$	2.28 °C,	7.53 °C	12.78 °C
<b>Reduced T° of external wall joint per plane</b>			
$T_{irw} = (T_{2plw} + T_{ic}) / 2 =$	0.65 °C,	6.14 °C	11.62 °C
<b>External and three-plane ceiling joint T°</b>			
$T_{3pl} = T_{irw} - T_{sv} =$	-4.75 °C,	0.74 °C	6.22 °C

## 2.2. Measurements

### 2.2.1. Microclimate measurements were taken in 7 churches.



**Figure 1.** Measuring Device LOG32.

In Krimulda, Cesis St. John and Limbazi Church the measurements were taken with measuring device LOG32, having measuring accuracy  $\pm 3\%$  for RH and  $\pm 1^\circ\text{C}$  for T.

**Table 5.** Time and place of LOG 32 measurements

Church	Location of the measuring device	Interval	Period
Limbazi (Measuring Device No.1)	3.5m above the ground on the pulpit's roof	2 h	2013.10 – 2015.01.
Limbazi (Measuring Device No.2)	1m above the floor at the first line of benches in the hall	2 h	2013.10 – 2015.01.
Krimulda (Measuring Device No.1)	3.5m above the ground on the pulpit's roof	1 h	2012.01 – 2012.02.
Krimulda (Measuring Device No.2)	3.5m above the ground on the pulpit's roof	1 h	2012.02 – 2012.05.
Cesis	2.5m above the ground on the pulpit's edge	1 h	2012.01 – 2012.05.



**2.Figure.** Measuring Device HT-9222

For Liepaja St. Trin., Kuldiga St. Anne, Riga Matthew, Turaida and Riga Jesus Church, measurements were taken with measuring device HT-9222, having accuracy  $\pm 3\%$  for RH,  $\pm 1^\circ$  for T. Measurement readings were put down by an especially assigned person in each building and results were written in the log. Next, we gathered and clustered the measurement results.

**Table 6.** Time and place of HT-9222 measurements

Church	Location of the measuring device	Interval	Period
Liepaja St. Trin.	3.5m above the floor on the balcony	5days	2014.01 – 2015.12.
Kuldiga St. Anne	3.5m above the floor on the balcony	3days	2010.09 – 2011.07
Riga Matthew	1.5m above the floor	6h	2008.07 – 2009.04.
Turaida	1.2m above the floor	1day 2days	2011.05 – 2012.05.
Riga Jesus	3.5m above the floor	6h	2009.01 – 2011.05.

**2.2.2. Thermography**



**Figure 3.** Thermal camera FLIR ThermaCam™ P640.

Thermal camera calibration Cert. No. F0080K10; 12.01.2010, LPMC  
 Camera resolution 640x480 pixels;  
 Spectral range 7.5-13 μm;  
 The emission rate was set to 0.97.

Thermography was performed in four churches: Cesis St. John, Riga Jesus Church and Krimulda Church, Liepaja St. Trin.

**3 Results**

**3.1. Impact of capillary moisture**

There is no research known regarding evaporation of capillary moisture into the room's air.



**Figure 4.** Wall of Cesis Church from outside

Judging from a thermogram taken from the outside of Cesis Church (Fig 4) and Krimulda Church (Fig 5) during winter at temperatures below -10°C and on the building walls above ground level, one can see thermal emissions, which can be explained by the presence of capillary moisture (in the figure below in text). Emission of capillary moisture from the wall in Cesis Church (Fig 4) is observed up to 3m above the floor level since the

cultural layer has elevated the surrounding ground level at side A of the building by ~1.5m.



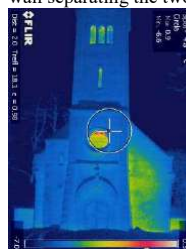
**Figure 5.** Krimulda Church from outside

Krimulda Church (Fig 5) is situated in a rural area. It does not have a significant cultural layer, which would materially elevate the surrounding ground level. However, the most ancient masonry walls with a thickness of 1.5-2m demonstrate a warmer masonry belt right above the surrounding ground level.

**3.2. Zones of church premises and air flows**

When analyzing a typical rural church, compared with Krimulda Church, Sigulda Church, Arais Church, Limbazi Church etc., the regional rural churches demonstrate the following common picture of temperature divisions in premises used for religious processes (services):

- church attendees mostly use the main entry door thus increasing the inflow of outside air,
- and some of the visitors also need sacristy entry for certain consultations with a minister or other officials of the parish (manager, clerk, churchwarden etc.), also thereby contributing to the inflow of cold air from the opposite side of the church,
- the organist, choir or other parish members use the balcony on the first floor in the parish room, which has a door leading to the tower exposed to outside temperature,
- meanwhile in churches with a separate stove-like heating element, often situated between the altar zone and parish zone due to two considerations: to supply radiating heat both to the minister and parish, and historical location of a chimney in the church - it is usually situated in this wall separating the two zones.



**Figure 6.** Tower



**Figure 7.** Tower floor in the attic.

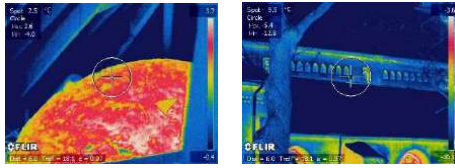


Figure 8. Ceiling vault in the attic Figure 9. Attic from the outside

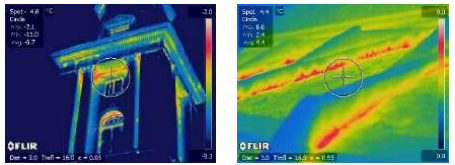


Figure 10. Tower Figure 11. Dome vault in the attic

- When evaluating the thermograms of Krimulda Church (Fig 6 and 7), Cesis St. John (Fig 8 and 9) and Riga Jesus Church (Fig 10 and 11), taken at air temperature of  $-10^{\circ}\text{C}$  it can be established:
  - The entire warm air mass ends up at the high ceilings of the room where it further travels to the cold premises and outside through the ventilation grilles in the ceiling or balcony and tower zone, being symbolic cardboard or plywood in the churches under examination. Warm air leaks through the tower can be seen in thermogram taken (Fig. 6 and 10) in Krimulda Church and Riga Jesus Church, and the thermogram shows it escaping through the attic room in Cesis St. John Church (Fig. 9).

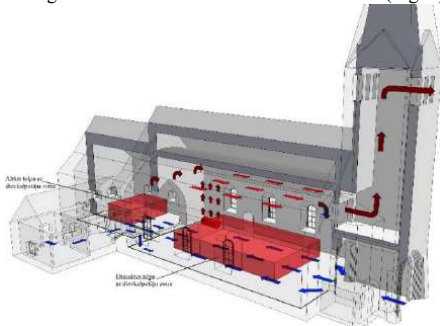


Figure 12. Air flow scheme of Krimulda Church

Church room areas have a virtually created air mass in the room, restricted with building envelopes featuring parallel (vertical, horizontal etc.) lines, keeping in mind that the planned area is actively used in that room. According to the laws of physics, as the air warms up its density decreases, and it rises up to the ceiling and is channeled away in the upper zone. Unlike the Orthodox Lutheran churches, these do not have adjacent monasteries and therefore the variety of rooms is less pronounced, with only one exception – the Riga Dome Church complex which initially was a monastery complex of a Catholic church. A comparison of all the rural churches in Latvia brought us to the conclusion that most of them,  $\sim 3/4$  of them, are similar in their planning and

architecture [14], [15]. So, in order to analyze air flows in the churches, we used Krimulda Church to demonstrate a typical spatial arrangement of churches. Based on this prototype, we created a spatial model (Fig 12) and showed areas of use, the heating element and actual air flows. When describing this model, in a majority of churches there are: longitudinal planning, a tower above the main entrance; at the end of the main entrance of the parish room there is a balcony with an exit to the tower; at the distal end of the parish room there is the altar or a separate altar room; a door leading from the altar or altar room leads to ancillary rooms (sacristy), and the sacristy has a separate entry from the outside.

### 3.3. Measurements of brick wall churches

- Limbazi Church is an architectural monument of national significance, and several art monuments of national significance are situated in it (set of internal doors, set of benches, altar, built-in cupboard). [1] Address: Limbazi, Libiesu Street 2. The church is situated in the center of Limbazi town. The church is surrounded by a church park, situated between streets and a ravine. The church stands on the mound of the old town [12].

The large hall and altar room of the church was not heated initially. The church is being used all year round, i.e. it has bi-weekly services and its doors are open for visitors, without organized gatherings, for the rest of the time. In the winter season, before the services, “infrared lamps”, which are situated in the parish hall above the bench rows under the gallery (balcony), are switched on.

Krimulda Church is an architectural monument of national importance [1].

Address: Riga region, Krimulda country, Krimulda parish, Krimulda Church.

Location: 50km from Riga, on the side of Ragana-Turaida road, in an open field, valley of the Runtins River, from the Southern side with forests in close vicinity.

Two centuries ago, and in the first half of the last century the church was heated with two round stone stoves [12]. Since the 1990s, the church has been heated for the Sunday service, often started in the previous week due to intense cold, and the heating element is an iron stove or so-called large ( $d=0.7$ ,  $h=1.8\text{m}$ ).

Cesis Church is located in the territory of a cultural monument of national significance, whereas the church itself hosts twenty-one individual cultural monuments of national significance [1].

Address: Cesis, Liela Skolas Street 8. The church is situated next to the front of the order's castle, to the south-east, in the middle of the Medieval town, on a block between Torna Street, Liela Skolas Street and Pils Street.

The heating system of the church operates permanently, ensuring between  $3^{\circ}$  and  $7^{\circ}\text{C}$  on workdays, while the heat supply is increased on Saturday so that on Sunday it reaches approximately  $10^{\circ}$  to  $14^{\circ}\text{C}$ .

Kuldiga Church is an architectural monument of national importance [1]. Address: Kuldiga town, Dzirnau Street 12. The church is situated in an urban area. [12]

The existing heating system in the church operates irregularly; the church is being heated twice a week, on

Thursdays and Sundays, trying to keep air temperature at 14°C.

- The Matthew Church is situated in Riga, Matisa Street 50, in an urban, densely built-up area.

During winter, by setting the maximum heating supply element, the maximum temperature reached for the heated floor was 17°C. The ceiling of the large hall has natural ventilation flow grilles, which are kept shut for the winter period.

- Liepaja St. Trinity Cathedral is an architectural monument of national significance and it is home to many

art monuments of national significance [1]. Address: Liepaja, Liela Street 9. The church is situated in the city centre [12].

The existing heating system of the church is operated in the coldest winter months and it is permanently operational, keeping the average temperature in the premises at +6°C. The church is heated for three months per year on average.

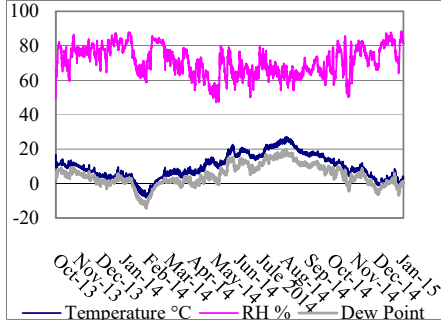


Figure 13. RH and temperature in Limbazi Church (No.1)

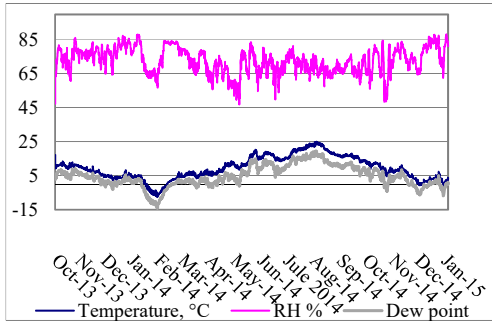


Figure 14. RH and temperature in Limbazi Church (No.2)

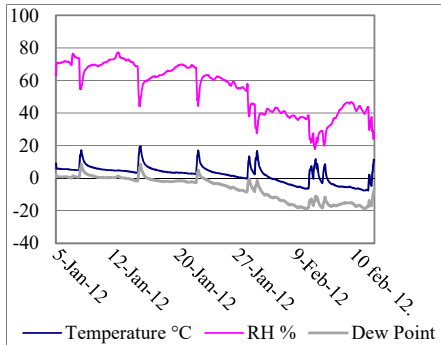


Figure 15. RH and temperature in Krimulda Church (No.1)

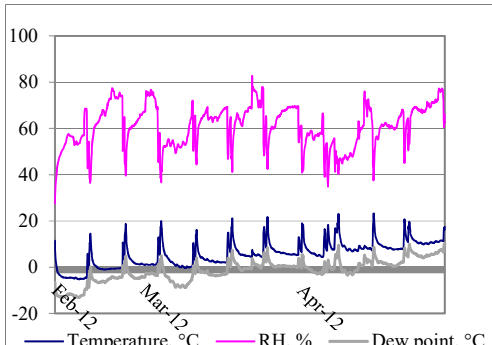


Figure 16. RH and temperature in Krimulda Church (No.2)

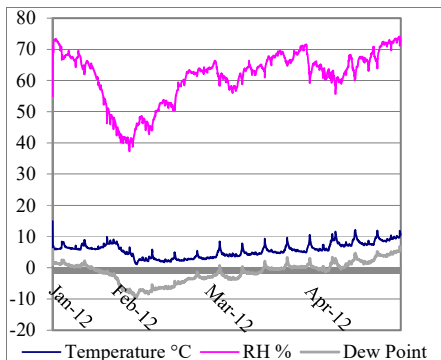


Figure 17. RH and temperature in Cesis St. John Church

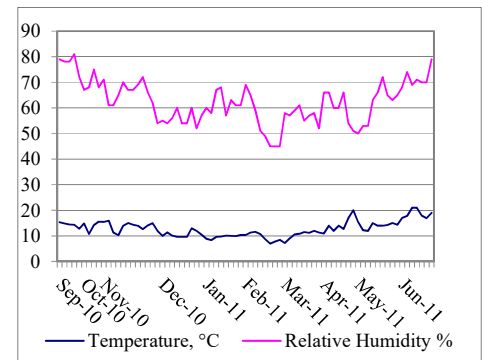


Figure 18. RH and temperature in Kuldīga St. Anne Church

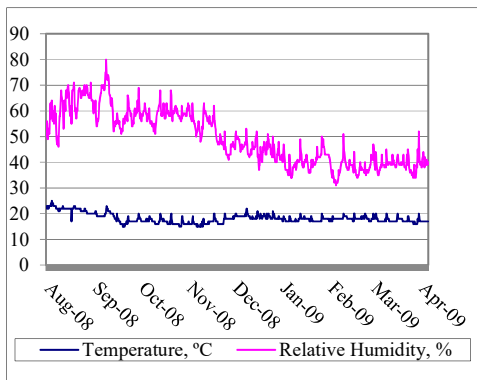


Figure 19. RH and temperature in Matthew Church.

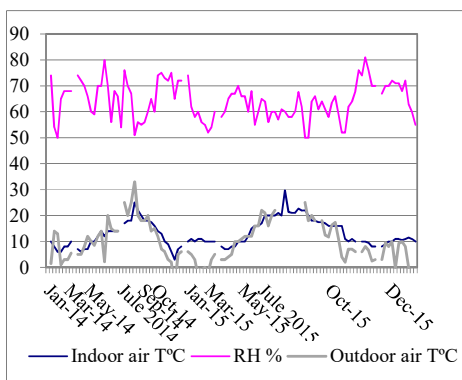


Figure 20. RH and temperature in Liepaja St. Trin. Church

### 3.1. Measurements of wooden churches

- Turaida Church is part of the Turaida museum reserve, which is also an architectural monument of national importance. Address: Riga region, Sigulda town, Turaida Street 10. The church is located in the area of the Turida museum reserve, on an open mound, ~300m North from the Bishop's stone palace fortress of the 13<sup>th</sup> century. [12] The church is not permanently heated, although a hot air generator is used during the cold winter period to heat the air temperature.

- Riga Jesus Church is an architectural monument of national importance, and there are several art monuments of national importance — organs, interior artefacts — situated in it. Address: Riga City, Elijas Street 18. The church is located in the city center at the crossing of Elijas Street and Jesus Street. [12] The church is permanently heated during the cold period, and it also has other administrative rooms which are used during workdays.

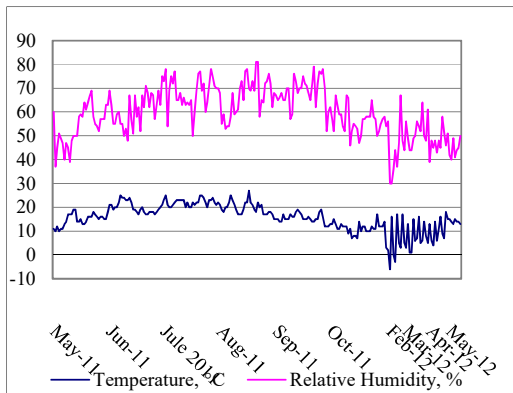


Figure 21. RH and temperature in Turaida Church

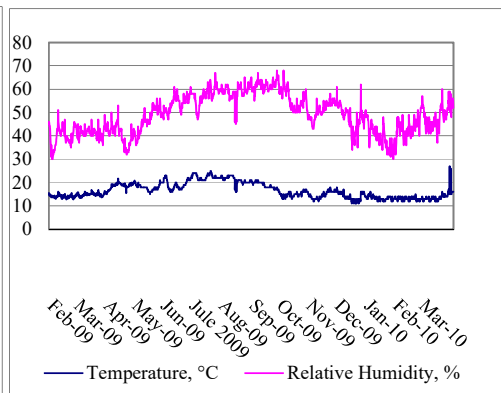


Figure 22. RH and temperature in Riga Jesus Church.

## 4 Discussion

### 4.1. Condensation risks and air flows

Condensation risks are determined by calculating the coldest air temperatures for five days in Priekuli -22.3° [11], and the various RH in the premises. Judging from these measurements, we actually see that during the cold winter months, room RH in the heated churches with inside temperature kept between 6° and 12°C falls below 60% and varies between 30% and 50%. Hence, we see that actually the condensation risk in wooden churches is

observed only in the case of elevated RH, as is the case in Turaida Church, where RH reaches 82%. And it is also true for stone churches with the ceiling structures. When comparing the measurement data to the determined condensation temperatures, we see that the main condensation risks are brought by occasional heating, especially for brick wall churches with large masonry wall heat inertia, giving rise to high temperatures and RH fluctuations, and a high risk of condensation when the heating is re-started. Meanwhile, we see from warm air flows that if the premises have a constant temperature of +6°C, the temperature at the ceiling is higher by +2°C,

and thus there are fewer risks of possible condensation. Cesis St. John Church is heated with a heated floor, which ensures an almost permanent inside temperature of T +6°C, and almost equaling the ceiling vault T +3.6°C at the side of cold attic space (Figure 8), but it also means that condensation does not form on this ceiling from the inside.

We can see from the examined air flows and microclimate measurement observations that outside air infiltration is not actually controlled in any of churches in question, which causes very high inter-seasonal RH fluctuations.

#### 4.2. Stone churches

The intensive use of Limbazi Church produces rapid short-term fluctuations in both temperature and RH. On average, short-term fluctuations of RH in 24 hours amount up to 15%, but very often they fluctuate twice within 24hrs, which can be explained by the change in frequency of the use of the building, and uncontrolled air admittance into the building. Long-term fluctuations of air parameters in the winter season vary between -7.6°C (31.01.2014 RH 59.2%) and +7.1°C (25.02.2014 RH 75.6%); meanwhile, during the summer period — between +13.5°C (24.06.2014 RH 66.7%) and +25°C (04.08.2014 RH 69.6%). In fact, the highest air parameter fluctuation is achieved during the winter, around Christmas (25.12.2014 T+8.3°C; RH 83.3%) when the church holds several services, and the number of visitors is three times higher than usual. Weather conditions play a significant role in the inside temperature and RH in rainy periods. Thus, the relative humidity is largely variable, between 47% and 88.2%. The mean value of RH is 67%. In fact, the brick structures, due to their mass, accumulate the collected heat very well, so the short-term fluctuations do not cause a frequent change of inside air temperature, whereas the short-term fluctuations of the premises' RH are significant: On 1 February 2014 at 01:18 T-6.9°C; RH 56.8% while at 15:18 T-6.5°C and RH 68% (Fig.13, 14). It shows that the church certainly does not have a stable RH, and that use and local heating of the building with infrared heating elements does not provide a stable climate.

Krimulda Church is heated once a week, although it is open to visitors all year round, 24/7. Therefore, the fluctuations are very considerable. Intense heating of the premises for the Sunday's service causes large and rapid short-term fluctuations of both temperature and RH. Temperature varies between -8°C and +24°C. Higher air temperatures are achieved in view of the fact that the building is not being heated for the rest of the week, so when the inside air is rapidly heated, the massive brick walls accumulate a much lower temperature causing discomfort and a wish to heat the air even more. Since the church is open 24/7, it is visited almost constantly by tourists, pilgrims (in the winter period ~ 200 persons during weekdays, and ~1000 persons during weekdays in the warm season), and the church has permanent natural ventilation (discussed in previous Sections). The indoor climate of this church is essentially influenced also by the weather conditions — in terms of temperature and relative humidity of the air (rainy season). Thus, the relative

humidity is largely variable, between 36% and 84%. The mean value of RH is 75% (Fig. 15, 16). RH standard deviations during this period amount to more than one tenth. This is evidence that the church definitely has no stable RH and this heating strategy does not provide a stable microclimate.

Cesis Church has the most stable indoor microclimate among the historic churches. Its relative humidity is 55.50%. However, the interval of relative humidity in the heating period is 37% to 74%, while the short-term fluctuations are 2.1%. In this period the temperature varies between +1 and +10.5 °C. The average temperature is +7.5. Temperature fluctuations during weekdays are rather high when the church is not being used, and also on Sunday. Therefore, RH varies between 37% and 74%. Short-term RH fluctuations are 2.1% (Fig. 17). Particularly larger fluctuations are observed in periods when the temperature is being constantly increased due to frequency of use of the church.

Relative humidity in Kuldiga Church is less stable than in Cesis Church. This is because the temperature difference between the service and other times of no-usage is much larger. The temperature in the church varies between +7°C and +19°C. Since the church measurements were taken on Thursday and Sunday, when the church is being heated, short-term fluctuations are not known. Nevertheless, judging from the experience of church users, the temperature falls to ±0°C from Sunday to Wednesday when the heating is re-started. Relative humidity depends on the season. Its mean value in the warm period is 70%. RH of the church is 52% in May when the heating season is just finished. Meanwhile between June and October RH stays from 70% to 80% tending to increase during later autumn (Fig. 18). RH fluctuations during the heating season vary by an interval of 25%, and therefore RH can be said to be unstable, which can be explained by periodic heating.

In Matthew Church both short-term and seasonal fluctuations are much lower than in other churches. This building has the most stable indoor microclimate, except for four days from 5 to 9 September 2008 when the relative humidity increases by 10% in comparison to the remaining period (Fig.19). Since the large hall, just as in other churches, is used on certain weekdays with the heat supply increased for those days, it causes RH fluctuations. It should be remembered that this building is not listed as a historic building as defined earlier by us. Hence the capillary moisture impact and condensation risk calculations do not apply to this building, because this building has different structures.

RH of Liepaja St. Trinity Cathedral varies between 50% and 80%. Measurements at this church were performed over large intervals and therefore we cannot make a judgement on the short-term microclimate fluctuations in this church, and it is difficult to compare them to measurements of other churches. The temperature varies between -3°C and +22°C. RH fluctuations have a common trend in outside temperature fluctuations, which proves the huge role that the outside air plays in the indoor climate. RH in the warm season is 60% on average, whereas it is 70% in the cold season (Fig. 20). Measurements in this church should be updated after

renovation of windows and vents at shorter measurement intervals.

#### 4.1. Wooden churches

Turaida Church, being a building of the museum reserve, has a relatively large number of visitors. Therefore, the indoor climate of the church is largely influenced by the outside air parameters (temperature and air humidity content). Since a high indoor temperature is achieved with a hot air generator during the cold winter season, it brings about major RH fluctuations of 34%. Even though the condensation risk in wooden churches, as discussed in previous sections, is unlikely to happen, nevertheless rapid and intense heating of the air in the church from -6°C to +16°C increases the condensation risk on the cold structures of the building, causing an air-drying process and also severe fluctuations of relative humidity. Large RH fluctuations from 30% to 79% are observed during the warm periods of the year, and they increase warm air flow into the church during the summer up to 27°C (Fig. 21). Periodic local heating of the church does not ensure a stable microclimate and, quite the opposite, it increases its fluctuations. The microclimate of this church is very unstable.

The temperature of Riga Jesus Church during the cold season is held permanently between +10° and +15°C, and in the warm season between +15°C and 28.9°C, regardless of its use, and it shows the major impact of outside air on the microclimate of the building which causes huge inter-seasonal changes in relative humidity between 28% and 70%. The interval of relative humidity in the church during the heating period is 30% to 50%, while the short-term fluctuations are 2.1% (Fig. 22). Short-term RH and temperature fluctuations of the church are relatively small. The indoor climate of this church is stable, with some short-term exceptions in a one-year period, up to ten times, when the temperature suddenly changes by +5°C in 6 hours, which can be explained by deliberate venting.

All the churches also demonstrate outside air infiltration, especially in the case of historic churches (Krimulda, Cesis, Limbazi, Turaida, Riga Jesus Church) and its impact on indoor climate. Therefore, the RH fluctuation range in all churches is between 28% and 88%.

### 5 Conclusion

When the buildings are used during the winter, we can see huge inter-seasonal RH fluctuations.

Outside air largely impacts the historic churches due to intense air infiltration.

Judging from the measurements it can be claimed that RH fluctuations in both stone and wooden churches definitely decrease when permanent conserved heating with minimum air temperatures between 6°C and 8°C and a maximum low temperature difference for the time of services (air temperature between 10°C and 14°C) is maintained.

In general, out of four historic brick wall churches (Krimulda Church, Limbazi Church, Cesis St. John Church, and Liepaja St. Trinity Church), Cesis Church with its average RH of 55% has the most stable microclimate due to permanent conserved heating.

Out of two wooden churches the most stable indoor climate is in Jesus Church with the average RH of 49%, where both short-term fluctuations and seasonal fluctuations are much lower than in Turaida Church.

In further research it would be necessary to examine the volume of vaporized capillary moisture and its impact on the indoor microclimate. It would be necessary to continue research of the microclimate in such historic churches which have prevented uncontrolled outside air infiltration through the building envelope, so that a possible microclimate variations simulation could be performed on the basis of data obtained.

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## Article

# Typology of Latvian Churches and Preliminary Study on Indoor Air Temperature and Moisture Behavior

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**Abstract:** When dealing with the indoor microclimates of cultural and historical heritage cult buildings, it is important to know the types of these buildings by their spatial volumes and by the types of enclosing structures, and it is also important to understand the moisture transfer processes in these buildings, which would allow one to generate solutions on how to more effectively control the indoor microclimate. Due to the antiquity and specific load of these buildings, the existing standards are not applicable. This study summarizes 275 churches in Latvia, dividing them both according to five spatial volumes and according to the types of the materials used, which makes it possible to create potential air flows for all spatial volumes and to predict condensation risks in the future. Additionally, the results of temperature and humidity measurements in two different churches from one region of Latvia are given and the absolute humidity was calculated, and the data were analyzed depending on the outside air temperature. These measurements have yet to be followed up with the data of a full year.

**Keywords:** church typology; humidity

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## 1. Introduction

Understanding the formation of moisture in cultural and historical heritage cult buildings is important in order to be able to properly maintain these cultural and historical heritage objects and to design appropriate ventilation systems for them. Until now, there are no established standards, regulations or studies on humidity parameters in cult buildings in Latvia. There are 226 cult buildings in Latvia that have the status of cultural monuments and another 2378 movable and immovable objects in these and other cult buildings [1]. As a result of an uncontrolled amount of moisture, condensation formed on the enclosing structures and equipment (organ, pulpit, altar), and as a consequence, both enclosing structures and equipment created a favorable environment for the spread of various fungi and other microorganisms [2,3], which often leads to the destruction of these objects.

In the study of the microclimate of seven Latvian churches, possible risks of condensation on the inner surfaces of external walls and ceilings were calculated at three different room temperatures and three different indoor relative humidities, where the materials and dimensions of the enclosing structures were taken from the Krimulda (LV) church [1]. Such a calculation does not give a complete picture of the possible formation of condensation risks in churches, because each church could have different materials and dimensions of the surrounding structures. In order to determine the risks of condensation on the internal walls and ceilings of buildings during periods of low temperature, it is necessary to take into account both the outdoor and indoor air temperatures, as well as the types and thicknesses of the enclosing construction materials. In Latvia, one of the three leading denominations—Lutheran—has 337 religious buildings [4–7]. There are several types of materials for the enclosing structures of these cult buildings, and their thicknesses are also different. Houses of worship in Latvia have been built since 1198, and accordingly, the construction technologies of these buildings have changed over the course of several hundred

years. Cultural and historical heritage cult buildings often have a specially protected status according to the Latvian Law of 1992 “On the Protection of Cultural Monuments”, as a result of which the exterior doors or windows of the cult building can only be restored and replaced with new ones that are more energy-efficient and air-tight is not allowed.

According to the actual humidity measurements and calculations of excess moisture in the apartments of multi-apartment residential buildings, it has been concluded that the actual excess moisture in the apartment at different outdoor air temperatures is slightly different [8], compared to how it is determined according to the standard [9]. The result of this study on residential buildings confirms that it is necessary to make sure of the suitability of these and other standards’ sizes also for historical cult buildings.

At the National Museum of Portugal, measurements were made for three different rooms built in different periods. Part of the museum building is in a palace built in the 17th century, another part in a monastery built in the 16th century and another in a 20th century annex, where a unified heating, ventilation and cooling system was built in 1990. These measurements show that as regards the relative humidity, it was possible to find limits of 45–66% for room 12, 40–64% for room 41 and 55–70% for the chapel [10]. The chapel is located in the historical part of the monastery, which proves that the microclimate parameters of historical buildings are also influenced by their enclosing structures. Considering that Portugal is located in a different climate zone, we cannot consider the values of air parameters for such a study. However, the fact of there being differences in air parameters between rooms of different construction periods indicates the influence of the enclosing structures. Different outdoor air parameters were compared by studying three churches, Sergey Radonezhskiy, Volgograd (RU), All Saints Orthodox Church, Riga (LV) and Liepaja Holy Trinity cathedral (LV) [11].

In a study of nine historic stone churches of the Baltic Sea, it was found that the short-term fluctuations of the relative humidity are smaller in the churches with regular preservative heating [12]. On the other hand, in this study, the buildings were not divided according to the dimensions of the materials used in the enclosing structures, therefore we cannot apply these results to other cult buildings, which may have other dimensions of the enclosing structures and also other thermal resistance values. On the other hand, in the study of the microclimate of a church in medieval Estonia (Church of the Holy Cross in Harju Risti, Estonia), an experiment was conducted with three different types of microclimate control (conservation heating by air-to-air heat pump, dehumidification, and adaptive ventilation) and it was found that “All three climate control systems proved to work and were able to lower the relative humidities in the church, but with different performance and energy use” [13]. In this same church, another study was also conducted without air heating of the premises, using the adaptive ventilation system by opening and closing windows and doors according to the CO<sub>2</sub> sensor, thus ensuring air exchange [14]. However, study was carried out in the spring period, when the outdoor air is the driest in the year, and such a solution is not applicable in other seasons.

The average air temperature was 3.34 °C, relative humidities 77.45% and with a significant outdoor air influence on the indoor microclimate in an 18th century Romanian wooden church without heating, ventilation and cooling systems during nine weeks of monitoring [2].

It is necessary to determine the types of cult buildings according to their spatial planning and the materials used for the enclosing structures. We performed a data analysis of excess humidity in indoor spaces, depending on the outdoor air temperature.

## 2. Literature Review

Historical buildings, such as castles, mosques and churches, require careful handling to preserve their cultural and historical value. The methodology of historical building analyses is complicated by the usage of ancient materials, the presence of artworks and a lack of documentation [15]. An important conservation factor is the indoor environmental parameters. Most of them comprise temperature and humidity. High humidity and temper-

ature will cause biodeterioration—a material destruction process caused by microbes [16] and fungi [17].

Biodeterioration is strongly affected by excess moisture [18] which enters the building through building structure defects in walls, roofs or foundations or through leaking plumbing pipes. It is impossible to eliminate some excess moisture, and that is why it is necessary to control the indoor parameters and if necessary, influence them.

The air temperature inside a building correlates with the outside temperature and it changes with it: when the outdoor air temperatures rise, the indoor air temperatures also rise and vice versa [19]. Additionally, there is temperature stratification in buildings, and the air on top of buildings is much hotter than that below. Temperatures also can be affected by movement of people in/out of the building and solar gains.

The indoor relative humidity highly depends on outdoor and indoor temperature. In a hot climate, the mean relative humidity in a historical building can be up 58% [20], but in a cold climate it can be 60–80% [21,22]. However, reduced indoor humidity can cause damage to the interior, which has never adapted to a lower humidity. Variations in relative humidity must be limited [22]. The research involved in the study of the climate change impact on the preservation of historical buildings claims that over the years, as the temperature increases, so does the humidity [23]. This may become a problem in the future. Measurements that were carried out over a year in another study show that with increasing ventilation rate, the drying effect also increased [22].

To control the internal air parameters for providing a comfortable temperature for occupants and preservation of the building in its original form, the building must be ventilated and heated. As the research shows, the forced hot-air system for heating is not suitable for historical types of buildings because of its low efficiency and inability to maintain thermal comfort [24]. The heating system must include a dehumidification unit for humidity control in buildings [22]. For buildings with frequent usage, the solution is heating with an air-to-air heat pump. Additionally, insulation materials can be used to improve resistance to heat transfer in building structures. If for any reason it is necessary not to use artificial insulation materials, natural insulation materials can be used, such as hemp fiber insulation [25]. The research also concludes that in the future, because of climate change, it will be necessary to cool buildings for their preservation [23]. For cooling in a historical building without a ventilation system, a ceiling-mounted cooling panel can be used [26]. If a historical building is reconstructed and has a ventilation system with a chiller, already existing equipment may be improved [27] to reduce power consumption, especially in a hot climate.

### 3. Materials and Methods

#### 3.1. *Creation of a Typology of Cult Buildings*

A total of 335 Latvian Lutheran churches were collected, surveying the types and dimensions of the materials used in their enclosing constructions. Taking into account the volumes of the buildings and the possible difference in air flows, as well as the types and dimensions of the materials of the enclosing constructions, the buildings have been classified according to their spatial differences and the types of materials used, which have different thermal resistances.

#### 3.2. *The Influence of Outdoor Air Humidity on the Indoor Microclimate*

Microclimate measurements were carried out simultaneously from 13 October 2021 to 7 July 2022 in two different churches:

- From 13 October 2021 to 27 December 2021 and from 10 January 2022 to 7 July 2022—Krimulda church, with exterior masonry walls and both brick and wooden vaulted ceilings. The Krimulda Church is a popular tourist attraction in Latvia, and its doors are open to tourists 24 h a day, 7 days a week, 365 days a year, which could give complete assurance about the influence of outdoor air humidity on the indoor climate. The church is located 45 km from Riga to the East.

- From 10 January 2022 to 7 July 2022—the Turaida church, with exterior walls of wooden logs and a wooden covered ceiling, is located in the territory of the Turaida Museum Reserve and is open six days a week for museum visitors from 10:00 a.m. to 6:00 p.m. The church is located 47 km from Riga to the East.

Temperature and relative humidity were measured with the HOBO MX Temp/RH/Light/Ext-Temp Kit (Onset Computer Corporation, 470 MacArthur Blvd., Bourne, MA 02532, USA) shown in Figure 1, at 30-min intervals, heaving measured with an accuracy of  $\pm 2.5\%$  for relative humidity  $\pm 0.2$  °C for temperature.



Figure 1. HOBO MX Temp/RH/Light/Ext-Temp Kit.

Two measuring devices were placed in the Krimulda church shown in Figures 2 and 3, one at the outer wall of the hall at a height of 2.9 m from the floor and the other in the ceiling arch of the hall and tower balcony at a height of 8 m from the floor shown in Figures 4 and 5.



Figure 2. Example of mounting HOBO MX measuring instruments on the outer wall.



Figure 3. Example of mounting HOBO MX measuring instruments on the ceiling arch.

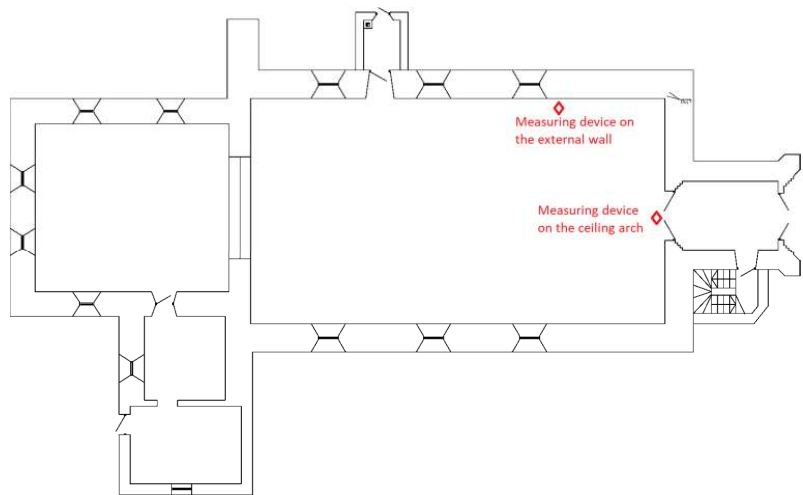


Figure 4. Krimulda church plan with locations of the measuring devices.

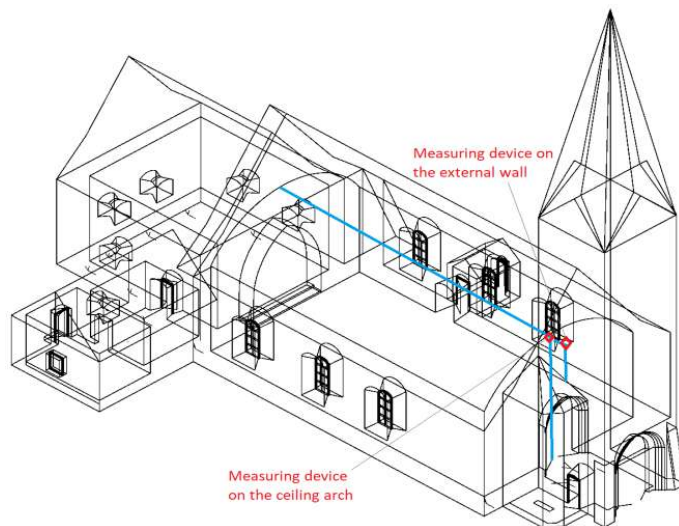


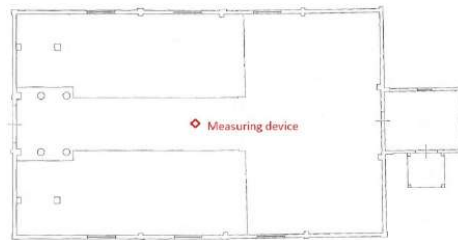
Figure 5. Krimulda church 3D model with locations of the measuring devices.

In the Turaida church, one measuring device was placed in the middle of the room on a chandelier at a height of 2.7 m from the floor shown in Figure 6.

Based on temperature and relative humidity measurements, the difference between indoor and outdoor air absolute humidity was calculated and the moisture excess  $\Delta_v$  ( $\text{g}/\text{m}^3$ ) was determined by the following equation:

$$\Delta_v = v_i - v_e \quad (1)$$

where  $v_i$  is the humidity by volume of indoor air ( $\text{g}/\text{m}^3$ ) and  $v_e$  is the humidity by volume of outdoor air ( $\text{g}/\text{m}^3$ ) [9].



**Figure 6.** Turaida church plan with the location of the measuring device.

From the thirty-minute interval data, the average moisture excess was calculated for each hour, so the hourly moisture excess data was used in the analysis. To analyze the dependency of moisture excess on the outdoor climate and to eventually determine the critical moisture excess values, the data for each place were sorted separately—according to the outdoor air temperature, using a 0.1 °C increment of the outdoor temperature. From these sorted values, maximum, minimum, mean and 10% critical levels (90% percentile and 10% percentile) for each place and temperature were determined.

To decrease the 90% moisture excess fluctuations caused by a limited amount of data for each temperature, an average 90% for 1 °C step outdoor temperature was calculated.

#### 4. Results and Discussion

##### 4.1. Typology of Cult Buildings

After surveying 335 Lutheran churches in Latvia, we found that 276 of them were currently functioning (Table 1), and we divided them according to:

- Spatial planning assuming that single span, two-span, three-span, cross and central churches will have different air flows, which requires further research and comparisons of air flow simulations. Additionally, it was found that out of 245 masonry churches, 29 churches have a partition wall between the altar room and the hall, which has a large-sized arch that is narrower than the altar room (Table 2). This type of partition wall with an arch can also create additional obstacles to air flow;

**Table 1.** The number of churches according to spatial planning and construction period.

Building Body Type	Total	Churches Building Period								
		13 c.	14 c.	15 c.	16 c.	17 c.	18 c.	19 c.	20 c.	21 c.
	59									
Single span	238	7	1	4	8	41	52	85	37	3
Two-span	3	-	-	-	-	-	-	1	2	-
Three-span	23	3	-	-	1	7	3	7	2	-
Cross	8	-	-	-	1	1	1	3	2	-
Central	4	-	-	-	-	-	2	2	-	-
Incl. wooden	26									

**Table 2.** The number of churches during construction periods with a separating wall between the altar and the hall.

Churches Building Period	Separating Wall with Arch
13 c.	6
14 c.	-
15 c.	2
16 c.	5
17 c.	13
18 c.	2
19 c.	1

- The construction period; since the 13th and 14th centuries, wall thicknesses for masonry churches are greater than for 19th century buildings. In the 19th century, brick was more widely used (see Table 3). The thermal conductivity  $\lambda$  of the enclosing structures was determined in accordance with the building code of Latvia [28]. The types of enclosing structures in churches of the 20th and 21st centuries are very numerous and different, but none of the churches of this period have the status of cultural and historical heritage, and therefore were not included in this study;

**Table 3.** Types and dimensions of enclosures by period of construction.

Churches Building Period	Wall Constructions, Thick (m), $\lambda$ (W/m·K)		Ceilings Constructions, Thick (m), $\lambda$ (W/m·K)	
	Brick/Stone (Homogeneous)	Wood (Homogeneous)	Wood (Inhomogeneous)	Brick Vault (Homogeneous)
13.gs.	1.5 m–2 m 0.87 (W/m·K)	-	-	0.15 m 0.8 (W/m·K)
14.gs.	1.5 m–2 m 0.87 (W/m·K)	-	-	0.15 m 0.8 (W/m·K)
15.gs.	1.5 m–2 m 0.87 (W/m·K)	-	0.2 m 0.1–0.3 (W/m·K)	0.14 m 0.8 (W/m·K)
16.gs.	1.5 m–2 m 0.87 (W/m·K)	-	0.2 m 0.1–0.3 (W/m·K)	0.14 m 0.8 (W/m·K)
17.gs.	1.2 m–1.5 mm 0.87 (W/m·K)	0.2 m 0.13 (W/m·K)	0.2 m 0.1–0.3 (W/m·K)	0.14 m 0.8 (W/m·K)
18.gs.	1.0 m–1.5 mm 0.87 (W/m·K)	0.2 0.13 (W/m·K)	0.2 m 0.1–0.3 (W/m·K)	0.13 m 0.8 (W/m·K)
19.gs.	0.8 m–1.0 mm 0.87 (W/m·K)	0.2 m 0.13 (W/m·K)	0.2 m 0.1–0.3 (W/m·K)	0.12 m 0.8 (W/m·K)
20.gs.	different	different	different	different
21.gs.	different	different	different	different

- In all churches, the ceiling of the altar and hall rooms serve as a barrier structure to the outside air. Surveys have found that the enclosing ceiling construction can be divided into three types (Table 4): a brick masonry vaulted ceiling, which is a homogeneous structure, a wooden vaulted ceiling, which is a non-homogeneous structure, and a straight wooden ceiling, which is also a non-homogeneous wooden structure.

**Table 4.** Number of churches with different types of ceilings over the rooms.

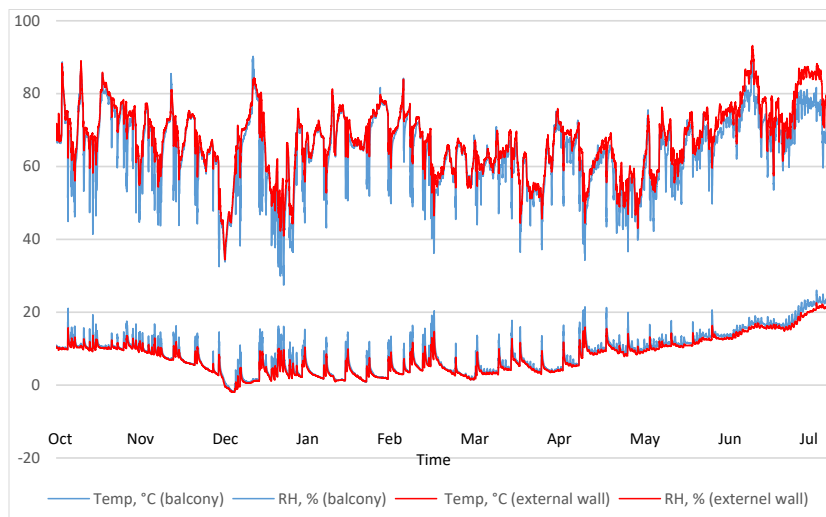
Room	Ceilings from Wood Construction Vault	Ceilings from Brick Vault	Straight Wooden Ceiling
Altar room	103	43	129
Parish room	107	29	139

Among the 26 wooden churches presented (Table 1), 3 are central and 23 are one-span churches. In further research, the external wall thermal insulation can be analyzed using thermal insulation materials for historical buildings [29] according to this church typology.

#### 4.2. Moisture

Relative humidity and temperature measurements in Krimluda church were made with two measuring devices, taking into account the high ceiling,  $h = 7$  m, and the orienting air flow on the hall and balcony ceilings found in the previous study [1]. Therefore, one measuring device was installed in the arch of the balcony, which separates the ceiling of the balcony and the hall, and the other measuring device was installed at the outer wall of the hall, where the firewood heating tap is located. 13 m away. The temperature increases shown in the graph in Figure 7 are related to the heating of the room once a week on Sundays (for example: 17 October 2021 01:30 p.m.), when the temperature

differences (+5.366 °C) on the outer wall (+15.697 °C) are also expressed, as well as on the balcony (+21.063 °C), which confirms the flow of warm air and the large heat losses found in the tower part of the balcony. On the other hand, there are differences in relative humidity fluctuations also at these same moments of the temperature fluctuations and when comparing the specific data in each of these measurements. For example: 17 October 2021 01:30 p.m.—on the balcony relative humidity 44.9638% temperature 21.063 °C and on the grass wall relative humidity 62.36% temperature 15.697 °C; putting these measurements on the Mollier diagram, it can be established that the absolute air humidity  $g/kg$  is the same. Accordingly, we can conclude from this that relative humidity fluctuations affect large temperature fluctuations, and in order to be able to analyze and evaluate humidity fluctuations, it is necessary to compare the effect of the actual moisture content of the outdoor air on the indoor air.

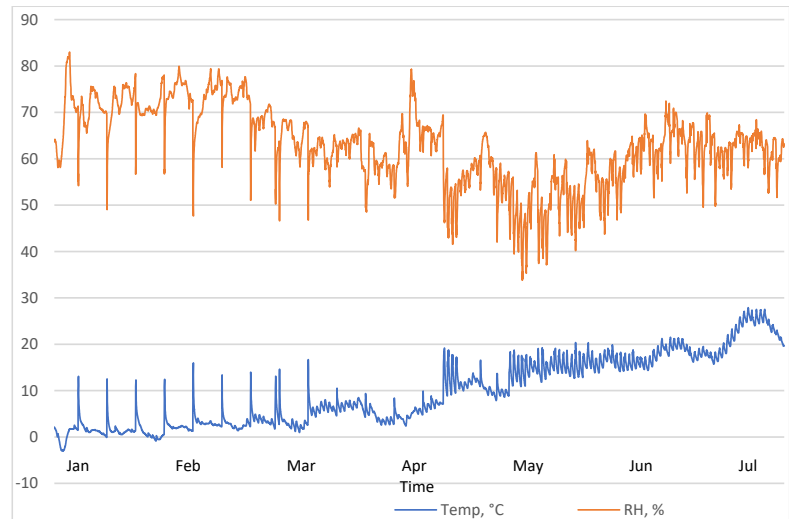


**Figure 7.** Humidity and temperature measurements in Krimulda church.

In the Turaida church, relative humidity and temperature measurements were made with one measuring device, which was placed on the chandelier in the middle of the room. The Turaida church has a 3.3 m low ceiling and one single altar and hall room, the internal dimensions of which are 17 m × 10 m. Taking into account the small size of the church room and the fact that the room is crossed longitudinally by one middle aisle separating the sides containing rows of pews, where the visitors form the main air flow, a decision was made to install one sensor in the middle part of the room. Figure 8 shows that in this church, as in the Krimulda church, the relative humidity and temperature fluctuations are related: 16 January 2022 at 9:00 a.m., the relative humidity is 71.348% and temperature is 1.805 °C. However, after three hours when the building is heated with an electric heater on the same date at 11:30 a.m., the relative humidity is 54.233% and temperature is 13.064 °C. According to the Mollier diagram, there is also an increase in absolute humidity from 2.5 to 4.5 g/kg at this stage, which is also related to the intense religious activity during this period, when there are several churchgoers at the same time.

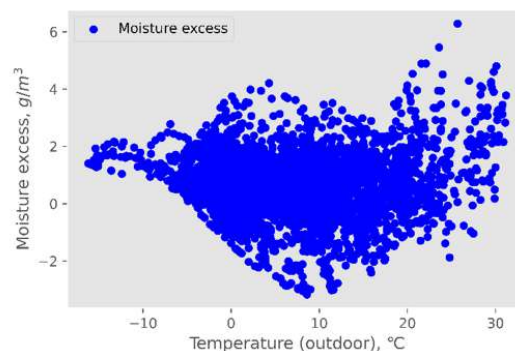
Indoor temperature and relative humidity measurements were collected and statistically analyzed. Outdoor air parameters were taken from the “Latvian Environment, Geology and Meteorology Center” database station in Sigulda, 10 km away from both churches. As you can see in Figures 9 and 10, the distribution density of the measurement points is very different, so in Figures 11–13, 10–90% data filtering is used for the minimum,

maximum, and average, as well as 10 and 90% excess humidity between the rooms and outside, depending on the temperature.



**Figure 8.** Humidity and temperature measurements in Turaida church.

As it can be seen in Figures 8–10, the excess moisture in relation to the outdoor air temperature from  $-10$  to  $+15$  °C is hardly noticeable, but in the outdoor air temperature range from  $+15$  to  $30$  °C, there is visible moisture increase. The excess outdoor air humidity for 90% values in the temperature range from  $-10$  to  $+15$  is from  $0$  to  $3$  g/m<sup>3</sup>, while in the temperature range from  $+15$  to  $30$  °C it is from  $0$  to  $6$  g/m<sup>3</sup>. Looking at and comparing all three in Figures 11–13, we did not see any significant difference in these fluctuations of excess moisture from the outdoor air temperatures, and all three graphs are very similar, since the measurements were made in the same time period. The similarity of these graphs confirms that the increase and fluctuation of excess moisture is not related to local moisture release that could be brought to these two different sites by the different number of tourist visitors. Additionally, the similarity of these graphs confirms that there is a large natural infiltration of outdoor air. Moisture is not related to the local moisture release that could be brought to these two different sites by the different number of tourist visitors. Additionally, the similarity of these graphs confirms that there is a large natural infiltration of outdoor air.



**Figure 9.** Moisture excess in Krimulda church on the balcony.

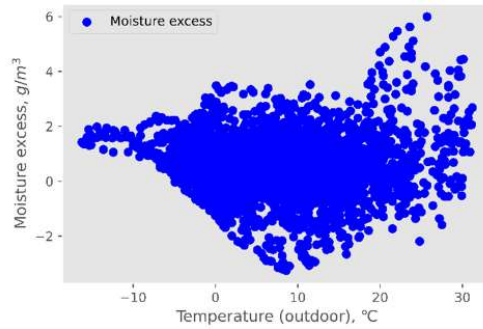


Figure 10. Moisture excess in Turaida church on the lamp.

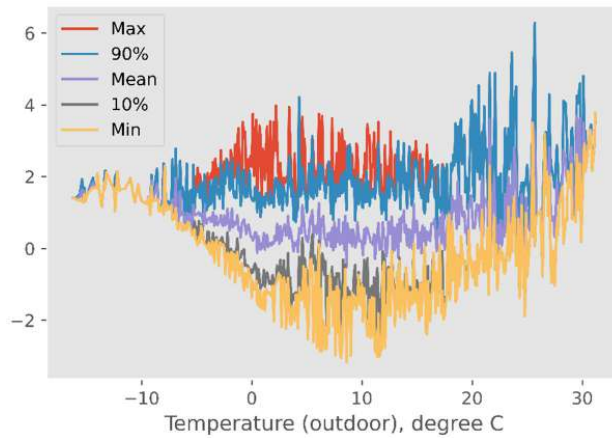


Figure 11. Average moisture excess in Krimulda church on the balcony.

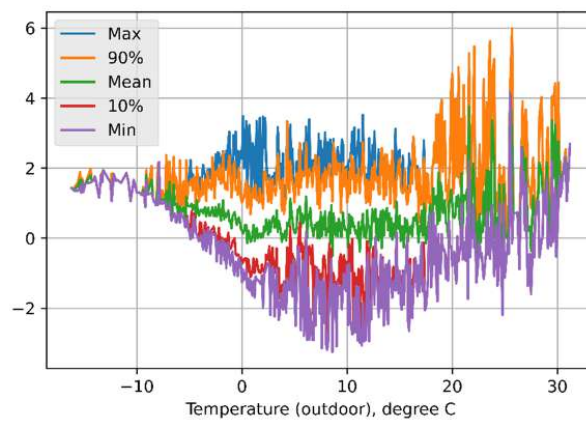
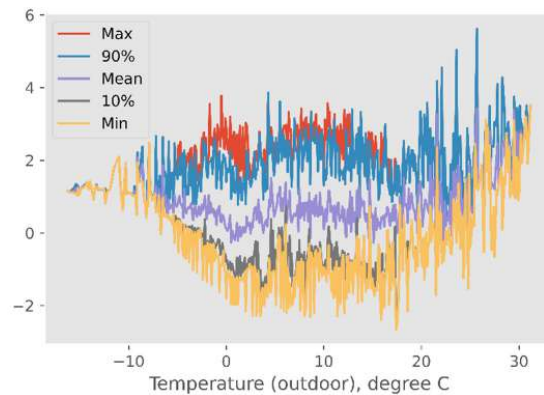


Figure 12. Average, oisture excess in Krimulda church on the external wall.



**Figure 13.** Average moisture excess in Turaida church on the lamp.

## 5. Conclusions

This article presents the initial data on the typology of churches, dividing churches according to the construction of their external walls into two types—there are 249 stone churches and 26 wooden churches. The surveys concluded that the thickness of the walls of stone churches depends on the period of construction, so the churches were divided according to the period of their construction and summarized for each period's typical enclosure divisions. The 20th century and the 21st century are not listed because they do not have the status of cultural and historical heritage. Churches are divided according to their spatial dimensions into five types—one-span, two-span, three-span, cross, and central churches. On the basis of this data, an analysis of possible air flows and condensation risks on the enclosing structures can be carried out.

The results of the measurements and calculations for excess humidity in the indoor air in two churches with different enclosing structures (wooden and masonry outer walls) but with similar visitor loads are also presented. The results show that the 90% curve reaches  $+6.0 \text{ g/m}^3$ , and in the cold period it reaches from 1 to  $2 \text{ g/m}^3$ . These measurements and calculations should continue throughout the year.

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## Article

# Preliminary Study on Indoor Air Temperature and Moisture Behaviour in 13th-Century Churches in Latvia

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**Abstract:** The microclimate plays a crucial role in the conservation of historical cult buildings and their artifacts for future generations. In order to conserve these buildings and their artifacts, it is imperative to ensure that the microclimate is conserved. The norms and standards existing so far in Latvia do not stipulate thresholds for air parameters that would ensure a conserving microclimate for historical cult buildings. In order to identify these thresholds, the air parameters were measured simultaneously at nine measuring points within the Krimulda Church (LV) of the 13th century. The temperatures of the surfaces of the building envelope and potential condensation were calculated using the actual data of indoor and outside air. The indoor and outdoor air humidity ratio was calculated for each measurement. The conservation threshold of indoor microclimate parameters was determined by using intermittent heating on the basis of the air parameter fluctuations and calculations. The moisture vapours from the building structures were quantified in this research. The indoor humidity ratio during the warm season and the upper threshold during the heating season were determined.

**Keywords:** church; humidity; microclimate



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## 1. Introduction

The microclimate is a crucial factor allowing for the preservation of buildings and the items within them. An inappropriate indoor microclimate may result in material losses or the loss of these items. There are 2604 cult buildings in Latvia which are or which contain cultural monuments of national importance. The norms and standards currently existing in Latvia regarding the preservation of the microclimate in historical cult buildings do not contain specific air parameters [1]. The standard LVS EN15759-1:2012 recognises two approaches to ensuring a microclimate for churches [2].

1. Indoor climate for conservation;
2. Indoor climate for thermal comfort.

This standard defines several heating system strategies for churches:

1. No heating;
2. Conservation heating;
3. Heating for thermal comfort.

Our goal was to identify the air parameter thresholds necessary to maintain a consensual air microclimate, adhering to which reduces the risk of condensation and thereby prevents the formation of mould and other fungi.

Out of the 276 Lutheran churches in Latvia, ten date back to the 13th century and are masonry buildings. Among these, seven are single-nave churches and three are three-nave churches. According to a compilation of Latvian Lutheran church typologies, building envelopes of the 13th century churches are homogeneous and with equal  $U = 0.87$  ( $W/m^2K$ ) values [3].

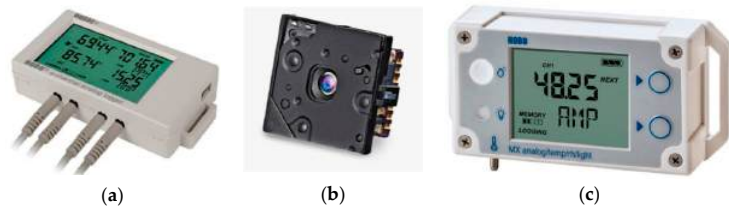
## 2. Literature Review

When reviewing the analysis of the air flow impact in historical churches in IDA-ICE 4.8 simulation software, particularly focusing on the largest vertical surfaces of the building, such as doors and windows, it becomes evident that the simulation data for such buildings do not align with the actual measurement data [4]. In the southern part of Europe (Spain, Italy, etc.) the indoor microclimate of historical churches is maintained mainly by expending energy to cool them down during the hot season. [5,6] In southern European countries [7], just like in the Baltic states [8,9], historical churches have huge air humidity fluctuations. Energy consumption for the indoor microclimate of historical churches in the Baltic states is related to the cold seasons [3,10]. Improper indoor air temperatures and relative humidity may facilitate the spread of wood-decay fungi in wooden structures [11]. One of the closest neighbouring countries to the Baltic countries is Poland, where air parameters differ from those in Latvia and align more closely with those of other European countries. Regarding historical churches in Poland, it has been observed that the indoor humidity ratio depends on the outside air humidity, and the highest humidity ratio of indoor air is reached in August, amounting to 13 g/kg [12]. In the Netherlands, the major moisture problems in historical buildings are caused by the high groundwater levels and overflowing of rivers [13]. When comparing modern churches to those from the Baroque period, specifically churches of the 17th–18th century in Malta, it has been observed that parameters of indoor air during summers are more stable in Baroque churches with larger thermal mass [14]. The 16th and 17th century churches of the Czech Republic use heating elements that are placed among the benches during the cold seasons and which are switched on for the worship, only thus ensuring local intermittent heating. These have average indoor temperatures of 16.7 °C and lowest indoor temperatures of 1.1 °C [15]. Huge differences in air parameters in one room accelerate the deterioration of materials [16]. A stable microclimate allows the life of cultural and historical heritage to be extended [17]. Thorough knowledge of the usage conditions within religious building spaces is essential to identify compatible and sustainable intervention strategies [18]. Cultural heritage is threatened by biotic attacks, moulds, and fungi, which tend to develop under certain favourable microclimatic conditions (mainly at the beginning and end of winter) [19]. Pollutants can be viewed as a significant contributor to the deterioration of construction materials used in the field, particularly in the case of heritage buildings that are part of and represent the culture of a country. These pollutants have a dual impact, affecting both the structural strength of the buildings in question and the visual aesthetics of the surroundings. Furthermore, their effects are enduring, influencing aspects such as living conditions, quality of life, tourism, economic activities, and various facets of local daily life [20]. The decay resulting from moisture, primarily due to inadequate ventilation of the hidden faces of wall plates, has been established as the most significant risk to structural stability [21].

## 3. Materials and Methods

### 3.1. The Warm Air Flow and Temperature Distribution in the Premises of the Krimulda Church and on the Surface of the External Wall

Temperature was measured with the measuring instrument HOBO 4-Channel Analogue Data Logger (UX120-006M; Onset, Bourne, MA, USA) in 30 min intervals, with a temperature measuring accuracy of  $\pm 0.1$  °C. These four temperature data sensors (Figures 1–3) were installed with the same reading intervals as other RH and T sensors. These temperature data sensors were installed at various heights and distance at the external northern wall, where the stove was situated, as described in Table 1 and Figures 4–6.



**Figure 1.** (a) HOB0 4-Channel Analogue Data Logger (UX120-006M; Onset); (b) LWIR Micro Thermal Camera Module FLIR Lepton (Teledyne FLIR, Wilsonville, OR, USA); (c) HOB0 MX1104 Temp/RH/Light/Ext-Temp Kit (Onset).



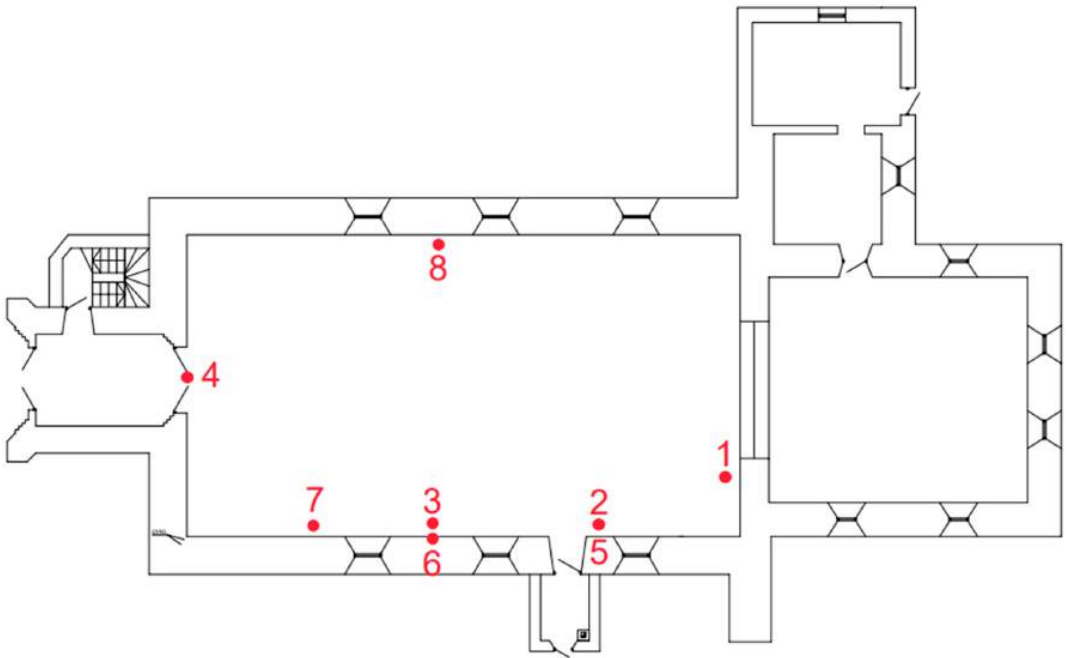
**Figure 2.** Indoor measurement devices (where 1, 4, 2 and 5: numbers of measuring devices).



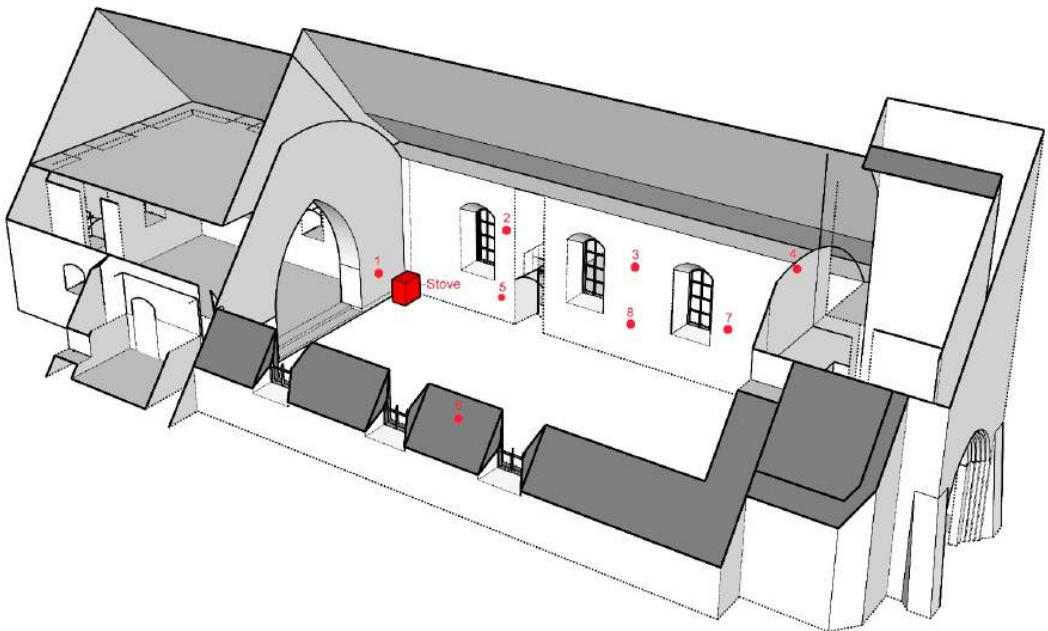
**Figure 3.** No. 9 outdoor measurement device.

**Table 1.** Measuring devices in the Krimulda Church.

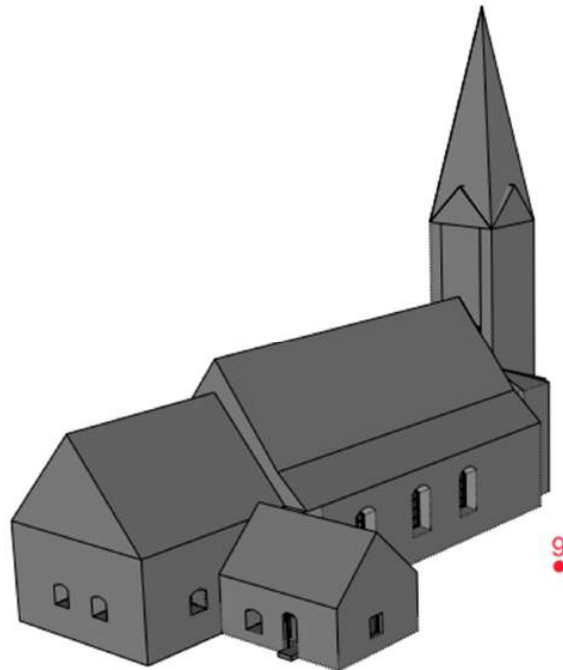
From	Measurement Type and Device Name	Measuring Period		Location and Description	Point Title																																																										
1	Relative humidity, temperature HOBO MX1104 Temp/RH	12/21/2022	2 p.m.	On the eastern partition wall, 2.35 m above the floor, and on the wall 0.82 m away from the metal chimney of the stove	“Stove”																																																										
		3/25/2023	12 p.m.			2	Temperature HOBO 4—Channel (UX120-006M)	1/27/2023	9 p.m.	On the southern external wall, 4.2 m above the floor and 2.8 m away from the stove	“At the first window”	3/25/2023	12 p.m.	3	Temperature HOBO 4—Channel (UX120-006M)	1/27/2023	9 p.m.	On the southern external wall, between windows, 4.15 m above the floor and 8.5 m away from the stove	Between S windows	3/25/2023	12 p.m.	4	Relative humidity, temperature HOBO MX1104 Temp/RH	7/7/2022	1 a.m.	8.8 m above the floor, at the centre of the ceiling and the balcony arch	On balcony	3/25/2023	12 p.m.	5	Temperature HOBO 4—Channel (UX120-006M)	1/27/2023	9 p.m.	On the southern external wall, at the corner of the lateral door opening, 0.9 m above the floor and 2.8 m away from the stove	“At the lateral door”	3/25/2023	12 p.m.	6	Relative humidity, temperature HOBO MX1104 Temp/RH	1/27/2023	9 p.m.	On the external northern wall between windows, 2.25 m above the floor and 12.9 m horizontally away from the stove	On N wall	3/25/2023	12 p.m.	7	Relative humidity, temperature HOBO MX1104 Temp/RH	7/7/2022	1 a.m.	On the external southern wall, 2.8 m above the floor and 12.7 m horizontally away from the stove	On S wall	3/25/2023	12 p.m.	8	Temperature HOBO 4—Channel (UX120-006M)	1/27/2023	9 p.m.	In direct contact with the southern wall, 1.95 m above the floor and 8.4 m away from the stove	“S wall”	3/25/2023	12 p.m.	9	Relative humidity, temperature HOBO MX1104 Temp/RH
2	Temperature HOBO 4—Channel (UX120-006M)	1/27/2023	9 p.m.	On the southern external wall, 4.2 m above the floor and 2.8 m away from the stove	“At the first window”																																																										
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3	Temperature HOBO 4—Channel (UX120-006M)	1/27/2023	9 p.m.	On the southern external wall, between windows, 4.15 m above the floor and 8.5 m away from the stove	Between S windows																																																										
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**Figure 4.** Layout of the Krimulda Church with the installed measuring devices (where 1–8: numbers of measuring devices).



**Figure 5.** 3D image of the Krimulda Church with the installed measuring devices (where 1–8: numbers of measuring devices).



**Figure 6.** 3D image of the Krimulda Church with 9: the measuring device installed outdoors.

On the basis of the measured data, the theoretical surface temperature  $\theta_{si}$ , of walls and ceiling is calculated by means of the following formula:

$$\theta_{si} = \theta_i - U * (\theta_i - \theta_e) * R_{si} \quad (1)$$

where  $\theta_i$ —the actual temperature of indoor air,  $^{\circ}\text{C}$ ;  $\theta_e$ —the actual temperature of outside air,  $^{\circ}\text{C}$ ;  $U$ —heat penetration rate in the building envelope,  $\text{W}/(\text{m}^2\text{K})$ ;  $R_{si}$ —heat transfer of the thermal resistance convection,  $\text{m}^2\text{K}/\text{W}$  [22].

During periods of church heating, thermal images were taken with a thermal camera, the FLIR Lepton 2.5,  $80 \times 60, 50^{\circ}$  (pixel size— $17\text{-}\mu\text{m}$ ; radiometric accuracy: high gain 5%; low gain 10%).

### 3.2. The Influence of Outdoor Air Humidity on the Indoor Microclimate

Microclimate measurements were carried out simultaneously from 7 July 2022 in four different churches:

- From 7 July 2022 to 24 April 2023 and from 10 January 2022 to 24 April 2022, microclimate measurements were taken in the Krimulda Church with exterior masonry walls and both brick and wooden vaulted ceilings. The Krimulda Church is a popular tourist attraction in Latvia, welcoming visitors 24/7 throughout the year. This accessibility provides a comprehensive understanding of how outdoor air humidity impacts the indoor microclimate. The Krimulda Church is situated in rural territory, in the middle part of Latvia, 34.45 km away from the border of the capital of Latvia, Riga, horizontally to the east. The parish hall's area is  $315.51 \text{ m}^2$  and the volume is  $3313 \text{ m}^3$ .

Temperature and relative humidity were measured with HOBO MX Temp/RH/Light/Ext-Temp Kit measuring instruments at 30-min intervals, with measuring accuracy of  $\pm 2.5\%$  for relative humidity and  $\pm 0.2^{\circ}\text{C}$  for temperature.

Four HOBO MX1104 Temp/RH/Light/Ext-Temp Kit measuring devices were installed inside the Krimulda Church. The locations are shown in Table 1 and Figures 4–6.

On the basis of air temperature and relative humidity measurements, the partial pressure of water vapour in moist air  $p_w$  (kPa) was calculated:

$$p_w = 6.11 \cdot e^{\left(\frac{17.625-T}{243.5+T}\right)} \cdot \frac{RH}{100} \quad (2)$$

where T—air temperature (°C), e—Euler's number [23], and RH—relative humidity (%).

The air humidity ratio W (g/kg) was calculated from the partial pressure  $p_w$ :

$$W = 622 \frac{P_w}{P - P_w} \quad (3)$$

where p—barometric pressure (kPa) [24].

Based on temperature and RH measurements, the difference between indoor and outdoor air absolute humidity was calculated, and the excess moisture  $\Delta_v$  (g/m<sup>3</sup>) was determined by the following equation:

$$\Delta_v = v_i - v_e \quad (4)$$

where  $v_i$  is the humidity by volume of indoor air (g/m<sup>3</sup>) and  $v_e$  is the humidity by volume of outdoor air (g/m<sup>3</sup>) [22].

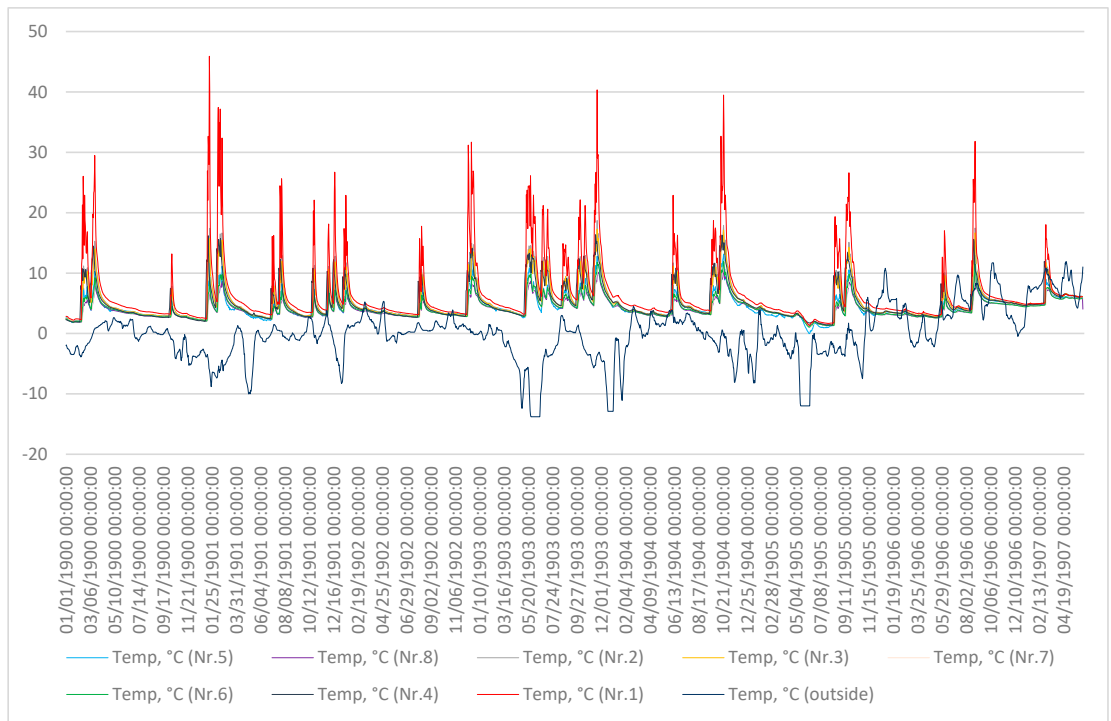
## 4. Results and Discussion

### 4.1. Temperature in the Krimulda Church

We can see from the overall temperature diagram in Figure 7 that the temperature peak was reached at Point No. 1. The peak temperature 45.9 °C at this point was reached on 2/4/2023 at 9:30 p.m. During all periods of elevated temperature, i.e., heating of the premises, the peak temperature was reached at this point, which retained a temperature difference between 1 °C and 3 °C during the periods with the lowest temperature fluctuation (Figure 6). The next highest temperature, 17.416 °C, in this period was reached at Point No. 2, which was 28.478 °C lower, and this degree of difference between these points remained during all temperature fluctuation peak periods. In Figure 7, is a diagram showing that the lowest short-term (48 h) temperature fluctuations in the outdoor air did not affect the lowest indoor air temperatures of that period. However, in the long term (more than 10 days), as the average outdoor air temperature rises or falls, the lowest temperature of the indoor air during the same period fell or rose depending on the outdoor temperature (Figure 7).

The largest temperature fluctuations between the measured points were observed in all periods of temperature elevation, as seen in Figure 7; therefore, we will look more closely at the period with the highest temperatures, which were reached at point No. 1 between 4 February 2023 and 8 February 2023, but without data on Point No. 1 in Figure 8. Point No. 1 was located nearest to the heating stove, and it had the greatest heat radiation influence, which can also be observed in the thermal images in Figures 8 and 9. From the temperature diagram in Figure 8, we can see that the temperature was similar in three points (points No. 2, No. 3, and No. 4), which were situated higher above the ground than other points, indicating a greater influence of thermal convection. The first highest temperature point during all elevated temperature periods was reached at Point No. 4, for example, on 2/4/2023 at 8 p.m., the temperature was 16.168 °C. This confirms a trend of warm air convection towards the tower. Meanwhile, the second temperature peak was reached at Point No. 2. At this point, at the same time, on 2/4/2023 at 8 p.m., the temperature was 13.206, 2.962 °C less than at Point No. 4, but after 2 h, on 2/4/2023 at 10 p.m., the temperature reached 17.416 °C, 1.248 °C more than at Point No. 4 two hours previously. Actually, the highest temperature was reached at Point No. 2, but with a delay of 2 h, and this or a smaller time delay could be observed during all temperature elevation

periods. A similar temperature was also reached at Point No. 3 on 2/4/2023 at 8 p.m. when the temperature was 12.033 °C, while on 2/4/2023 at 10 p.m., the temperature exceeded 15.694 °C. This temperature difference trend remained during all episodes of occasional temperature elevation or heating of the premises.



**Figure 7.** Temperatures in the Krimulda Church.

The temperatures at other points, i.e., No. 5, No. 6, No. 7, No. 8, during these temperature elevation periods were lower by several degrees in comparison to previously described points. By looking at the previously mentioned period, shown in Figure 8, the highest temperature of these four points during the fluctuation periods was reached at Point No. 5 on 2/4/2023 at 10 p.m., when the air temperature was 12.158 °C. Thermal images taken during the same period, in Figures 9 and 10, show the high impact of heat radiation at this point. The next temperature peak (Table 2) in the fluctuation period was located at Point No. 6 on 2/4/2023 at 10 p.m., where the air temperature was 9.4 °C. Meanwhile, at Point No. 7 on 2/4/2023 at 10 p.m., the air temperature was 6.9 °C, 2.5 °C lower than at point No. 6, but 30 min later, on 2/4/2023 at 10:30 p.m. at Point No. 7, the air temperature reached 8.1 °C, 1.3 °C lower than 3 min previously in point No. 7 but at the same time the temperature has not changed. This difference of 30 min in the temperature peak period between those two points was observed during all temperature elevation periods. Points No. 6 and No. 7 were situated at the same ( $\pm 0.1$  m) distance from the stove, but on different planes of the premises, and the differences of such temperature periods indicate varied heat radiation and convection influences on these points. Meanwhile, the lowest temperature was observed at Point No. 8. This point showed the temperature of the southern external wall. The temperatures at this point were 0.5 °C to 2 °C lower than the air temperature at Points No. 6 and No. 7 during all measurement periods. Throughout the measurement period, the lowest temperature of the wall surface, 1.5 °C, was reached

on 3/11/2023 at 6 a.m., but the highest temperature, 10.5 °C, was reached on 3/5/2023 at 1 p.m. Meanwhile, during the entire measurement period, the average wall temperature was 4.0 °C, which indicates great heat accumulation by the masonry walls.

The calculated wall and ceiling surface temperatures for each air parameter measurement “On the balcony” are shown in a diagram in Figure 10, together with the dew point in each measurement. Based on the measurement and calculation results shown in Figure 11, it is evident that during the intense fluctuation periods, the temperatures of the wall and ceiling surfaces closely approached the dew point. However, none of the temperatures calculated for each point reached the dew point. These calculations did not take into consideration the thermal inertia of the building envelope (including the masonry of the external walls) during the fluctuation periods when the indoor air, with the help of the heating, was heated by 10 °C from 2 °C to 12 °C. The stone masonry external wall accumulated the heat from the previous period, and its temperature was 2 °C.

Table 2. Measurement data for the temperature peak period.

Date Time, GMT+02:00	Temp, °C (No 5)	Temp, °C (No 8)	Temp, °C (No 2)	Temp, °C (No 3)	Temp, °C (No 7)	Temp, °C (No 6)	Temp, °C (No 4)	Temp, °C (No 1)	Temp, °C (Outside)
2/4/2023 06:30:00 a.m.	2.4	2.1	2.4	2.4	2.1	2.1	12.2	4.0	−3.6
2/4/2023 07:00:00 a.m.	5.5	2.9	8.7	7.8	2.1	3.7	11.9	26.9	−3.5
2/4/2023 07:30:00 a.m.	6.2	3.9	9.5	9.0	2.1	4.9	14.5	22.0	−3.9
2/4/2023 08:00:00 a.m.	8.5	5.1	13.2	12.0	3.7	6.4	16.2	32.6	−4.2
2/4/2023 08:30:00 a.m.	8.7	5.5	12.7	11.7	4.9	6.8	12.9	30.6	−4.8
2/4/2023 09:00:00 a.m.	7.9	5.7	12.5	11.7	6.4	6.9	10.5	28.0	−5.8
2/4/2023 09:30:00 a.m.	11.37	6.4	16.1	14.3	6.8	8.0	9.40	45.9	−6
2/4/2023 10:00:00 a.m.	12.2	7.6	17.4	15.7	6.9	9.4	8.8	39.8	−6.5
2/4/2023 10:30:00 a.m.	8.9	7.0	13.1	12.3	8.1	8.0	8.3	22.5	−6.8
2/4/2023 11:00:00 a.m.	7.4	6.2	10.4	10.0	9.4	6.8	7.8	16.6	−7.5
2/4/2023 11:30:00 a.m.	6.7	5.7	9.3	9.1	8.0	6.2	7.5	14.0	−8.2

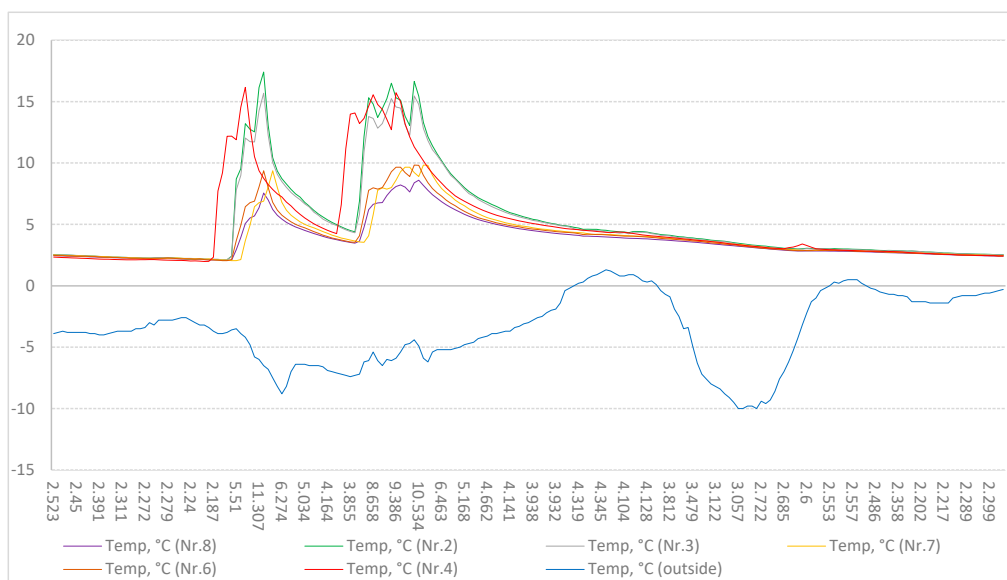


Figure 8. Temperatures in the Krimulda Church between 04/02/2023 and 08/02/2023.

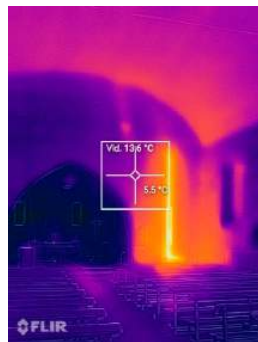


Figure 9. Thermal image from the Krimulda Church on 04/02/2023 at 7:12 p.m.



Figure 10. Thermal image from the Krimulda Church on 05/02/2023 at 12:33 p.m.

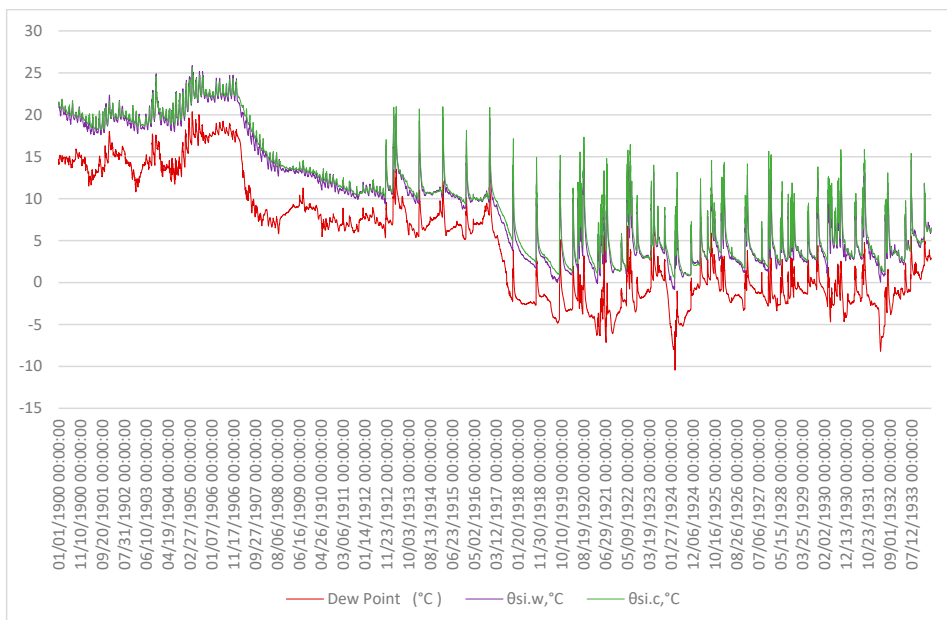
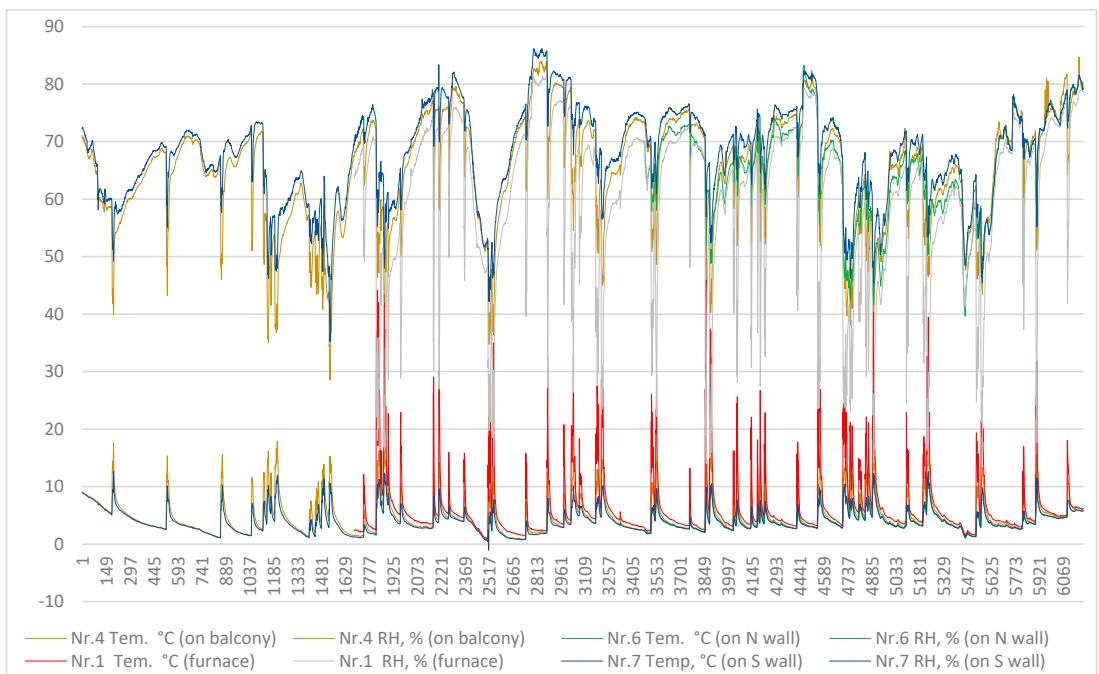


Figure 11. The calculated temperatures in the wall and ceiling surface, as well as the dew point.

#### 4.2. Moisture in the Krimulda Church

There is no permanent heating and ventilation system in the Krimulda Church. During the cold season, the indoor air of the church is heated with a steel wood-burning stove (~60 kW) prior to religious activities in the church. Fluctuations of indoor temperature and relative humidity in the Krimulda Church during all temperature elevation periods showed symmetrical differences among the points, as in Figure 12. This indicates that the direction of change in the air at all points was equal, but the air temperatures were different. The air temperatures differed at each of these points because there were different heat radiation and convection impacts on each of these points, as described above.

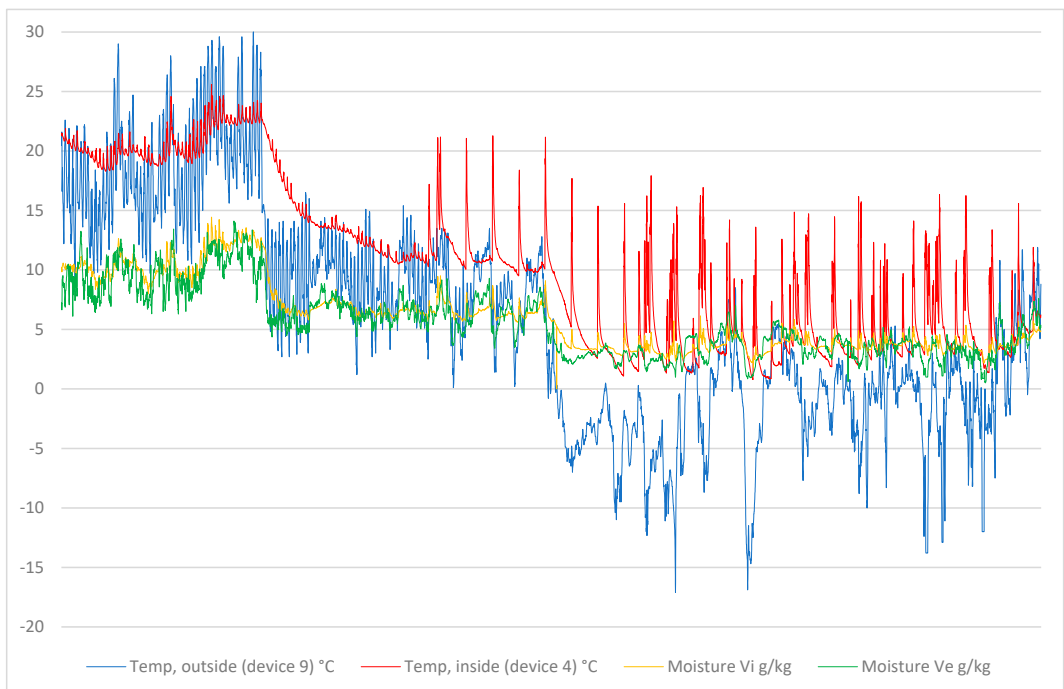
On the basis of measurement data at Point No. 4, “On the balcony”, we chose to further analyse the air moisture content within the premises, because this point was situated in the centre of the ceiling and, as concluded previously, the convection direction of the heated air in the premises moves towards this point, No. 4. On the basis of the measured relative humidity and temperature, we calculated the absolute humidity for each of those measurements, both for indoor air and outside air (Figure 14). When looking at the diagram in Figure 14, one can see that the highest indoor air humidity was  $w_i = 14.33$  g/kg on 8/15/2022 at 1 p.m., but the outside air humidity content at this moment was  $w_e = 12.6$  g/kg, and the outside temperature was 27.6 °C. Meanwhile, the highest outside humidity content was  $w_e = 14.25$  g/kg on 8/22/2022 at 8:30 p.m., while the outside air temperature was 20.6 °C and the internal air humidity ratio was  $w_i = 12.84$  g/kg. The diagram in Figure 14 shows that as the outside temperature fell, the average humidity ratio in the outdoor and indoor air also decreased.



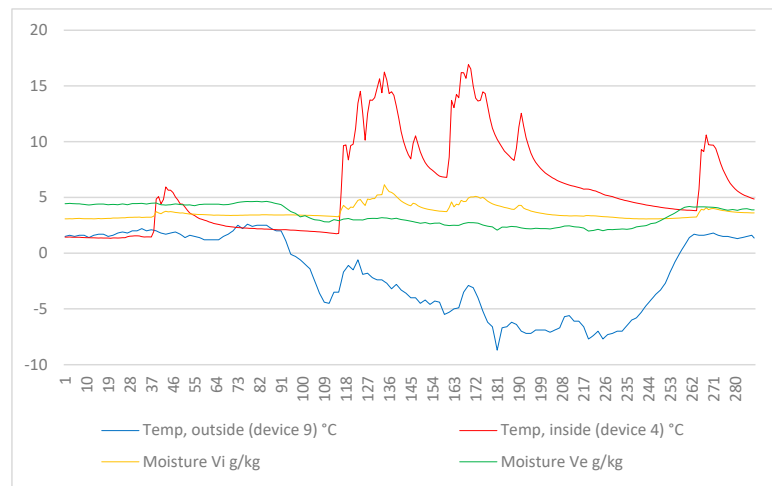
**Figure 12.** RH and temperature in the Krimulda Church between 11/16/2022 and 25/03/2023.

In order to analyse the impact of visitors on the air humidity and short-term fluctuations, we will look at time periods with the maximum numbers of visitors, such as 12/24/2022 at 6 p.m., with up to 200 persons (0.63 pers/m<sup>2</sup> or 0.06 pers/m<sup>3</sup>), and on 12/25/2022 at 12 p.m., with up to 90 visitors (Figure 13). From Figure 13, we can see that

on 12/24/2022 after 8:30 a.m. ( $1.74\text{ }^{\circ}\text{C}$  and  $v_i = 3.08\text{ g/kg}$ ), the air inside of the church heated up rapidly as the visitors to the church entered, with a maximum of three persons simultaneously. Before a large number of visitors gathered simultaneously in the building at 17:30, the indoor air heated up to  $15.6\text{ }^{\circ}\text{C}$  and the indoor humidity reached  $5.18\text{ g/kg}$ . This increase in the room's humidity ratio when the room temperature became elevated indicates that moisture vapours were coming from all structures of the building, including the external masonry walls [3], slabs, and interior details. Meanwhile, at 6:30 p.m., when the number of visitors reached its peak, the indoor air temperature was  $16.2\text{ }^{\circ}\text{C}$  and  $v_i = 6.1\text{ g/kg}$ . The simultaneous gathering of 200 persons in the church increased the air humidity ratio, both in terms of measurements by  $v_{i\Delta} = 1.08\text{ g/kg}$  and in terms of calculation from 1 to  $2.5\text{ g/kg}$  if one visitor were to release 20 to 50 g/h of moisture [25]. These fluctuations in air parameters, when shown in the h-x diagram, allowed us to notice that, given the quantity of visitors and to prevent condensation risks, the minimum temperature must be  $7\text{ }^{\circ}\text{C}$  or the maximum humidity ratio— $4.5\text{ g/kg}$ . The same tendency was observed the next day, on 12/25/2022 (Figure 13); when they began heating the indoor air, the air humidity ratio also increased by  $w_{i\Delta} = 2\text{ g/kg}$ , and at 12:30 p.m., when the number of visitors reached 87 persons, the air humidity ratio increased by another  $w_{i\Delta} = 0.5\text{ g/kg}$  and reached  $4.8\text{ g/kg}$ .

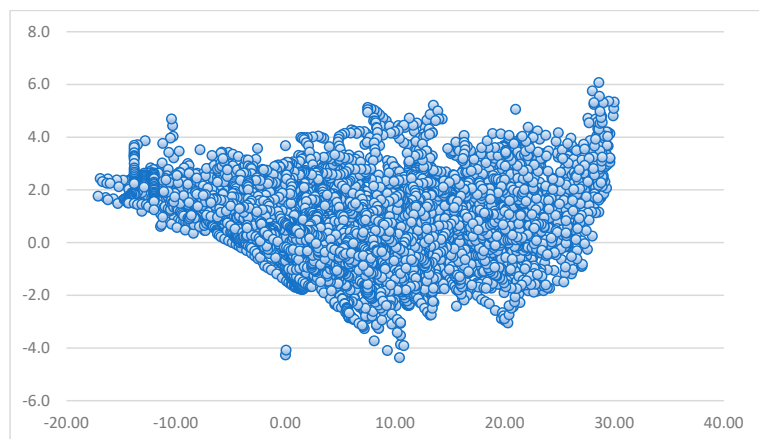


**Figure 13.** Outdoor (device 9) and indoor moisture and temperature in the Krimulda Church on the balcony (device 4) between 12/22/2022 and 12/28/2022.



**Figure 14.** Outdoor and indoor humidity and temperature in the Krimulda Church “on the balcony”.

According to the data measured at Point No. 4 “On the balcony”, the absolute excess moisture in indoor air and outdoor air,  $\Delta v$ , was calculated, and the values are shown in the diagram in Figure 13. We can see from the diagram in Figure 15 that, according to the building’s standard [22] humidity classes, the cult buildings can be placed into the third humidity class, with an unknown load on the building where the upper threshold of the excess moisture was  $6 \text{ g/m}^3$ . From this diagram in Figure 15, we can observe that the upper threshold of the excess moisture mostly reached and slightly exceeded  $6 \text{ g/m}^3$  when the outside temperature ranged between  $27^\circ\text{C}$  and  $30^\circ\text{C}$ . Taking a closer look at the time periods at which the upper threshold of the excess moisture, namely,  $6 \text{ g/m}^3$ , was reached, one can conclude that these were short-term periods in August 2022 with high outside air temperature fluctuations and moisture concentration fluctuations related to precipitation during that period. Meanwhile, as concluded previously, the outside air humidity has a huge impact on the building as it has high indoor-air heat inertia; therefore, an excess of distance forms between the asymmetrical indoor and outside air values, which can cause additional short-term condensation risks.



**Figure 15.** Excess moisture in the Krimulda Church on the balcony.

## 5. Conclusions

For the heating strategy of a cult 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. Therefore, this heating strategy cannot be defined as a heating system providing a preserving microclimate. Further research should complement the analysis of the internal surface temperatures of stone masonry building envelope of under rapid fluctuations of internal air with computer-aided simulations.

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.

During the summer period, the upper threshold of moisture difference, 6 g/m<sup>3</sup>, is reached in the Krimulda Church, and according to the standard [22], this is comparable to specialised high-humidity premises, such as catering premises. Therefore, we conclude that ventilating historical masonry buildings during the warm season is not recommended. 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.

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.

This type of research is ongoing in other churches of Latvia, including both masonry and wooden structures, that are equipped with permanent heating systems. Continued research will provide more complete thresholds of indoor air parameters in the microclimate for conservation purposes.

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# Ventilation and air conditioning design approach based on ASHRAE psychrometric chart and Mollier diagram

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Society needs long-term sustainability and healthy building projects, and indoor air quality assurance engineering systems play a pivotal role in the energy performance of buildings. Therefore, when designing heating, ventilation, and air conditioning systems, it is crucial to make the most technically sound decisions in terms of energy consumption and assess their impact on the building's energy performance. This article delves into the design of ventilation and air conditioning systems, presenting a method for evaluating their performance. The foundation of project development is an agreement on the design criteria, which are developed based on a preliminary analysis of the building concept. This agreement ensures cohesive collaboration among all stakeholders: the client, the architect, the system designer, the contractor, and ultimately the personnel responsible for commissioning, operating, and maintaining the systems post-construction. We suggest conducting a comprehensive analysis of the processes occurring within the space without initially linking them to room air exchange. From this analysis, we derive the angular coefficient for the direction of the air condition change on both a psychrometric chart and a Mollier diagram. The process line on the psychrometric chart provides insights into how the performance factor of the air distribution system will influence the desired supply air parameters. We can then evaluate how significantly the gap between the supply air and the exhaust air parameters expands if the room's air exchange volume is reduced for budgetary reasons. The article showcases this design methodology using a simplified case study.

## KEYWORDS

ventilation, air conditioning, building renovation, public buildings, energy saving

## 1 Background and purpose

Our hypothesis centers on the performance factor of the air distribution system and a detailed analysis of air parameters within air handling unit and serviced rooms. We propose a novel approach that diverges from traditional reliance on room air exchange rates. We advocate for a comprehensive analysis of the processes within the space without initially tying them to room air exchange. Our method relies on the angular coefficient for the direction of air condition change within the serviced room, resulting in a familiar process line on the psychrometric chart. Our approach focuses on the angular coefficient indicating

the direction of air condition changes within the room, our method reveals critical insights from the psychrometric chart. This approach provides an immediate understanding of the detrimental effects on room comfort when air exchange volume is reduced for budgetary reasons, a common yet overlooked issue. With this comprehensive analysis, using specific air exchange volumes and selected air treatment processes in the air handling unit, we can optimize energy consumption for both cooling and heating. Our article delves into the air treatment for cooling and drying mode, employing the psychrometric chart or the Mollier diagram as tools for enhancing communication among specialists. This method not only aids in developing sustainable system projects but also assists in accurately determining the cooling and heating capacities of air handling units. Use of the psychrometric chart or the Mollier diagram can create better communication between specialists, regardless of the habit of using one or the other diagram.

## 2 Introduction

The design criteria for air conditioning projects require meticulous coordination and documentation of various aspects. We present a description of the sequence of theoretical judgments essential to the successful development of ventilation and air conditioning projects. 1) The intended use of the building, including the modes of use, technological processes within the premises, projected number of occupants, workplaces, and lighting. 2) Detailed insights on the thermal attributes of external boundaries and the thermal inertia of the premises' internal structures (Saleh Pascha et al., 2016; Millers et al., 2020; Borodinecs et al., 2022a; Borodinecs et al., 2022b; Metals et al., 2022; Prozumants et al., 2023; Staveckis and Zemitis, 2023). 3) The type and operational principles of the envisioned heating system. 4) The target temperature and indoor humidity levels for which the comfort systems are designed. 5) The preferred design system types, which can range from pure ventilation to combinations such as ventilation with air heating, room cooling with either partial or non-guaranteed dehumidification, controlled dehumidification, air humidification, and comprehensive air conditioning as formulated in Table 2 (Types of ventilation, air conditioning, and room conditioning systems based on functions) in Claus, 2015. 6) The maximum conceivable outdoor air climatic parameters essential for the design of ventilation and air conditioning systems (ASHRAE climatic design conditions, 2021; Krumins et al., 2022). 7) The desired class or category of indoor air quality, along with the volume of air necessary to purge harmful emissions. 8) The optimal or architecturally viable method for distributing the supply air and draining exhaust air from the rooms; this also considers the air pressure distribution across different areas. 9) Lastly, the strategy for the indoor air quality control building management system (Krumins et al., 2022). Our study's hypotheses and theoretical approach aim to expand the understanding among air conditioning system designers about the extensive capabilities of performance analysis using the psychrometric chart or Mollier diagram. By examining a simplified case study, we make a significant contribution to both the theory and practice of air conditioning. This aligns with our ultimate goal of improving

energy efficiency in air conditioning systems, an increasingly vital aspect of sustainable building design.

## 3 Methodology

We appreciate Professor S.A. Sherif's publication "Overview of Psychrometrics" in ASHRAE Journal 2022 (Sherif et al., 2002). The publication provides a comprehensive overview of air conditioning processes on the psychrometric chart. The considered air handling unit serves a virtual room in which the air is distributed according to the principle of mixed ventilation. It is possible that due to architectural spatial considerations, only a mixed distribution of ventilation air was possible in this conditioned space. We hope that our manuscript complements and expands the discussion on the design of air conditioning systems initiated by Professor S.A. Sherif's publication.

Professor S.A. Sherif's publication discusses the case where the exhaust air parameter point coincides with the desired room air parameter point. However, it is much more energy efficient to distribute supply air according to the displacement principle, where the point of the supply air parameters coincides with the desired point of the air parameters in the conditioned space. Therefore, we propose the hypothesis that in the design practice of air conditioning systems, it is necessary to apply the performance factor of the supply air distribution system, which is marked with " $M_{ad}$ ". Eqs 3–6 allow to implement a new approach to the theoretical analysis of the air conditioning system by using a psychrometric chart or a Mollier diagram and performance factor  $M_{ad}$  of the supply air distribution system. We also theoretically prove that in the an enclosed area within a building devoid of external walls and windows (congress halls, theaters, conference rooms), which are not affected by outdoor air parameters and solar radiation, it is recommended to move the cooling coil before the recirculation mixing chamber. Such an option for improving the energy performance of air conditioning is not discussed in Professor S.A. Sherif's publication.

Heat and moisture load balances for the premises can be constructed using the information from the design agreement. For both the heating and cooling periods, the heat loss and heat inflow loads are calculated. These should be gauged at their maximum potential, keeping in line with the permissible room air temperature variations and any potential outdoor climate conditions specified in the design brief. In determining these balances, one must factor in the heat and moisture inflows from occupants, which should be estimated based on the premises' full occupancy capacity. A similar approach applies when computing the loads from technological processes and lighting within the room (Sherif et al., 2002).

The heat offered by heating systems must be accounted for, as must the influence of any local cooling units present within the premises. In certain cases, a well-designed heating system might entirely offset a room's heat loss. Alternatively, the local coolers in a room (such as internal units of direct-expansion systems, fan coils, cooled ceilings, or cooling beams) might either partially or wholly counterbalance the influx of solar heat.

The rate of sensible heat gain for the space is represented by  $H_s$ , measured in kilowatts, and we have that the room's  $\Sigma q_s$  is the rate of addition (or removal) of sensible heat, also given in kilowatts

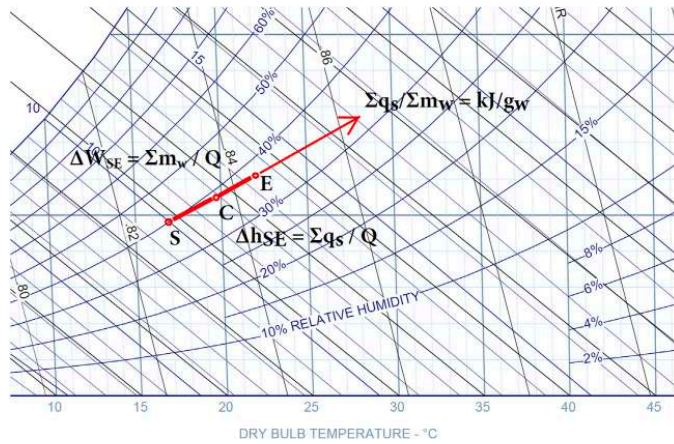


FIGURE 1 Principle of reference line on ASHRAE psychrometric chart protractor, where the angular coefficient of changes in air condition is in units of kJ/g<sub>w</sub>.

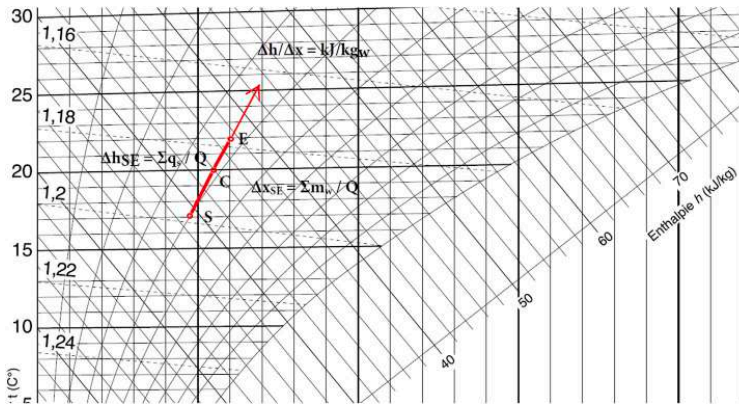


FIGURE 2 Angular coefficient of process change of air parameters on Mollier diagram, where  $\Delta h/\Delta x$  is in units of kJ/kg<sub>w</sub>.

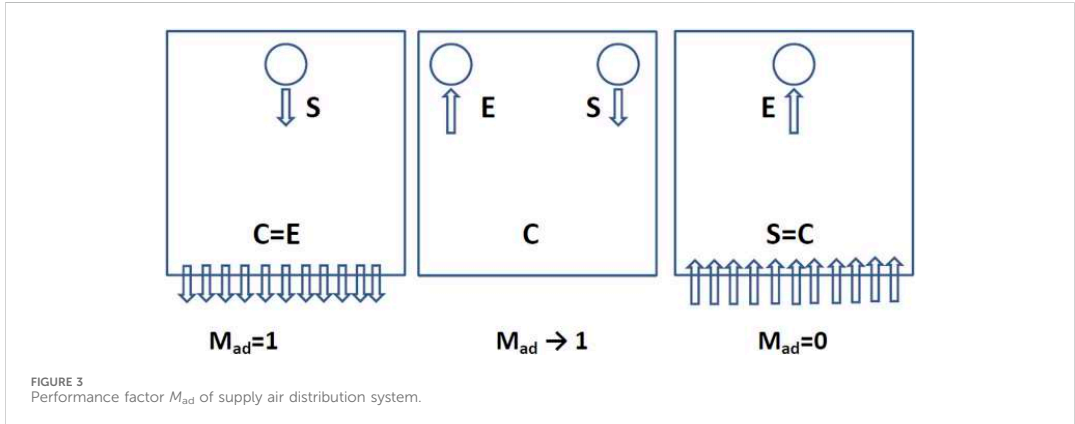
(remember that 1 kW equals 1 kJ/s). Similarly, for the room, the cumulative rate of moisture gain within the space is represented by  $\Sigma \dot{m}_w$ , given in units of kg<sub>w</sub>/s.

The ratio of a room’s sensible heat balance to its moisture inflow balance dictates the angular coefficient of the direction of the air condition change process in units of kJ/kg<sub>w</sub>. This is also expressed as the ratio of air enthalpy change ( $\Delta H_a$ ) to air moisture content change ( $\Delta W$ ), given as  $\Delta H_a/\Delta W$ . As defined in the ASHRAE Handbook, this is represented in units of kJ/kg<sub>w</sub> or kJ/g<sub>w</sub> and can be visualized on a psychrometric chart (Figure 1) (ASHRAE handbook online, 2023). Similarly, a Mollier diagram demonstrates this as the angular coefficient of the process change in air parameters and  $\Delta h/\Delta x$  is given in units of kJ/kg<sub>w</sub> where  $\Delta h$  is change of the enthalpy of moist air and  $\Delta x$  change of the humidity ratio of moist air (Figure 2) (Claus, 2015).

It is important to understand that when evaluating the functioning of room air conditioning systems, the angular coefficient of the reference line on the psychrometric chart remains constant. Irrespective of the air parameters introduced into the room, this coefficient persists because the heat and moisture processes within the space are not conditional on the introduced air parameters.

With this, we can theoretically locate the following three points: point C represents the desired air comfort parameters within the serviced room; point S describes the parameters of the incoming supply air; point E indicates the parameters of the room’s exhaust air.

The enthalpies of the supply, room, and exhaust air sources are denoted respectively by  $h_s$ ,  $h_c$ , and  $h_E$  (in units of kJ/kg<sub>da</sub>). The



moisture content of these respective air sources is symbolized by  $W_s$ ,  $W_C$ , and  $W_E$  (in units of  $g/kg_{da}$ ).

The relative positioning of points S, C, and E on the reference line is contingent upon the performance factor  $M_{ad}$  of the supply air distribution system (Figure 3) (Krėslinš and Ramata, 2011; Kosonen et al., 2017). For instance, if the air is distributed throughout the occupied zone based on displacement ventilation system principles, then we have  $M_{ad} = 0$ . However, if a mixing air distribution system is utilized, where air is spread remotely from the occupied zone and polluted air is directly extracted from this zone, then we have  $M_{ad} = 1$ . Indeed, for mixing ventilation, the coefficient  $M_{ad}$  tends to a limiting value of 1.

When mixed ventilation is employed, the properties of the expelled air are virtually identical to those of the occupied zone, i.e., points C and E coincide. In instances of displacement ventilation, the parameters of the supply air align closely with the desired air comfort criteria of the occupied area, meaning that points C and S coincide. The span between points S and E on the reference trajectory is dictated by the volume of ventilation air passing through the space.

Assuming steady-state conditions, the positioning of air parameter markers on the psychrometric chart can be deduced via the following equations:

$$\Delta h_{SE} = \frac{\sum q_s}{Q} \tag{1}$$

$$\Delta W_{SE} = \frac{\sum m_w}{Q} \tag{2}$$

$$W_s = W_c - \left( M_{ad} \times \frac{\sum m_w}{Q} \right) \tag{3}$$

$$h_s = h_c - \left( M_{ad} \times \frac{\sum q_s}{Q} \right) \tag{4}$$

$$W_E = W_C + \left( (1 - M_{ad}) \times \frac{\sum m_w}{Q} \right) \tag{5}$$

$$h_E = h_C + \left( (1 - M_{ad}) \times \frac{\sum q_s}{Q} \right) \tag{6}$$

where  $h$  [ $kJ/kg_{da}$ ] is the specific enthalpy of moist air,  $W$  [ $kg_w/kg_{da}$ ] is the humidity ratio of moist air,  $x$  [ $g_w/kg_{da}$ ] is the humidity ratio of

moist air on the Mollier diagram,  $\sum q_s$  [ $kW$  or  $kJ/s$ ] is the rate of addition (or removal) of sensible heat in the space,  $\sum \dot{m}_w$  [ $kg_w/s$ ] is the net sum of all rates of moisture gain per second on the space,  $M_{ad}$  [dimensionless] is the performance factor of the air distribution system,  $Q$  [ $kg/s$ ] is the volume of supply air,  $\sum q_s / \sum \dot{m}_w$  [ $kJ/kg_w$ ] is the angular coefficient guiding the direction of air condition alteration, and  $\Delta H_s / \Delta W$  is the reference line on the chart protractor. In these terms and units, the subscripts are as follows: da stands for dry air, w indicates water in any phase, s signifies sensible heat gain, ad denotes air distribution, SE indicates the distance from the supply air point to the exhaust point on the chart, and C indicates the targeted air comfort parameters in the serviced room.

The volume of air that must be cycled should be established either via hazard assessment or by referring to indoor air quality norms. This is essential to mitigate health risks in spaces designed for studying, working, or leisure. Multiple international benchmarks exist that outline indoor air quality parameters in public buildings (EN ISO 7730:2005, 2005; EN 16798-1:2019, 2019).

The technologies employed in such buildings can differ greatly, and their influence on indoor air quality necessitates meticulous assessment during air conditioning system design. If the sole source of contamination in a room is human occupants, then a rough estimate suggests that an allocation of 15  $m^3/h$  per individual implies subpar air quality in the space. By factoring in 30  $m^3/h$  per person in the project, one can anticipate achieving moderate air purity. When accommodating 45  $m^3/h$  for each person, the ambient air quality would be rated as average. To ensure premium indoor air standards, it is vital to provide at least 60  $m^3/h$  per individual, if not more (EN 13779:2007).

Heating, ventilation, and air conditioning (HVAC) professionals bear the responsibility of advocating for the significance of indoor air quality when stakeholders make investment decisions regarding the development and operation of air conditioning systems. This advocacy is pivotal for the construction of healthy, sustainable edifices.

In practical terms, during the budgeting phase of designing a building, there is often a tendency toward curbing the expenses by reducing investment in HVAC systems. However, that approach overlooks instances in which modest expenditures can lead to

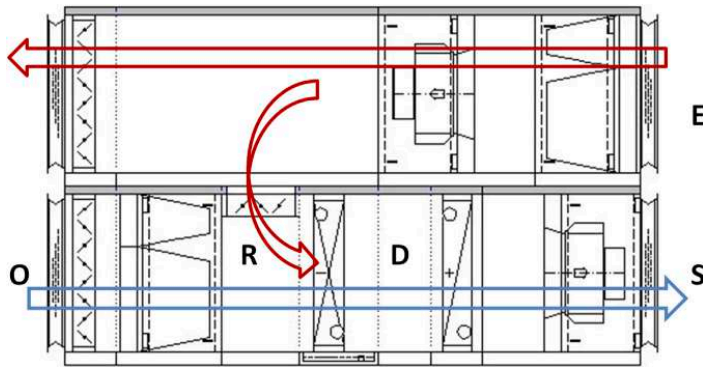


FIGURE 4  
Air handling unit 1 (E—exhaust air; O—fresh incoming air; R—air post-recirculation; D—air post-cooling and dehumidification; S—supply air).

notable enhancements in work efficiency and simultaneously decrease illness incidences and subsequent sick leaves (Wargorcki et al., 2006). The same way, recreational areas are mandated to guarantee both comfort and a wholesome environment.

## 4 Simplified case study

Air Conditioning System in a Historical Theater Hall.

As an illustrative example, we consider the air conditioning system of an auditorium within a historical theater hall. A theater hall typically epitomizes an enclosed area within a structure devoid of external walls and windows. In vast theaters with multistory balconies, it is imperative to facilitate enhanced air circulation to preclude zones of stagnant air. The air exchange rate in such halls should be sufficient to remove the heat and humidity generated by the densely seated audience. As a result, usually the air exchange rate significantly exceeds the amount of air required for CO<sub>2</sub> removal.

To economize on the energy expended on heating and cooling, air recirculation can be an alternative (Sherif et al., 2002). Balancing the mix of fresh and recirculated air can be managed adeptly using CO<sub>2</sub> concentration sensors. Leveraging polluted air heat via recuperators or regenerators is not a viable strategy because theater performances are infrequent and relatively brief.

Auditoriums can accommodate up to a thousand attendees, and when assessing the total sensible heat load of a packed auditorium and factoring the heat influx from the balcony floodlights, the comprehensive sensible heat rate is  $\Sigma q_s = 130 \text{ kW}$  or  $130 \text{ kJ/s}$ . Gauging the moisture inflow from attendees is challenging, but a ballpark figure suggests  $\Sigma \dot{m}_w = 70 \text{ kg/h}$  or  $19.44 \text{ g/s}$ .

A century ago, the air conditioning system of this historical theater hall was devised to accommodate a peak output of  $50000 \text{ m}^3/\text{h}$  of supply air. Modern renovations adhered to this original capacity, which translates to roughly  $60,000 \text{ kg/h}$  or  $16.67 \text{ kg/s}$  of air throughput. As a result, the air enthalpy rises from supply point S to exhaust point E by  $\Delta h = \Sigma q_s/Q = 130 \div 16.67 = 7.8 \text{ kJ/kg}_{da}$ , and the moisture content changes by  $\Delta W = \Sigma \dot{m}_w/Q = 19.44 \div 16.67 = 1.17 \text{ g/kg}_{da}$ .

This calculation establishes the process line, with the air condition's angular coefficient given in units of  $\text{kJ/g}_{wv}$ . By referencing the ASHRAE psychrometric chart protractor, the angular coefficient is  $7.8 \div 1.17 = 6.67 \text{ kJ/g}_{wv}$ , which on the Mollier diagram is  $7.8 \div 0.00117 = 6700 \text{ kJ/kg}_{wv}$ .

During the nascent stages of redesigning the historic theater's air conditioning system, a blueprint was proposed incorporating an air handling unit with recirculation capabilities (see Figure 4). The proposed strategy was to channel cooled air via ceiling grates and extract contaminated air through grates placed beneath each audience member's seat during the cooling season. Conversely, during the heating phase, the design involved channeling the supply air through floor grates and extracting polluted air via the ceiling grates. This proposition is arguably flawed, but to ensure the selection of an energy-efficient solution, both approaches—ceiling grate and beneath-seat grate distribution—are evaluated. Also, a modification to the air handling unit is recommended.

When air is distributed far from the occupied zone, it should be treated as a mixing air distribution. Consequently, the performance factor of the air distribution system will be  $M_{ad} = 1$ . As such, the parameters of the air in the occupied zone (denoted as point C on the chart) practically mirror the parameters of the polluted air extracted from the room (points E and C coinciding on the chart, as illustrated in Figure 5).

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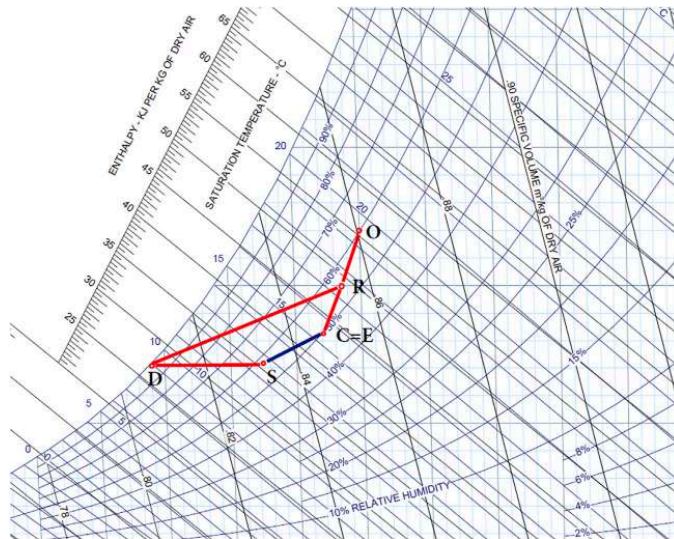


FIGURE 5  
Schematic of air conditioning process on a psychrometric chart, illustrating a design concept utilizing recirculation.

chart) practically mirror the parameters of the polluted air extracted from the room (point  $E = C$  on the chart, as illustrated in Figure 5).

The inlet air parameter (point  $S$  on the chart) aligns with the reference line based on the angular coefficient of the changes in the air conditions. The distance  $SE$  represents the anticipated sensible heat load  $\Sigma q_s$ , and supply air volume  $Q$ , as determined by Eqs 4, 6.

A pivotal query arises: should the design agreement for ventilation and air conditioning systems be grounded based on the outdoor air climate parameters? Specifically, in the context of this theater, the considerations include its operational nuances during the cooling season and the climatic data about its geographical location. The consensus dictates that air conditioning will account for an outdoor air temperature of  $+25^\circ\text{C}$  and an enthalpy of  $55\text{ kJ/kg}$ , which is represented by point  $U$  on the chart.

Should the project's designer posit that the  $\text{CO}_2$  concentration in the occupied zone remains non-problematic, even with 50% recirculation, then points  $O$  and  $E$  must be linked on the chart. Point  $R$  on the line  $OE$  designates the air parameters resulting from the amalgamation of both air flows; in this specific scenario, it is precisely at the midpoint. A reduction in the recirculation percentage would cause point  $R$  to gravitate toward point  $O$ .

The subsequent phase entails cooling and dehumidifying the processed air until it matches the desired humidity ratio  $W$  of the supply air, indicated by point  $D$  on the chart. The next step involves heating this air to the necessary supply air temperature, as indicated by point  $S$ .

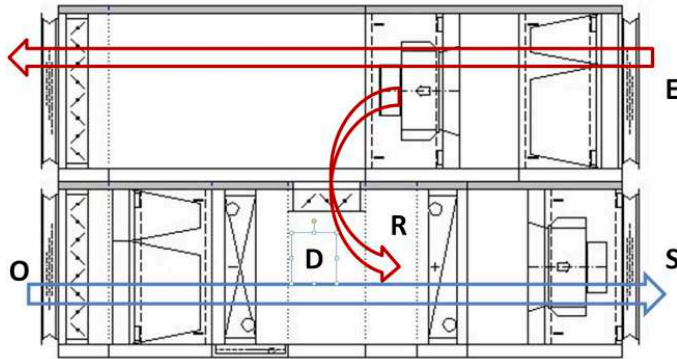
One should not be concerned about discomfort when disseminating supply air via grates beneath each spectator's seat in the cooling mode. Given that the theater hall essentially remains insulated from external climatic fluctuations, factors such as the

sensible heat load, moisture gain rate, and the angular coefficient of air condition changes are influenced solely by the audience number and hall lighting.

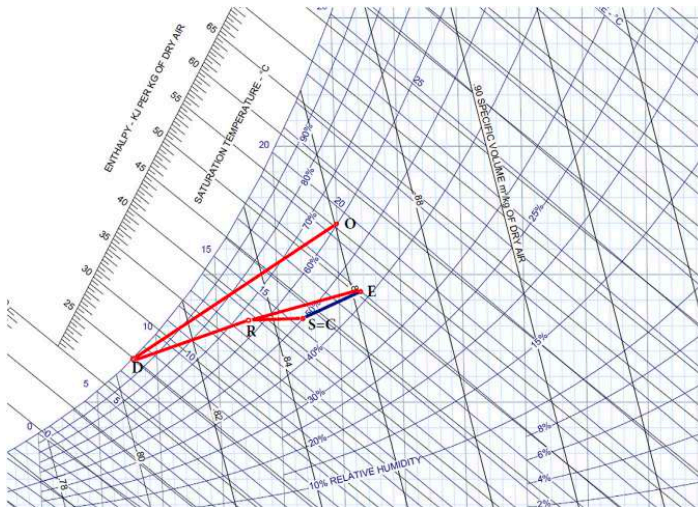
Observing the comfort zones on both the chart and Mollier diagram across heating and cooling seasons reveals a notable insight: to maintain comfort, the heated air should be cooler during winter, and conversely the cooled air should be warmer in summer. The rationale for this is straightforward: theater attendees wear warmer clothing in winter and cooler attire in summer. Consequently, achieving displacement air distribution using grates beneath each spectator is viable, ensuring year-round comfort.

Some modifications to the air handling unit are proposed. By relocating the air recirculation grills behind the cooler relative to the airflow direction, the sequence of cooling and drying shifts from point  $O$  to point  $D$ . It is essential to recognize that only fresh air void of recirculated air undergoes this cooling and drying process. In the discussed scenario, merely half of the overall supply air volume will traverse the cooling coil (as depicted in Figure 6). It might be possible to maintain the mixing point  $R$  on the supply-air humidity ratio  $W$  line. Consequently, the air would need to undergo minor heating from parameter  $R$  to parameter  $S$  (Figure 7).

When we replicate these processes on the Mollier diagram and calculate the necessary cooling and heating capacities using the Menerga software, the outcomes are as depicted in Figures 8A, B and Figures 9A, B. (Claus, 2015; Geometrico GmbH & Co, 2021). The derived requirements amount to  $366\text{ kW}$  for cooling and  $140\text{ kW}$  for air heating when dispersing the supply air through the ceiling's air grills. Furthermore, to extract the excess heat from the room, supply air at a temperature of  $17^\circ\text{C}$  must be channeled through these ceiling air grills. Such cool air distribution, especially through historic,



**FIGURE 6**  
Air handling unit 2 (E—exhaust air from room; O—incoming fresh outside air; D—air after cooling and dehumidification; R—air post-recirculation of outgoing air; S—supply air). After the cooling and drying process of fresh air, the recirculation is facilitated by combining the cooled and dried air (point D) with the exhaust air (point E).



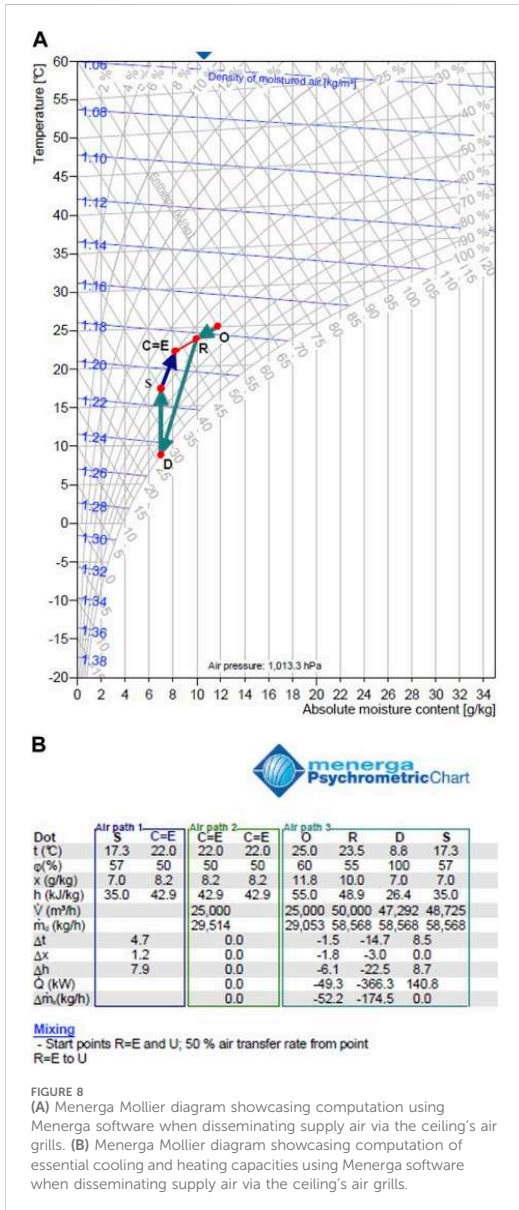
**FIGURE 7**  
Schematic of air conditioning process on psychrometric chart for design concept utilizing recirculation prior to cooling and dehumidifying the incoming fresh outside air.

rudimentary ceiling air grills, might induce a vertical downward flow of cool air, potentially discomforting the audience members seated below.

## 5 Results

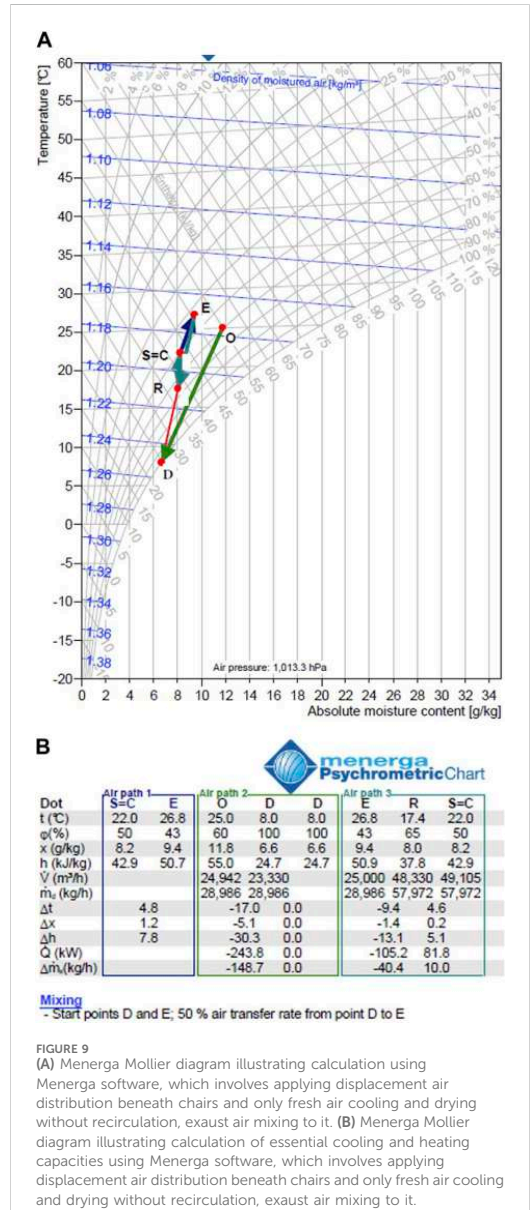
Employing displacement air distribution beneath the chairs and only fresh air cooling and drying without recirculation, exhaust air mixing to it, reduces the cooling requirement to

244 kW, while heating needs just 82 kW. It is vital to remember during the automation of air handling equipment that all air parameters exhibit some fluctuations. The desired air parameters do not represent single fixed points but rather a range of comfortable conditions. Recirculation percentages might also shift based on the CO<sub>2</sub> sensor readings of the exhaust air quality. External air conditions can fluctuate significantly. This discussion has not delved into air treatment during the heating season, a time when air humidification becomes crucial.



## 6 The conclusions

Drawn from this study are as follows. 1) Detailed design criteria agreements are essential and merit attention. 2) Ventilation and air conditioning designs should begin with analyzing both technological and human activities within the space and the impact of external climates. However, these should not be tied exclusively to ventilation flow or conditioned air



circulation within the room. 3) Intake air quantities should be ascertained based on indoor air contamination, while also considering the external air quality in the specific construction location. 4) Adjustments to the supply air volume might be necessary to meet indoor air quality standards and cost-effectiveness. 5) Analyzing ventilation and air conditioning processes on psychrometric charts or Mollier diagrams is

pivotal for developing sustainable system projects and determining the type, cooling, and heating capacities of air handling units. 6) Only after these steps have been followed can an annual energy consumption simulation for the proposed ventilation or air conditioning system be conducted. 7) With the cooling and heating capacity optimization calculation for the simplified case study has proven the hypothesis that it is purposeful to use the performance factor of the air distribution system and the process line on the diagram for finding an optimal air treatment processes.

## Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

## Author contributions

AL: Conceptualization, Methodology, Validation, Writing—original draft. US: Resources, Visualization, Writing—review and editing. MM: Resources, Writing—review and editing. RM: Resources, Writing—review and editing. VA: Resources, Writing—review and editing.

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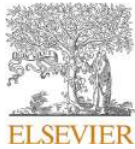
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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

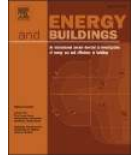
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# Study on indoor air temperature and moisture behaviour in historical churches

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## ABSTRACT

Increased indoor air humidity in cultural heritage buildings in the Baltic States region results in the deterioration of cultural heritage values. Existing norms, standards, and research do not specify the necessary conservational microclimate indoor air parameter limits. Two main types of historical cultural heritage building constructions exist based on enclosing structures – wood and masonry, with various heating strategies and usage intensities. This study complements previous research on the microclimate of Krimulda Church and compiles measurements of three additional Latvian churches: Turaida Church, Riga Jesus Church, and Liepaja St. Trinity Cathedral. Microclimate measurements were conducted in two wood and two masonry churches. Humidity ratio and moisture excess calculations were derived from the measurement data. Results indicate that in certain cases, the moisture excess threshold of  $6 \text{ g/m}^3$  and indoor air humidity ratio threshold of  $15,6 \text{ g/kg}$  are exceeded, posing a significant risk of condensation. Moisture evaporation levels from masonry church constructions were identified. The study reveals conservational microclimate indoor air parameter limits for various types of churches in the Baltic States climatic region.

## 1. Introduction

The major issue with microclimate of historical cult buildings situated in the region of Latvia (Baltic countries) is related to uncontrolled increase in the indoor air humidity [1]. Indoor humidity which increases uncontrollably either condenses on various cultural items (paintings, equipment, structures) or infiltrates them, providing a favourable environment for the spread of “fungi” and consequently leading to “erosion” of these cultural values [2-4].

European standard which is adapted to Latvia states “Indoor climate specification for conservation” [5] and also that parameters of such microclimate humidity and temperature are aimed at conserving the items in the building. The mentioned standard defines “Conservation heating - Conservation heating uses heat to improve the indoor climate for conservation. The primary aim is to keep RH at a stable and appropriate level throughout the year in order to minimize damage due to RH variations and to prevent dampness and biodeterioration.” Current norms and/or standards do not provide thresholds for conserving microclimate parameters.

In order to identify the necessary temperature and humidity thresholds for indoor climate for conservation purposes that could be

applicable also to other churches, the thresholds of said parameters should be determined in different churches. According to typology of churches in Latvia, as classified in previous studies [6] they are classified by their spatial parameters in five categories: single span, two span, three-span, cross, central. Meanwhile, typology categories by the types of building envelope are – masonry and wooden churches. In this Latvian church typology, the study has determined that the thermal conductivity resistance in the external walls of wooden churches regardless of their age is equal, namely  $k = 0.13 \text{ W/(mK)}$ . Nevertheless, the thermal conductivity of masonry churches dated between 13th and 16th century is  $0.87 \text{ (W/mK)}$  and of those dated between 16th and 19th century is  $1.12 \text{ (W/mK)}$ . External walls of masonry churches have larger mass than the wooden churches, but masonry churches have thicker walls [6]. Buildings with differing external wall structures have different thermal mass, therefore it translates into different heating consumption [7].

Taking into account the differences of the mentioned church typology and in accordance with Standard EN 157591-1 “Conservation of cultural property - Indoor climate - Part 1: Guidelines for heating churches, chapels and places of worship” [5] it is possible to discern the following classes of air parameter thresholds that conserve indoor air

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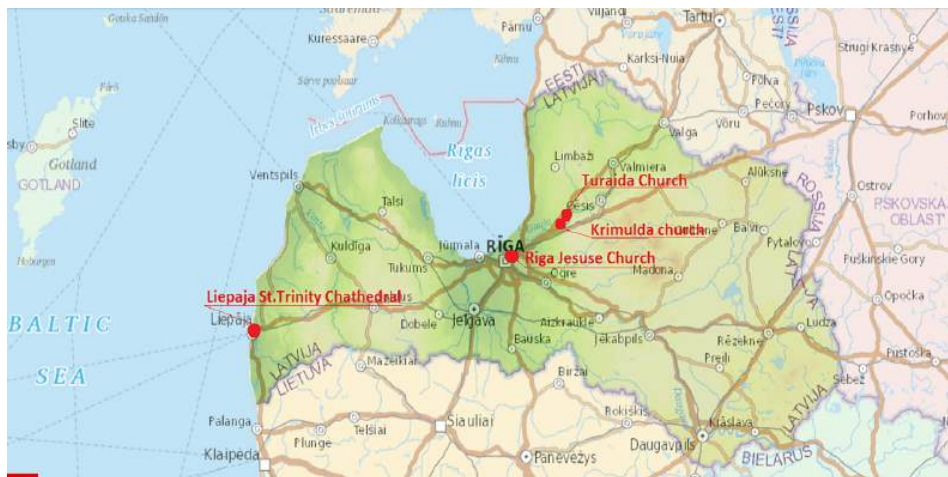


Fig. 1. The map of Latvia with marked churches where the measurements were taken.

microclimate:

#### Churches without heating

Microclimate thresholds in wooden churches  
Microclimate thresholds in masonry churches

#### Churches with heating

##### Churches with continuous heating

Microclimate thresholds in wooden churches  
Microclimate thresholds in masonry churches

##### Churches with intermittent heating

Microclimate thresholds in wooden churches  
Microclimate thresholds in masonry churches

To determine the minimum indoor air temperature parameters during the winter period, it is necessary to understand visitors' comfort requirements. However, to establish these comfort requirements, it is also important to know the insulating capacity of visitors' clothing, expressed in units of clo (EN – clothes). According to ASHARE Standard 55-2020 [8] winter clothing value corresponds to 2 Clo, which is not deemed to be permissible in the indoor climate, while the Latvian Construction Standards do not regulate the level of comfort in religious buildings [9,10]. A study conducted in Italy's church of San Vito in L'Aquila [11] regarding the level of comfort and heating of indoor premises during the cold season established that if the air temperature is kept at 13.5 °C and the relative humidity at 55 % and the visitors arrive dressed in outdoor clothes with 2clo value, the level of comfort is actually ensured. On the basis of data of the mentioned level of comfort, if a person wears outdoor clothes, and the measurement data in the churches of Latvia [1,12], where the air temperature drops to –5 °C in the cold season in absence of heating, our further study is not conducted in churches without any heating devices. Also, it has been concluded from data gathered from 263 Lutheran churches in Latvia [6] that churches without any heating device during winter, when the air temperature drops below 0 °C, are not used for religious activities. If the indoor climate of the churches in Latvia and outdoor climate [1,12] is compared to a church – the Jerónimos Monastery in Lisbon (Portugal) [13], where the measured temperature varies between the extreme values of 14.5 and 26.2 °C, while the relative humidity varies between 31 and 91 % RH, we can establish that studies from Southern region are not applicable to the territory of Latvia [2,14-16].

Our goal is to determine the thresholds for conserving indoor microclimate air temperature and air humidity that do not lead to risks

of spreading of "fungi".

For favorable fungal proliferation, it is necessary for the material to have an elevated moisture content above 25 % [17,18] or moisture condensation on the material surface. In order for the moisture in the air to condense on any material surface, it must reach 100 % relative humidity. As air is a gaseous substance, according to the h-x diagram, we see that air with significantly different absolute moisture, or humidity ratio, values can reach 100 % relative humidity. Meanwhile, standard EN 13788 [19] specifies that if the surface relative humidity exceeds 80 % for several days, there is a risk of mold fungus spreading.

Until now, most studies on the microclimate of historical churches have been conducted in southern European countries, where the climate differs, and their results are not applicable to northern countries, especially in the Baltic States' climate. One study has been conducted on various climate control solutions for the Baltic States' climate zone [14], but none of the studies analyze and specify the necessary conservation indoor climate parameters that need to be ensured. In this study, for the first time, conservation indoor microclimate threshold values for historical churches in the Baltic States' climate zone are determined based on different types of churches' structural designs, intensity of use, and varying heating strategies.

## 2. Materials and methods

Considering this diversity, our study was performed in four churches (Fig. 1) featuring different building envelope (Table 1), different spatial typology and heating strategy (Table 2). The churches were chosen in different locations in Latvia, because each of them have different outdoor air parameters [20,21].

Microclimate measurements were taken simultaneously from 7 July 2022 in four different churches (Tables 1 and 2).

Temperature and relative humidity were measured with measuring instruments HOBO MX Temp/RH/Light/Ext-Temp Kit at 30-minute intervals, having measuring accuracy of  $\pm 2.5$  % for relative humidity and  $\pm 0.2$  °C for temperature Fig. 3.

In the Turaida Church, two measuring devices:

- one was placed in the middle of the room on a chandelier at a height of 2.7 m from the floor.
- the other was placed at the first row of seats, at the external northern wall, 1.2 m above the floor, as shown in Figs. 4 and 5.

**Table 1**  
Measurements in the churches.

From	Church location	Opening	Measuring period	Building type
1	The Turaida Church is situated 5.49 km north-east from the Krimulda Church (Fig. 2) and 39.94 km from the border of Riga, horizontally to the East.	The Turaida Church is located in the territory of the Turaida Museum Reserve and is open six days a week for museum visitors in the summer season from 9 AM to 8 PM, during spring and autumn season from 10 AM to 7 PM and winter season from 10 AM to 5 PM	From 7 July 2022 to 19 June 2023	Exterior walls of wooden logs and a wood-covered ceiling. The parish hall area is 172 m <sup>2</sup> and its volume is 516 m <sup>3</sup> .
2	Liepaja St.Trinity Cathedral is located in the city centre, 1.540 km to the East from the Baltic Sea, 145 m to the West from Liepaja Lake, and 0.286 km to the South from the city channel which connects the Baltic Sea with Liepaja Lake.	The church is open for tourists every week from Tuesday to Saturday, 10 AM to 6 PM, on Sundays from 12 PM to 3 PM, and the religious activities take place every Thursday between 6 PM and 8 PM, and on Sundays between 10 AM and 12 PM. Liepaja City is situated at the Baltic Sea coast, between the Baltic Sea and Liepaja Lake.	From 23 October 2022 to 30 April 2023	The Cathedral has masonry external walls and three-span [6] brick vault ceiling. The parish hall area is 868.14 m <sup>2</sup> and its volume is 11,077.34 m <sup>3</sup> .
3	Riga Jesus Church is situated in the city centre 0.33 km from Daugava River and 13.42 km horizontally from Gulf of Riga.	The church is used for religious activities every Sunday between 10 AM and 12 PM, and every Thursday between 6 PM and 8 PM. Meanwhile, the parish office, which is situated in the auxiliary premises of this building, is occupied four days per week, 6 h each.	From 28 August 2022 to 6 July 2023	External walls and partition walls made of horizontal beams, and wooden vaulted ceiling with a central [6] layout Fig. 9; 10. The parish hall area is 769 m <sup>2</sup> and its volume is 5733 m <sup>3</sup> .
4	The Krimulda Church [12] is situated in the rural territory, in the middle part of Latvia, 34.45 km away from the border of the capital of Latvia, Riga, horizontally to the East.	The Krimulda Church is a popular tourist attraction in Latvia, welcoming visitors 24/7 throughout the year.	From 7 July 2022 to 24 April 2023	In the Krimulda Church with exterior masonry walls and both brick and wooden vaulted ceilings. The parish hall area is 315.51 m <sup>2</sup> and volume is 313 m <sup>3</sup> .

**Table 2**  
Church types.

Church	Heating strategies	Spatial type
The Turaida Church	Intermittent heating	Single span
Liepaja St.Trinity Cathedral	Continuous heating	Three-span
Riga Jesus Church	Continuous heating	Central
The Krimulda Church [12]	Intermittent heating	Single span

Liepaja St. Trinity Cathedral has three RH and T measuring devices installed:

- one in the middle part of the hall at the column,
- another one on the information stand at the hall’s entrance door,
- the third is located behind the closet, at the external northern wall of the hall, as shown in Figs. 6 and 7.

There are three RH and T measuring devices installed in Riga Jesus Church:

- one is placed in the middle part of the hall, at a height of 5,62 m above the floor
- the other is placed in the church office premises, at a height of 2,82 m above the floor
- the third is placed outdoors, at a height of 9,35 m above ground level, as shown in Figs. 8 and 9.

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

$$P_w = 6,112 \cdot e^{\frac{17,67 \cdot T}{243,5 + T}} \cdot \frac{RH}{100} \tag{1}$$

where T – air temperature (C°), e – Euler’s number [22], RH – relative humidity (%). The air moisture content W (g/kg) is calculated from the partial pressure Pw:

$$W = 622 \frac{P_w}{P - P_w} \tag{2}$$

where P – total pressure (Pa). [23].

Based on temperature and RH measurements, the difference between indoor and outdoor air absolute humidity is calculated and the excess moisture Δ<sub>v</sub> (g/m<sup>3</sup>) is determined by the following equation:

$$\Delta_v = v_i - v_e \tag{3}$$

where v<sub>i</sub> is the humidity by volume of indoor air (g/m<sup>3</sup>) and v<sub>e</sub> is the humidity by volume of outdoor air (g/m<sup>3</sup>) [19].

### 3. Results and discussion

#### 3.1. Moisture in the Turaida Church

There is no permanent heating and ventilation system in the Turaida Church. During the cold seasons, at low outside temperatures, when the church is used for religious activities (once a week), the inside air is heated with electric heaters (one VEAB calorifer 15 kW and two radiators EWT, NOC903 TLG III – 2 kW). Maintenance institution of the building “Turaidas muzejrezervāts” permanently monitors indoor air with manual means and if the relative humidity of indoor air is found to reach 98 %–100 %, dehumidifiers are placed in the building. Considering that both churches are situated in a hilly plain in the middle part of Latvia (Krimulda is situated 43.2 m above mean sea level, and Turaida – 96.2 m above mean sea level) and in such distance, if measured horizontally, the weather does not differ significantly – we adapted the outside air parameters from the measuring device No 9 outside the Krimulda Church. Fluctuations of indoor temperature and relative

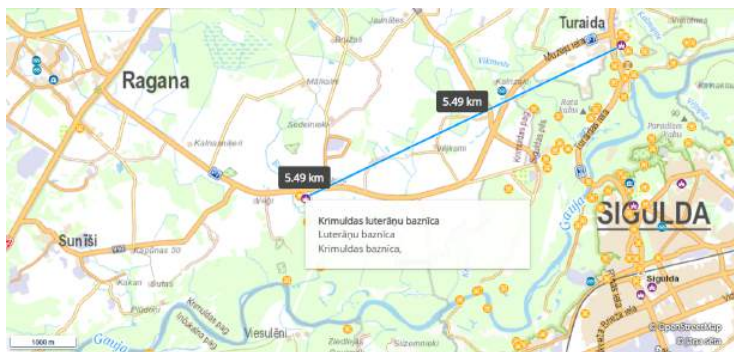


Fig. 2. The part of the Latvian map indicating the Krimulda and Turaida churches.



Fig. 3. HOBO MX1104 Temp/RH/Light/Ext-Temp Kit.

humidity in the Turaida Church, similarly to the Krimulda Church, have symmetrical differences among the points during all temperature elevation periods Fig. 10. It means that the direction of change in the air in all points is equal, but it has different air temperatures. Air temperatures differ in each of these points because there is a higher convection impact on each of those points.

Analysis of further tendencies of air moisture content change is performed for the measurement point “On lamp” as it is situated at the centre of building’s premises. In order to evaluate the humidity fluctuations, the content of outdoor and indoor air moisture is calculated from all measurements. The calculated outdoor and indoor air moisture values are shown in a diagram in Fig. 11, together with outdoor and indoor air temperature measurement data. Diagram in Fig. 11 shows

that during periods when the indoor air is not heated, the indoor air temperature fluctuations are symmetrical to outside air temperature fluctuations, just with shorter long-term fluctuation ranges. It indicates an intense impact of the outside air parameters on the indoor air parameters. We also see from Fig. 19 that the fluctuations of absolute humidity of outside air and indoor air are symmetrical. The largest air moisture content concentration is reached the same way as in the Krimulda Church at the end of August 2022, on 8/27/2022 at 1:30PM, when the outside temperature is 28.2 °C and air moisture content  $w_e = 11.12$  g/kg, while the indoor air temperature is 24.6 °C and air moisture content is  $w_i = 13.52$  g/kg. According to the data recorded by the museum, 643 persons attended the museum on said date Table 4. There is no exact information about a distribution of visitors in each hour, but it is 58 visitors per hour on average, and they stay for up to 15 min, meaning that the average number of visitors during one hour was up to 14 persons. Knowing the room volume of 516 m<sup>3</sup> in Table 1 – that equates to 0.08 pers./m<sup>2</sup> or 0.03 pers./m<sup>3</sup>. We determined the potential moisture evaporation from visitors without considering air exchange, which is unknown with natural ventilation and continuously open exterior doors. During the summer period, one person can evaporate up to 70 g/h of moisture. With this average number of visitors (0.03 pers./m<sup>3</sup>) in the room volume, it would amount to 2.1 g/m<sup>3</sup>. Knowing that the room air temperature at that time was 24.6 °C, the weight of one m<sup>3</sup> of air is 1.1839 kg. Thus, expressing in g/kg, the room air humidity ratio can increase by 1.77 g/kg. Reviewing the room air parameters on 8/27/2022 in Table 3 at 9:00 a.m., when the museum begins admitting

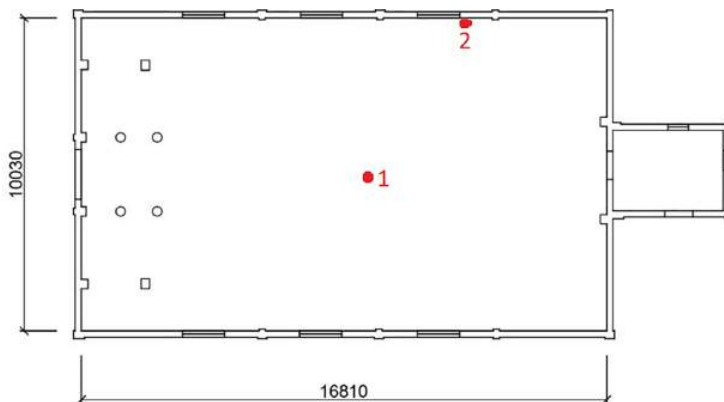


Fig. 4. Layout of the Turaida Church with the installed measuring devices.

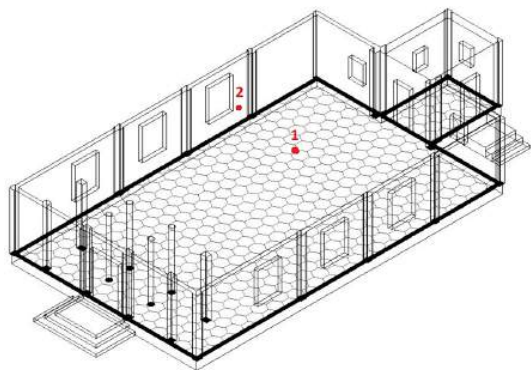


Fig. 5. 3D of the Turaida Church with the installed measuring devices.

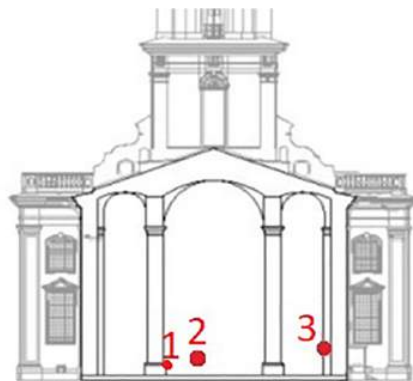


Fig. 7. Cross-section of the Liepaja St. Trinity Cathedral with the installed measuring devices.

visitors, and at the mentioned time, 1:30p.m., we observe a higher actual humidity ratio increase of 1.92 g/kg. This increase at that moment can be explained by the fact that the actual number of visitors is not an arithmetic average, but varies with higher intensity during certain time periods and lower during others. Additionally, during this time period, the outdoor air humidity ratio is similar or lower; for example, at 1:30p.m., it is 11.1 g/kg, which does not indicate significant outdoor air moisture influencing indoor air. On 7/27/2022 the number of museum visitors was 683 persons throughout the day and at 7 PM the indoor air humidity  $w_i = w_e = 15.6$  g/kg, outdoor temperature 21,2 °C and indoor air temperature 22.9 °C. In July and August, the highest outdoor air humidity ratios are reached. By the end of August, it can be observed that at an outdoor air temperature of 30 °C, the indoor humidity ratio exceeds that of outdoor air. The calculation of indoor and outdoor moisture excess for August is reflected in Fig. 12. Meanwhile between 12/21/2022, when the indoor air temperature is -1.1 °C and air humidity is 2.59 g/kg and 12/24/2022 at 3 PM, when the building is simultaneously visited by up to 70 persons (0.41 pers/m<sup>2</sup> or 0.14 pers/m<sup>3</sup>) the indoor air temperature is heated up to 12.1 °C and humidity reaches 5.79 g/kg. When calculating the moisture release from the

visitors into the indoor air during said period per one person, the humidity increases from 20 to 50 g/h per person by 2.29–5.54 g/kg in terms of its volume. The measurements show that the indoor air humidity in this period increases by 2.66 g/kg. When reflecting these air parameter fluctuations in h-x diagram, we can see that, in order to ensure a microclimate without potential condensation risks with the given flow of visitors, the minimum permanent indoor air temperature must be 6.5 °C or the air needs to be dried from 5.79 g/kg to 3.5 g/kg.

According to data measured in point “On lamp”, the calculated absolute excess moisture in indoor air and outside air  $\Delta v$  which are shown in diagram in Fig. 12. From diagram in Fig. 12 we see that the upper threshold of excess moisture reaches 6 g/m<sup>3</sup> only when the outside air temperature is 30 °C, which is reached at the end of August 2022. This tendency is related to the opening hours of the museum reserve when the church entrance doors are open, and it is attended by many visitors, Table 3. As a result, the outside air is increasingly infiltrated over the course of the day. Meanwhile, during the night, as the parameters change behind the locked doors and without visitors, the parameters of

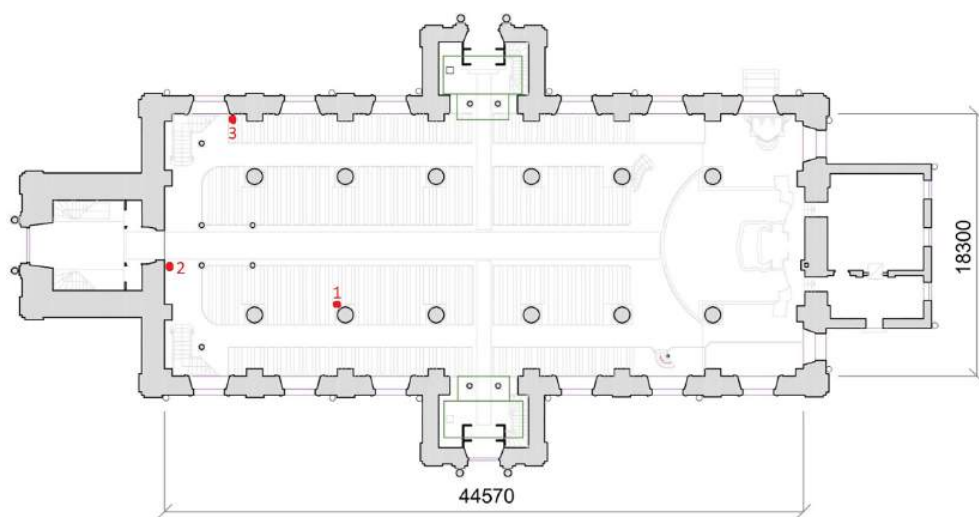


Fig. 6. Layout of the Liepaja St. Trinity Cathedral with the installed measuring devices.

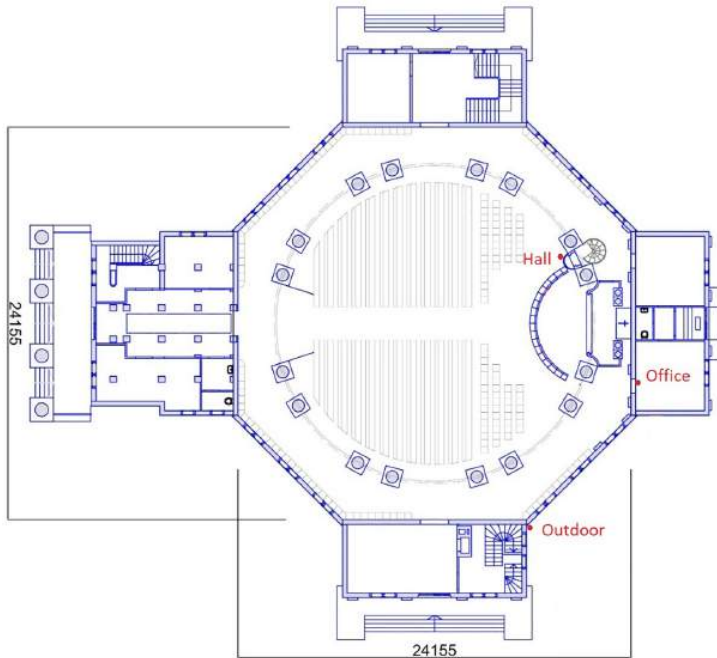


Fig. 8. Layout of the Riga Jesus Church c.

previously infiltrated air remain, and it causes short-term differences in air parameters and absolute excess moisture. As previously mentioned, by the end of August, the indoor air humidity ratio exceeds that of outdoor air, expressed in g/kg. However, in Fig. 12, the displayed moisture excess is expressed in  $\text{g}/\text{m}^3$  of air. At an atmospheric density of 101.325 kPa and air temperature of 20 °C, the density of one cubic meter of air is 1.2041 kg. This means that the difference between the indoor and outdoor humidity ratios ( $w_i$  and  $w_e$ ) depicted in Fig. 11 is presented in Fig. 12 in different units. In Fig. 12, the moisture excess reaches  $6 \text{ g}/\text{m}^3$ . In this case, it is not related to moisture from specific visitors but rather to the fact that the church's exterior doors are open throughout visitor admission at an outdoor air temperature of 30 °C. Considering the

number of visitors specified in Table 4, it is evident that the highest number of museum visitors occurs in October rather than August. This indicates that during the summer period with open church doors, moisture excess is not directly dependent on the number of visitors. In October, both indoor and outdoor absolute humidity levels are lower, resulting in a smaller difference in moisture. The outdoor air temperature in October ranges from 5 °C to 13 °C, and from Fig. 12, we observe that the lowest moisture excess of  $-3 \text{ g}/\text{m}^3$  is reached within this temperature range. The moisture excess values of 5–6  $\text{g}/\text{m}^3$  are occasional and not a general trend, as indicated by the number of measurement points. Moisture excess below zero indicates that the outdoor air is more humid than indoor air, while above zero indicates the opposite, that



Fig. 9. Cross-section of the Riga Jesus Church with the installed measuring devices.



Fig. 10. RH and temperature in the Turaida Church.

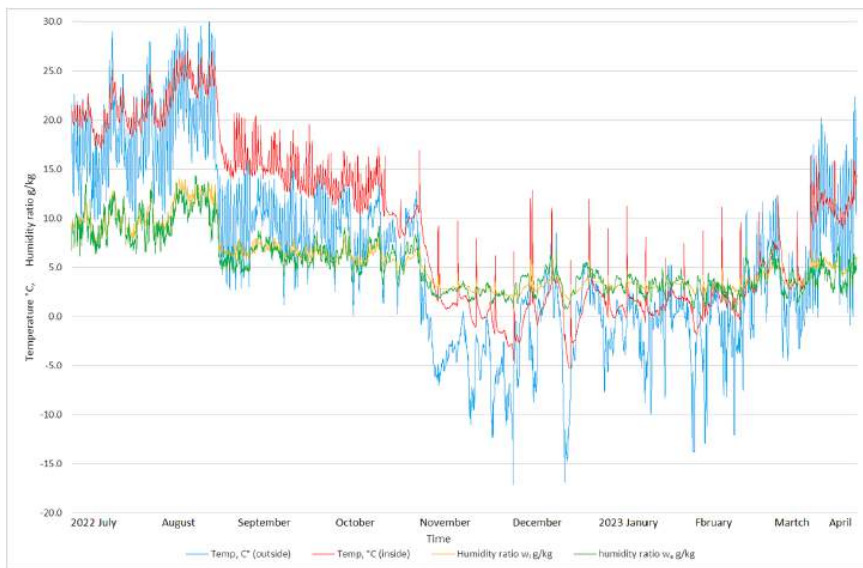


Fig. 11. Outdoor and inside moisture and temperature in the Turaida Church on the lamp.

indoor air is more humid than outdoor air. Overall, the number of points above zero is greater than below zero, indicating that indoor air is often more humid than outdoor air. As previously concluded, the inter-seasonal fluctuations in outdoor and indoor air moisture are symmetrical, suggesting that indoor air parameters are directly influenced by outdoor air parameters. Moisture excess in this building is directly related to short-term fluctuations in air parameters, indicating that there are no processes promoting air drying within the building. Negative

moisture excess fluctuations, associated with high outdoor humidity, do not affect building occupants, but during these periods, it is important to restrict indoor air exchange with outdoor air. Following a negative moisture excess, changes in outdoor air parameters can lead to positive moisture excess, as shown in Fig. 11, where there are rapid and frequent short-term fluctuations in August when the outdoor air temperature reaches 30 °C. In the churches under consideration, the moisture excess threshold of 6 g/m<sup>3</sup> is not reached, but measurements were also taken

**Table 3**  
Indoor air parameters on August 27.

Time	Temperature, T	Relative humidity, RH	Humidity ratio, $w_i$
9:00 AM	22,6 °C	67,6 %	11,6 g/kg
1:30 PM	24,6 °C	69,7 %	13,52 g/kg
An increase PM – AM	2,0 °C	2,1 %	1,92 g/kg

near (within a 5 km distance from Turaida Church) Krimulda Church during the same period, yielding similar results. Data on Krimulda Church are published in the previous article “Preliminary Study on Indoor Air Temperature and Moisture Behaviour in 13th-Century Churches in Latvia” [12]. Comparing Krimulda Church with Turaida Church, these churches have completely different enclosing construction materials; Turaida Church has log walls, while Krimulda Church has stone masonry walls. The common feature of both churches is their similar load, i.e., the openness of exterior doors. The exterior doors of Turaida Church are open during museum operating hours and are visited by tourists, whereas the exterior doors of Krimulda Church are open 24/7 and are visited by a similar number of tourists, as it is located on a tourist route. The results of measurements and calculations for these two churches with a moisture excess threshold of  $6 \text{ g/m}^3$  confirm the uncontrolled infiltration of outdoor air into indoor air. Considering the 0.2 m thickness of the log walls of these buildings with a total water vapor resistance for air diffusion equivalent to  $s_d = 8 \text{ m}$  [10], it can theoretically be assumed that moisture migration between indoor and outdoor air through the walls is possible. However, the frequent and rapid fluctuations in indoor and outdoor air parameters raise doubts about such tendencies. To draw conclusions, additional detailed measurements from the cross-section of the walls are necessary.

3.2. Moisture in Liepaja St. Trinity cathedral

Liepaja Cathedral has a permanent radiator heating connected to the district heating system with a heat exchanger power 250 kW. The heating system is installed in the heating season so that the indoor

temperature stays between 5 °C and 7 °C. The measured air parameters are reflected in a diagram in Fig. 13. It can be seen from a diagram in Fig. 13 that the outside air has little impact on the indoor air in the church. In all indoor measurement points the air temperature has little differences of  $\pm 0,3 \text{ }^\circ\text{C}$ , while the relative humidity measurement data differ much more, with  $\pm 4 \%$  from measurement point to point. The highest relative humidity volume during all measurement times is in point “On board”.

We will perform further detailed air humidity analysis according to the data measured and calculated from point “On board” because that point has larger relative humidity measurements. Consequently, the calculated values of air humidity and measured air temperature data are shown in a diagram in Fig. 14. We can see from Fig. 14 that the short-term fluctuations of the outside air humidity do not influence the building’s indoor air humidity, which is evidenced by the asymmetry of both these curves. Meanwhile, the interseasonal air humidity fluctuations have a common tendency to increase or decrease. In order to determine the scope of changes in the actual air humidity, we separate out an individual diagram, just like for Krimulda in Fig. 15, for a period between 12/22/2022 and 10/02/2022. The mentioned period has the largest number of visitors on 24 December 2022 at 6 PM when the cathedral was simultaneously attended by 220 persons ( $0.25 \text{ pers/m}^2$  or  $0,02 \text{ pers/m}^3$ ) and on 31 December 2022 at 10 PM when the cathedral was attended by 410 persons ( $0.46 \text{ pers/m}^2$  or  $0.04 \text{ pers/m}^3$ ).

We can see in a diagram in Fig. 15 that, starting from December 22 the air temperature is increased slowly and steadily from 5.7 °C to 6.2 °C on the event of December 24 for a short while (2 h) the indoor temperature is increased to 7.1 °C, and until December 31 at 5 PM it is slowly and steadily increased to 7.2 °C and is steeply increased for a short event at 10 PM to 10.6 °C. In a diagram in Fig. 15 the same symmetrical increase is observed in the absolute air humidity just like in the indoor air temperature. This symmetry of parameters is explained by the fact that the short-term rapid increase of indoor air takes place on the moment then the planned number of visitors increase. Meanwhile, if every visitor of the premises releases 20 ~ 50 g/h of moisture [24], the calculated human moisture discharge in the evening of 31 December was between 0.61 g/kg and 1.52 g/kg, which creates a rapid short-term

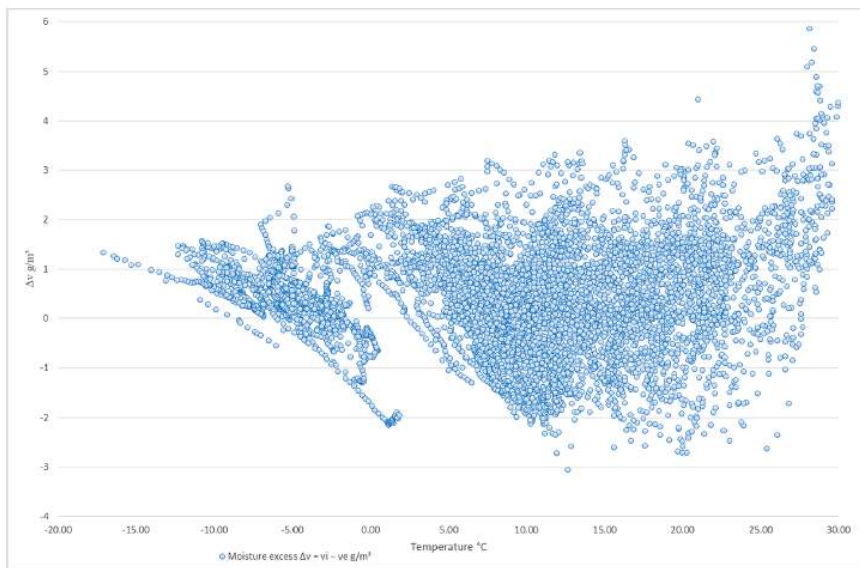
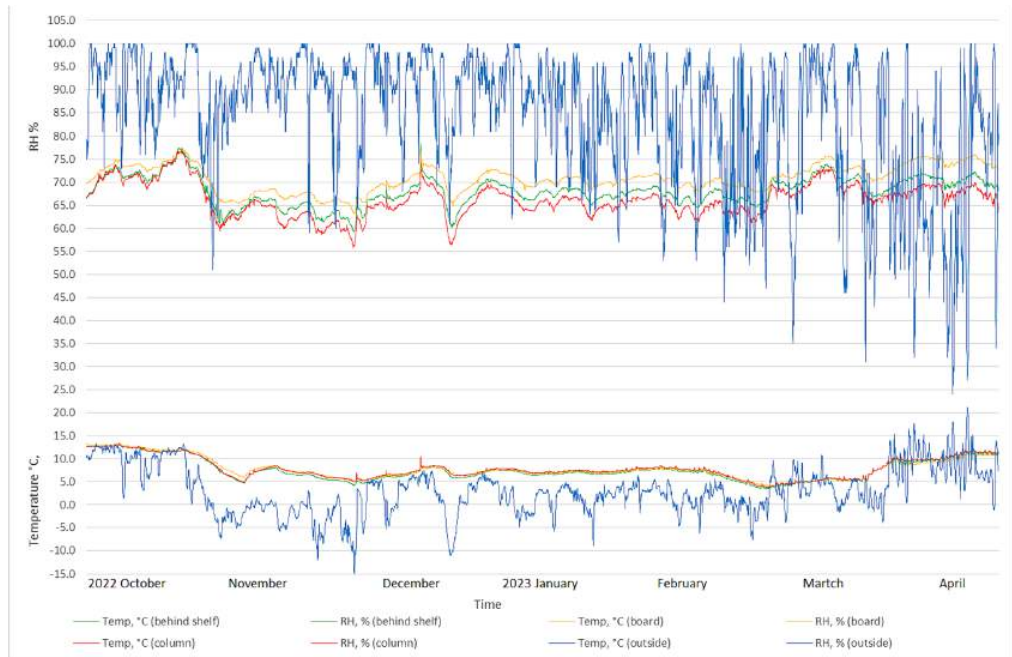


Fig. 12. Excess moisture in the Turaida Church on the lamp.

**Table 4**  
Number of Turaida Museum Reserve visitors by days of months.

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	193	18	34	64	348	320	405	213	330	1078	149	29
2	131	9	42	265	150	355	496	516	155	1412	142	77
3	31	12	25	361	199	363	645	660	597	306	84	74
4	39	28	35	46	485	525	356	585	341	169	133	67
5	17	130	319	41	141	538	363	544	314	264	303	29
6	28	66	223	16	249	174	768	799	274	456	212	32
7	33	10	25	34	372	315	826	966	299	731	60	73
8	110	24	55	97	350	392	640	615	289	3202	74	54
9	132	24	3	249	73	639	688	502	480	2927	140	56
10	14	27	14	256	101	379	840	502	789	409	34	125
11	18	28	46	31	294	504	412	775	729	308	52	55
12	30	195	260	56	145	485	388	670	224	635	284	49
13	19	150	380	117	515	381	784	795	209	533	412	87
14	39	28	43	166	268	172	823	781	272	616	18	81
15	190	50	73	262	477	545	527	443	281	2470	10	75
16	98	24	79	530	223	257	657	481	465	1194	76	137
17	3	19	61	566	324	407	709	410	528	405	40	83
18	16	53	157	381	568	681	455	595	605	302	129	108
19	17	99	296	75	267	399	803	486	158	377	169	63
20	19	135	448	116	374	325	764	663	267	407	142	56
21	29	17	42	180	368	298	484	704	310	374	48	72
22	101	22	101	251	590	560	475	453	291	1389	19	106
23	104	12	28	395	418	629	986	389	432	471	112	34
24	29	30	56	119	524	741	773	442	1174	226	26	64
25	24	26	111	108	672	774	719	386	970	217	86	79
26	12	348	119	74	406	495	737	488	290	216	22	98
27	40	271	336	183	560	217	683	643	403	389	68	68
28	19	53	27	135	585	307	607	509	472	243	21	59
29	154		6	237	401	277	601	259	338	401	34	60
30	77		62	738	447	304	1018	107	479	646	60	97
31	9		65		453		773	278		193		179
<b>Total in month</b>	<b>1775</b>	<b>1908</b>	<b>3571</b>	<b>6149</b>	<b>11,347</b>	<b>12,758</b>	<b>20,205</b>	<b>16,659</b>	<b>12,765</b>	<b>22,966</b>	<b>3159</b>	<b>2326</b>
Average per day	57	68	115	205	366	425	652	537	426	741	105	75



**Fig. 13.** RH and temperature in Liepaja St. Trinity Cathedral.

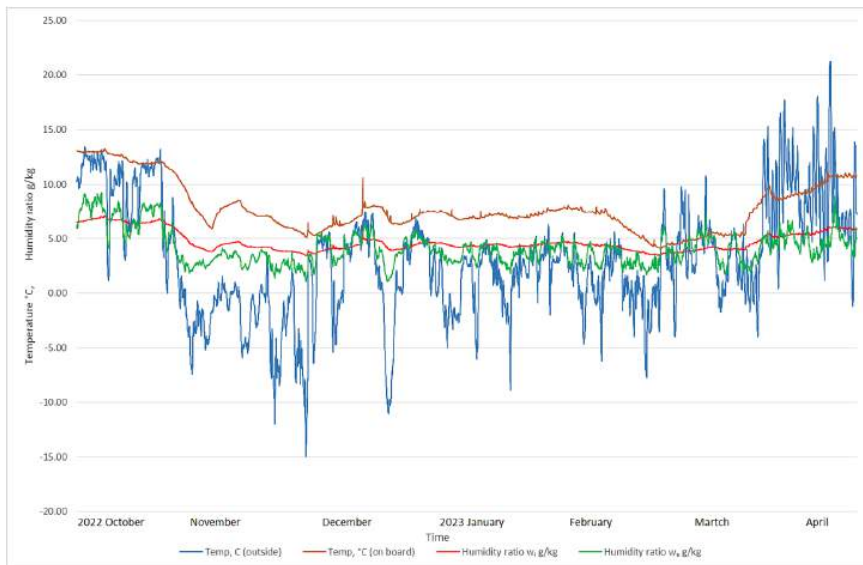


Fig. 14. Outdoor and inside moisture and temperature in Liepaja St. Trinity Cathedral on the column.



Fig. 15. Outdoor and inside moisture and temperature in Liepaja St. Trinity Cathedral on the board between 12/22/2022 and 01/02/2023.

increase in the humidity, and it coincides with the measured results. Meanwhile, a steady increase of indoor air for a long-term period increases also the moisture vaporisation from the building's structures, incl. floor and external walls which have no water proofing and furniture / interior details (organ, pulpit, altar, bench constr., balcony construct.). We can see from a diagram in Fig. 15 that this kind of vapour increases the air humidity in the premises up to 1 g/kg. We can see from a diagram in Fig. 15 also that the nature of fluctuations of the indoor air humidity and temperature does not depend on the outdoor humidity and temperature which indicates at low infiltration of the outside air.

The calculated excess moisture in Fig. 16 from the measured data between 24 October 2022 and 30 April 2023 reaches the upper

threshold  $4 \text{ g/m}^3$  during that time period. In general, these data are not comparable to the measurements and calculations of other (Krimulda and Turaida) data, because these are different periods of seasons. Expressing the possible migration of outdoor air and indoor air moisture through 1.25 m thick clay brick masonry walls, given the existing rapid fluctuations in air moisture and temperature, we consider it unlikely. In Fig. 16, a greater number of points above zero indicates that indoor air is often more humid than outdoor air. Conversely, points below zero indicate that outdoor air is more humid than indoor air, especially when the outdoor air temperature is above zero, with a particularly large cluster of points above an outdoor air temperature of  $10^\circ\text{C}$ . Taking into account the historical brick walls with lime plaster and paint, with a

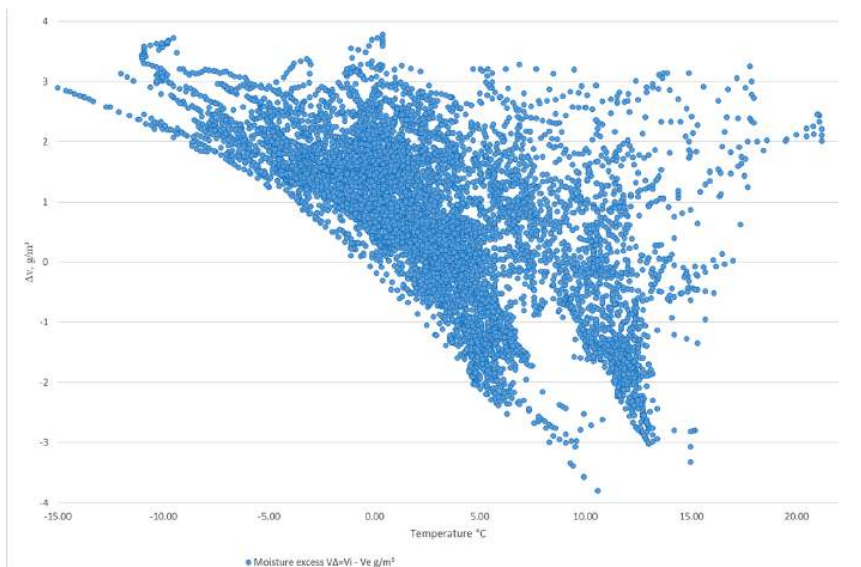


Fig. 16. Excess moisture in Liepaja St. Trinity Cathedral on the board.

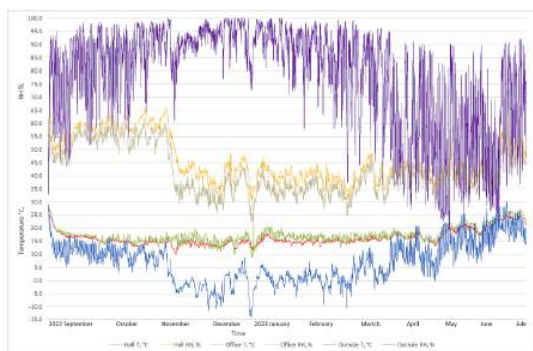


Fig. 17. RH and temperature in Riga Jesus Church in the hall.

total water vapor resistance for air diffusion equivalent to  $s_d = 6 \text{ m}$  [10], theoretically, during the winter period when the heating system maintains a constant minimum temperature, indoor air moisture migration through the walls is possible. However, upon analyzing Fig. 15, we observed the opposite trend, indicating moisture releases from the structures. For historical buildings older than 300 years with thick clay brick masonry walls without waterproofing, capillary moisture migration in the vertical direction occurs due to osmotic pressure effects [1].

### 3.3. Moisture in Riga Jesus church

Riga Jesus Church has a permanent radiator heating with a local boiler house in the basement of the building where the heat comes from 35 kW pellet heating boiler. During the heating season, the heating system in the church hall maintains between 12 °C permanently and up to 17 °C on average when the air in the premises is heated for a period of religious and other activities. The building has natural ventilation with an air leak along the built-in air trunk and air admittance through the doors and windows. The measured air parameters are reflected in a

diagram in Fig. 17. It can be seen from a diagram in Fig. 17 that fluctuations in the outdoor air parameters are not symmetrical to the indoor air fluctuations, which indicates that the impact of outside air infiltration is not large. Fluctuations of the internal air parameters, in comparison to Liepaja St. Trinity Cathedral, are much larger. In order to evaluate the impact of moisture on the building, we will look at the measured data in point “Hall” in more detail, because the hall has more intense visitor flow.

From the indoor parameters in point “Hall” and outside air temperature and relative humidity parameters, the air moisture content has been calculated for all measurements. The moisture content is shown in the diagram in Fig. 18, together with indoor and outdoor air temperature. It can be seen from a diagram in Fig. 18 that the indoor and outdoor air humidity fluctuations during the heating season are symmetrical, and it indicates at the impact the outside air infiltration has during the cold or heating season.

In order to evaluate humidity impact in more detail, we have to look at the time period between 20 December 2022 and 28 December 2022. On 24 December 2022, Fig. 19, between 6 PM and 5 PM the church had up to 500 visitors (0.65 pers/m<sup>2</sup> or 0.087 pers/m<sup>3</sup>) and on the same day, between 6 PM and 7 PM the church had up to 300 visitors (0.39 pers/m<sup>2</sup> or 0.052 pers/m<sup>3</sup>). Indoor temperature until 4 PM was heated from 12 °C to 15.5 °C with a heating system. We can see from a diagram in Fig. 19 that between 4 PM and 5 PM the air humidity increased by 1 g/kg or from 4.6 g/kg to 5.6 g/kg. Meanwhile, if one person releases 30–50 g/h [24], then the air moisture increase for the volume should vary from 2 to 3.5 g/kg. Moisture content difference of such theoretical calculation against the actual one indicates at well operating natural ventilation. Performance of the natural ventilation is improved also the fact that the entrance door of the building is open due to so intense visitor flow and it promotes large outside air infiltration. Meanwhile, we can see from Fig. 19 that the outdoor air humidity in this period is lower, and therefore it causes indoor air drying.

The calculated difference in absolute humidity in the indoor and outdoor air is shown in a diagram in Fig. 20. We can see from a diagram in Fig. 20 that the upper threshold of the humidity difference is reached in 5 g/m<sup>3</sup> when the outside temperature is 5 °C. Meanwhile the majority

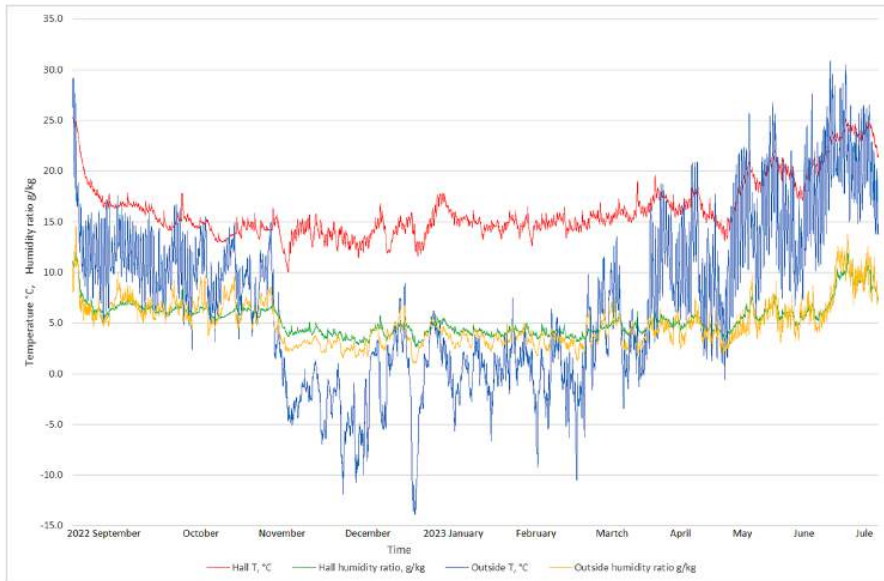


Fig. 18. Outdoor and inside moisture and temperature in Riga Jesus Church in the hall.

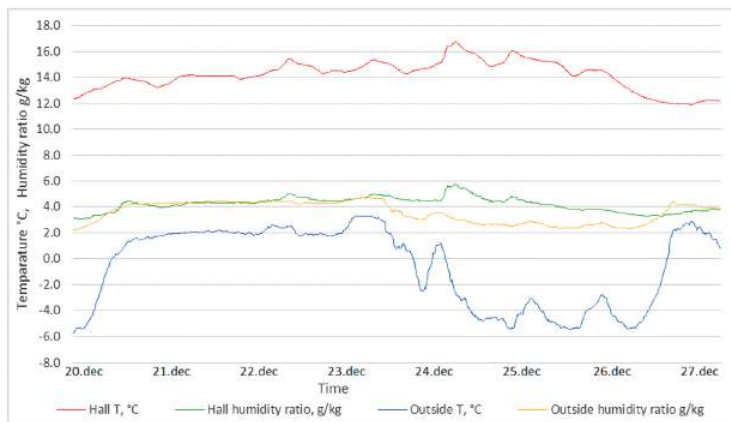


Fig. 19. Outdoor and inside humidity ratio and temperature in Riga Jesus Church in the hall between 12/20/2022 and 12/28/2022.

of other measurement points with outside temperature above or under 5 °C the upper threshold of the humidity difference does not exceed 4 g/m<sup>3</sup>. When comparing these data to Krimulda and Turaida churches during the warm season, Riga Jesus Church has less outside air infiltration and more stable indoor microclimate. The same trend is observed as in the measurements of Liepaja Church, where outdoor air is more humid than indoor air when the outdoor air temperature is above zero. This church, like Turaida Church, also has log walls with a thickness of 0.2 m and a total water vapor resistance for air diffusion equivalent to  $s_d = 8$  m. During the winter period, when a constant minimum temperature is maintained inside the building and the outdoor temperature is below freezing, as seen in Fig. 20, it is evident that indoor air is more humid than outdoor air. In other words, the moisture excess during this period is only above zero, indicating the possibility of indoor air moisture migration through the walls.

## 4. Conclusions

### 4.1. Turaida

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, and the difference of indoors and outside air humidity difference reaches the upper threshold of 6 g/m<sup>3</sup> which, according to a standard [19], is comparable to specialised high humidity premises, such as catering premises, kitchens and sports halls. 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 up the indoor air and a large number of simultaneous

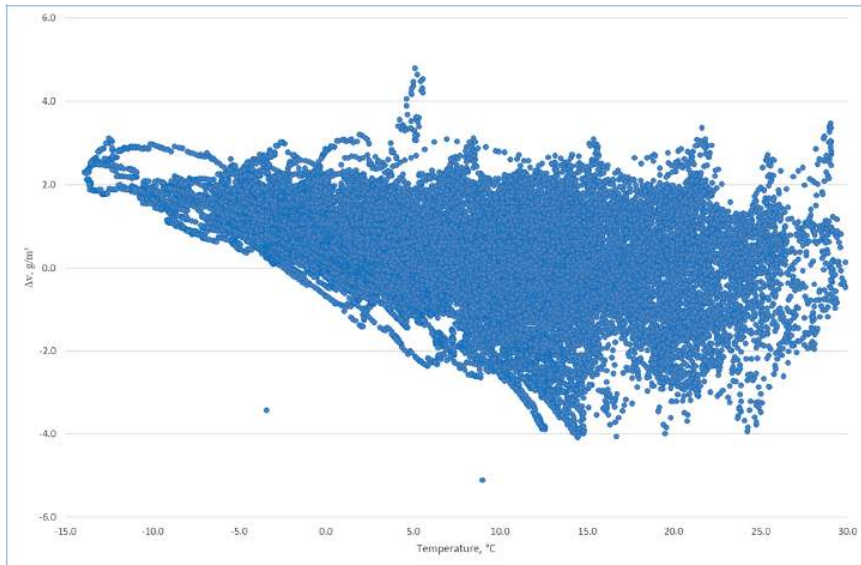


Fig. 20. Excess moisture in Riga Jesus Church in the hall.

visitors in the church (0.41 pers/m<sup>2</sup> or 0.14 pers/m<sup>3</sup>) 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.

#### 4.2. Liepaja

It can be concluded that, if comparing the microclimate of Liepaja St. Trinity Cathedral to the Krimulda Church and Turaida Church which do not have a regular heating systems, that of Liepaja St. Trinity Church is more stable (has less 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/m<sup>2</sup> or 0.04 pers./m<sup>3</sup>) 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 do not cause large microclimate fluctuations as well as 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 indoor air humidity ratio by 1.1 g/kg, which is explained by moisture vapours from the building's structures and interior items.

#### 4.3. Riga Jesus church

The natural ventilation ensures that during the cold season or heating period simultaneous 500 visitors (0.65 pers/m<sup>2</sup> or 0.087 pers/m<sup>3</sup>) do not create huge moisture fluctuations and the actual increase of indoor humidity is twice as less as the calculated one for the number of visitors. During the warm season periods the microclimate of Riga Jesus Church is more stable than in the Turaida Church, because Riga Jesus Church is not visited by so many persons on a daily basis. 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 high number of visitors would have more stable indoor climate if it had a steady and permanent indoor temperature between 5° and 10 °C, which allows for a higher air humidity up to 7 g/kg.

As the wooden churches (the Turaida Church and Riga Jesus Church) increase their indoor temperature, one cannot detect 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.

#### CRediT authorship contribution statement

**Martins Metals:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Arturs Lesinskis:** Writing – review & editing, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Anatolijs Borodinecs:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Kristaps Turauskis:** Visualization.

#### Declaration of competing interest

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## Data availability

Data will be made available on request.

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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.