Internal microclimate of the space of a sacred building.

Ronald Allan M. Mabunga Jr.
DIPLOMA THESIS ASSIGNMENT FORM

I. PERSONAL AND STUDY DATA

<table>
<thead>
<tr>
<th>Surname:</th>
<th>Mabunga</th>
<th>Name: Ronald Allan Jr.</th>
<th>Personal number: 530153</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assigning Department:</td>
<td>Department of Construction Management and Economics</td>
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<td>Study programme:</td>
<td>Civil Engineering</td>
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<td>Study branch/spec.:</td>
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II. DIPLOMA THESIS DATA

Diploma Thesis (DT) title: Internal microclimate of the space of a sacred building

Diploma Thesis title in English: Internal microclimate of the space of a sacred building

Instructions for writing the thesis:
The aim of diploma thesis is to analyze long-term collected data from the measurement of the internal microclimate taken in Sedlec cathedral. The student will prepare a detailed analysis of the behavior of the space from the point of view of its operation, the risk of condensation, changes in relative and specific humidity.

1) Detailed definition of the monitored area and specification of risk moments
   - fluctuations in specific humidity values outside the appropriate limits
   - the presence of relatively abrupt changes in specific humidity and relative humidity
2) comparison of risk factors between the monitored regulated space and non-regulated neighboring areas (dew points, fluctuations in relative humidity and specific humidity)
3) a proposal for measures that would improve the current state of the space and be minimally invasive to the given space. That is, measures that would alter the course of risk factors. Design appliances (e.g. ventilator, humidifier, heating, dryer), its placement in the room and argumentation.
4) suggestions for switching control system – limit factors

List of recommended literature:
Standards: EN 15757; EN 15759-1; EN 16242

Literature:


DT assignment date: 15.3.2024

DT submission date in IS KOS: 7.7.2024

see the schedule of the current acad. year

DT Supervisor's signature

Head of Department's signature

III. ASSIGNMENT RECEIPT

I declare that I am obliged to write the Diploma Thesis on my own, without anyone's assistance, except for provided consultations. The list of references, other sources and consultants' names must be stated in the Diploma Thesis and in referencing I must abide by the CTU methodological manual "How to Write University Final Theses" and the CTU methodological instruction "On the Observation of Ethical Principles in the Preparation of University Final Theses".

15.3.2024

Student's name
Internal microclimate of the space of a sacred building
DECLARATION

Name: Ronald Allan M. Mabunga Jr.
Email: ronjmabunga@gmail.com

Title of the MSc Dissertation: Internal microclimate of the space of a sacred building
Supervisor(s): Ing. Lukáš Balík, Ph.D. and Ing. arch Mgr. Klára Nedvědová, Ph.D.
Year: 2024

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

I hereby declare that the MSc Consortium responsible for the Advanced Masters in Structural Analysis of Monuments and Historical Constructions is allowed to store and make available electronically the present MSc Dissertation.

University: Czech Technical University
Date: July 7, 2024
Signature: ____________________________
DEDICATION

This research study is dedicated to my parents, siblings, and grandparents whose unwavering support and encouragement enabled me to complete my master’s studies.

I also dedicate this work to the Filipino heritage conservation practitioners and advocates – from architects, engineers, historians, material scientists, to the workers who passionately devote their time and efforts to promote and preserve Filipino cultural heritage.
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Finally, I wish to acknowledge my mentor, Ar. Michael Manalo, whose introduction to the field of heritage conservation has been a pivotal influence on my academic and professional journey.
ABSTRACT

In recent years, there has been a growing body of research on microclimate of historic buildings. Most of these studies have primarily concentrated on the parameters of temperature and relative humidity. Recently, however, specific humidity has become a topic of interest, and has now emerged as a developing area of research.

This dissertation thesis contributes to the expanding field of research of focusing on specific humidity as the main parameter for monitoring, controlling, and enhancing the microclimate of sacral spaces. By understanding and managing specific humidity levels, professionals and researchers in this field can better protect heritage buildings and its elements.

The core objective of this thesis is to analyze the microclimate behavior of a space and propose improvement measures based on specific humidity as a key parameter. Through detailed analysis of the data collected during the monitoring campaign, this thesis identifies the microclimate behavior of the selected space. This involves examining parameters such as temperature, dew point temperature, relative humidity, and specific humidity to highlight periods of increased risk.

Based on the analysis of its microclimate behavior, this study formulates practical recommendations to effectively address and mitigate the issues of extreme humidity levels and significant fluctuations. These problems have substantial implications to the preservation of the building materials. While the immediate effects on these materials may not be apparent, long-term deterioration can manifest due to internal stresses induced by changes in their equilibrium moisture content, leading to cycles of expansion and contraction.

To address these challenges, this study suggests the implementation of optimal humidity limits for the specific humidity tailored to the distinct microclimate characteristics and behavior of the space. Implementing such measures is crucial for mitigating the negative impacts of humidity extremes and fluctuations within the space, thereby safeguarding its architectural and historical integrity over time.

Keywords: Internal microclimate, specific humidity, relative humidity, sacred buildings, heritage conservation
ABSTRAKT

Vnitřní mikroklima sakrální stavby

V posledních letech roste počet výzkumných studií zaměřených na mikroklima historických budov. Většina těchto studií se soustředila na parametry teploty a relativní vlhkosti. Nedávno však začala odborná veřejnost věnovat pozornost měrné vlhkosti, která se stala novým tématem výzkumu.

Tato diplomová práce přispívá k rozvoji výzkumu zaměřeného na měrnou vlhkost jako hlavní parametr pro monitorování, kontrolu a zlepšování mikroklimatu sakrálních staveb. Díky porozumění a nastavení limitů měrné vlhkosti je možné lépe chránit historické budovy a jejich mobiliář.

Hlavním cílem této práce je analyzovat chování mikroklimatu prostoru a navrhnout opatření ke zlepšení, založené na měrné vlhkosti jako klíčovém parametru. Práce zkoumá chování mikroklimatu vybraného prostoru prostřednictvím podrobné analýzy dat z dlouhodobého monitoringu. Tato analýza zahrnuje parametry jako je teplota, rosný bod, relativní vlhkost a měrná vlhkost a identifikuje období zvýšeného rizika.

Na základě analýzy chování mikroklimatu poskytuje tato studie praktická doporučení pro účinné řešení a zmírnění problémů s extrémními úrovněmi vlhkosti a jejími významnými výkyvy. Tyto problémy mají vážné důsledky pro zachování stavebních materiálů. I když okamžité účinky na tyto materiály nemusí být zřejmé, dlouhodobé zhoršování může nastat kvůli změnám obsahu vlhkosti v materiálu, opakujícím se cyklům expanze a kontrakce.

Studie navrhuje implementaci optimálních limitů měrné vlhkosti vycházejících z charakteru a chování mikroklimatu daného prostoru. Realizace těchto opatření je klíčová pro zmírnění negativních dopadů extrémních hodnot a výkyvů vlhkosti, čímž se ochrání architektonická a historická integrita budovy a jejího mobiliáře.

Klíčová slova: vnitřní mikroklima, měrná vlhkost, relativní vlhkost, sakrální stavby, ochrana kulturního dědictví
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ABSTRAK

Internal na mikroklima ng espasyo sa isang sagrado na istruktura

Sa mga nakalipas na taon, lumalaki ang bilang ng mga pananaliksik tungkol sa internal na mikroklima ng mga makasaysayang gusali. Karamihan sa mga pag-aaral na ito ay nakatuon sa mga pamantayan ng temperatura at relatibong antas ng halumigmig. Kamakailan lamang, ang tiyak na antas ng halumigmig ay naging interes ng interes at ngayon ay nagpapakita bilang isang panibagong tema ng pananaliksik.

Ang tesis na ito ay naglalaan ng kontribusyon sa paglagaw ng pag-aaral na nakatuon sa tiyak na antas ng halumigmig bilang pangunahing pamantayan para sa pagmamasid, pagkontrol, at pagpapabuti ng internal na mikroklima ng mga sagradowa istruktura. Sa pamamagitan ng pag-unawa at pagkontrol sa tiyak na antas ng halumigmig, mas magagabayan ng mga propesyonal at mananaliksik sa larangan ito ang pagproteksa sa mga makasaysayang gusali at ang mga nakapaluob rito.

Ang pangunahing layunin ng tesis na ito ay suriin ang kondisyon ng internal mikroklima ng isang espasyo at magpanukala ng mga hakbang sa pagpapabuti batay sa tiyak sa antas ng halumigmig bilang pangunahing pamantayan. Sa pamamagitan ng detaladong analisis ng mga datos na nakuha sa panahon ng pagsubaybay, natutukoy ng tesis na ito ang katangian ng internal na mikroklima ng napiling espasyo. Kasama sa pag-aaral ang pagtukoy sa mga pamantayan tulad ng temperatura, dew point na temperatura, relatibong antas ng halumigmig, at tiyak na antas ng halumigmig upang bibigyan-diin ang mga pagkakataon kung kailan hindi kanais-nais ang kundisyon ng kapaligiran.

Batay sa analisis ng katangian ng internal na mikroklima nito, binubuo ng tesis na ito ang praktikal na mga rekomendasyon upang maibsan at maibsan ang mga problema ng labis na antas ng halumigmig at malalaking pagbaba at pagtaas ng lebel nito. Ang mga suliranin na ito ay may malalim na implikasyon sa pangangalaga ng mga materyales ng istruktura. Bagaman ang mga agarang epekto sa mga materyales na ito ay maaring hindi magpakita sa maliit na panahon, ang pagmamahayag ng mga suliranin ay maaaring mangyari dahil sa mga internal na stress na nagdulot ng mga siklo ng paglaki at paglalakad.

Upang tugunan ang mga hamong ito, inirerekomenda ng tesis na ito ang pagpapahalagahan ng pinakamainam na limitasyon ng tiyak na antas ng halumigmig na natatanging mga katangian ng internal na mikroklima ng espasyo. Mahalaga ang pagpapahalagahan ng mga hakbang na ito upang maibsan ang negatibong epekto ng mga mataas at mabababang antas ng halumigmig at malalaking pagbabago sa antas nito sa loob ng espasyo, na gayundin naglalayong mapanatili ang arkitektural na integridad ng espasyo ngayon.

Mga pangunahing salita: Internal na mikroklima, tiyak na antas ng halumigmig, relatibong antas ng halumigmig, sagradowa istruktura, pagpapahalaga sa pamana
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1. INTRODUCTION

Architectural heritage serves as a tangible link to a society’s past. Historic buildings possess immeasurable cultural value, providing a sense of identity to communities (Aste et al., 2019). The conservation and protection of these structures and its elements for future generations is thus one of the main challenges for professionals in this field (Bienvenido-Huertas et al., 2021). Environmental condition is one of the main factors that affects these kinds of buildings, with the internal microclimate significantly influencing the historic fabric and the heritage elements inside them (Balík et al., 2020). Studying the microclimate behavior inside these buildings is of utmost importance for ensuring their proper conservation (Silva & Henriques, 2014). Conservation is no longer solely focused on the structural integrity of buildings. Increasingly, various aspects of conservation such as the microclimate are being considered, leading to a more comprehensive and multidisciplinary approach.

Sacred buildings are a big part of this cultural heritage, specifically churches. Most of them have experienced climate changes over time, with their materials undergoing changes to adapt to local climate (Silva & Henriques, 2014). The building materials and interior elements of these churches react to parameters such as temperature and relative humidity, which can cause mechanical, biological, and chemical degradation (Silva & Henriques, 2015).

In recent years, there has been a growing body of research on microclimate of historic buildings. These studies address building response evaluations, the efficiency of climate control systems, climate-induced degradation mechanisms, and thermal comfort (Silva et al., 2020). Most of these studies have primarily concentrated on the parameters of temperature and relative humidity. Recently, however, specific humidity has become a topic of interest, and has now emerged as a developing area of research.

This dissertation thesis contributes to the expanding field of research of focusing on specific humidity as the main parameter for monitoring, controlling, and enhancing the microclimate of sacral spaces. By understanding and managing specific humidity levels, professionals and researchers in this field can better protect heritage buildings and its elements. This approach not only helps in preserving the physical aspects of sacral spaces but also ensures that the cultural and historical values of such are maintained for future generations.

1.1 OBJECTIVES

The core objective of this thesis is to analyze the microclimate behavior of a space and propose improvement measures based on specific humidity as a key parameter. This includes the following aspects:

- Definition of the microclimate behavior and specification of risk moments
- Comparison of risk factors between the selected space and adjacent area
- Recommendations for the enhancement of the internal microclimate of the selected space
Through detailed analysis of the data collected during the monitoring campaign, this thesis identifies the microclimate behavior of the selected space. This involves examining parameters such as temperature, dew point temperature, relative humidity, and specific humidity to highlight periods of increased risk. To provide a more substantial assessment, the findings are subsequently compared with the data from the adjacent area. Upon identifying these risk periods, this study then formulates practical recommendations to effectively address and mitigate these identified issues, thereby contributing to the improvement of microclimate monitoring and management practices in similar environments.

1.2 METHODOLOGY

This thesis is structured into two main parts: a theoretical study and practical application. The theoretical component delves into the fundamental concepts of microclimate, providing definitions and context. It also includes the review of literature related to microclimates in sacred buildings, discussing optimal environmental conditions for its conservation and the impact of microclimate to the building materials. These elements aim to establish a comprehensive understanding of the theoretical framework underlying microclimate studies.

Conversely, the practical part of the study focuses on the application of monitoring methodologies within a specific case study, data collection, and the discussion of results. This includes the analysis of microclimate parameters such as temperature, dew point temperature, relative humidity, and specific humidity, which results to the definition of the behavior of the selected space through the trends and critical periods.

The study concludes with a practical design proposal aimed at enhancing the microclimate conditions within the selected space. This includes defining set-points, establishing limits, as well as designing a switching control system. Through this approach, this thesis not only advances theoretical knowledge in the field of microclimate studies but also provides practical solutions aimed at ensuring the proper conservation of historic buildings.
2. THEORETICAL PART

This component of the thesis delves into the current body of research about the internal microclimate of sacred buildings. It begins with a discussion of several studies on the topic, followed by a definition of the fundamental parameters that characterize microclimates. It also mentions the basic requirements needed for an optimal environment, as well as the significant impact that microclimate conditions have on the building materials commonly used in sacred structures. Lastly, it outlines general strategies and measures recommended in the literature to achieve an optimal indoor environment. Through this comprehensive review, this section aims to provide a cohesive understanding of how microclimate management can contribute to the conservation efforts of sacred buildings.

2.1 Indoor Microclimate in Sacred Buildings

This section reviews recent literatures pertaining to indoor microclimates in sacred buildings across different geographical contexts. It highlights the specific objectives of each study, the environmental parameters investigated, and their significant findings.

A study by Martinez-Molina et al. in 2022 aimed at assessing the relationship between indoor microclimate and thermal comfort inside a historic religious building in San Antonio, Texas, USA. Their study encompassed an analysis of various environmental factors, including temperature, relative humidity, and air velocity or speed. One of the significant findings derived from their research pertains to the stability of the church’s indoor temperature due to the high thermal mass of the structure and its limited openings or fenestrations. The utilization of limestone also contributes to the consistent thermal conditions because of its substantial heat storage capacity. The incorporation of thick walls and porous hygroscopic materials in historic buildings regulate the indoor environment, effectively preventing any fluctuations. Furthermore, the study identified a notable increase in relative humidity during the periods when the church is open to the public, indicating the impact of the presence of people on indoor environment (Martinez-Molina et al., 2022).

Another study concerning the indoor microclimate of sacred buildings involved a comprehensive analysis focusing on the hygrothermal behavior inside the Milan Cathedral in Italy, with the primary objective of assessing the potential risks to the conservation of its materials – specifically wood, stones, and metallic elements. Air temperature, surface temperature, relative humidity, mixing ratio, air velocity or speed, light, and air pollution are the environmental parameters that were considered in this study. Notably the research highlighted relative humidity as the most critical indoor environmental aspect that poses a significant threat to material conservation due to its high variations and large fluctuations. Discussion of the degradation processes were also mentioned in this study, categorizing them into two primary groups: physiological or the natural aging of materials, and pathological which may manifest either internally due to material instability or externally as a response to environmental conditions. Furthermore, optimal ranges for temperature and relative humidity for the conservation of these materials were also identified in this research (Aste et al., 2019).
In 2021, a study about the impact of climate change on the preservation of heritage elements in historic buildings was conducted. This was represented through a case study of a church in Spain. Different from the other literatures, this research also explored the feasibility of using Artificial Intelligence to forecast the time series of the indoor microclimate. The study monitored environmental conditions, particularly temperature and relative humidity, with a specific focus on their implications for the conservation of wooden objects and paintings. The assessment of indoor microclimate was analyzed through the application of Performance Index or PI, calculated as the proportion of the number of monitored observations within predefined preservation limits, as per the Italian standards UNI 10829 (Figure 1). The study revealed that historic buildings with deficient environmental climates pose a considerable risk to the preservation of heritage elements (Bienvenido-Huertas et al., 2021).

![Figure 1: Use of Performance Index in the assessment of indoor microclimate (Bienvenido-Huertas et al., 2021).](image)

A climate monitoring campaign was conducted in 2020 using low-cost data loggers, having the Jeronimos Monastery in Lisbon, Portugal as the case study. The primary objectives were to characterize the historic climate profile of the church and to establish sustainable targets for mitigating mechanical damage to hygroscopic materials. The environmental parameters of temperature, relative humidity, and ventilation (expressed as air changes per hour or AHC) were the ones monitored in the study. Among the important points that we can derive from this study was the fact that historic buildings generally exhibit reduced ventilation rates, which contributes to moisture-related issues. Also, while relative humidity is valuable in assessing risk of degradation, it has been proved insufficient in discerning the cause of fluctuations – may it be from temperature variation or water vapor pressure. Lastly, the study also mentioned the concept of acclimatization, discussing how certain materials can adapt to their historic climate (Silva et al., 2020).
In another study in 2020, researchers investigated the impact of external environmental conditions on the internal microclimate of a historical church located in Sedlec, Czech Republic. The study aimed to determine optimal conditions for preserving bone artefacts within the church. Notably, this study stands out for its consideration of specific humidity in the analysis in addition to the other parameters – temperature, dew point temperature, and relative humidity. Key findings revealed that during spring and winter, both temperature and humidity levels exceeded optimal limits, leading to excessive moisture in spring and over-drying in winter. Instability in indoor microclimate was also observed during these periods. Additionally, variations in microclimate behavior were observed at different heights of the church: with lower areas tended to have dense and cold air, while higher spaces were characterized by increased moisture content. Further analysis determined that high humidity levels were due to the infiltration and retention of humid exterior air due to inadequate air circulation and ventilation, moisture seepage from damp walls and floors, and presence of large number of people. Regarding the preservation of bone artefacts, the study concluded that excessively low specific humidity level could damage the inventory, whereas high specific humidity levels could lead to water vapor absorption into the material. Overall, the study highlighted the complex interaction between the environmental parameters in the preservation of cultural artefacts within sacred buildings, emphasizing the value of implementing stable and optimal microclimatic conditions. (Balík et al., 2020).

A study about the monitoring of microclimate in a historic church in Spain equipped with modern heating was conducted in 2018. Its objective was to identify the implications of modern heating systems to the conservation of the church and its elements, particularly its artworks and substrates. In addition to monitoring the common parameters of temperature and relative humidity, the study also considered CO₂ levels in the analysis. Notable findings clarified that routine heating should be limited and controlled to maintain relative humidity within an optimal range critical for preserving the church’s heritage assets. The study also highlighted that wide variations in relative humidity can cause internal stress in materials and frequent condensation episodes may lead to biodeterioration. Furthermore, the study mentioned a central recommendation in accordance with the current standards (EN 15759-1), which includes the removal of older centralized hot air convection systems, as these systems can severely alter the indoor microclimate and pose risks to the architectural and artistic heritage of churches (Varas-Muriel & Fort, 2018).

Lastly, a study in 2018 was conducted in Russia which aimed to identify the cause of negative impact of microclimatic conditions on the conservation of monumental paintings. The results of the study served as the basis for the modernization of the church’s HVAC system. The research involved long-term monitoring as well as thermal camera studies, specifically for the wall fresco paintings. Key conclusions included that high temperatures and relative humidity during summer increase the risk of microbiological deterioration of wall fresco paintings, while low relative humidity in winter disrupts the sorption equilibrium of paintings. Fluctuations in these conditions also facilitate physical, mechanical, chemical, and biological degradation of painting materials. The study emphasized the necessity of designing air drying, moistening, heating, and cooling systems tailored to the church and the paintings. Such systems
are crucial to allow the possibility of controlling the temperature and air humidity during the problematic seasons to ensure the preservation of both the church fabric and its artworks (Dorokhov & Pintelin, 2018).

All the aforementioned studies converge on the same issues concerning the indoor microclimate of sacred buildings. They highlight the challenges posed by extreme levels of temperature and humidity, ranging from excessively high to low values, as well as the significant fluctuations experienced throughout the annual cycle. These conditions pose considerable risks to the integrity and preservation of the buildings and their heritage elements. Furthermore, the studies emphasized the importance of implementing effective systems to control the environmental parameters wherever possible. By regulating temperature and humidity levels, these systems play a crucial role in assuring a proper conservation approach for these invaluable heritage assets.

### 2.2 Basic Parameters for Microclimate

This section outlines the definitions of the fundamental microclimate parameters: temperature, dew point temperature, relative humidity, and specific humidity. These definitions are derived from literature, industry standards, and established norms.

The European standard (EN 15757) defines temperature as “the parameter read on a thermometer which is exposed to air in a position sheltered from direct solar radiation or other energy sources” (CEN, 2008). Another definition, from the University of Nebraska, describes temperature as a measure of the heat content of air, which can refer to dry bulb temperature, wet bulb temperature, or dew point temperature (Shelton, 2008). For the purposes of this thesis, temperature is simply defined as the measure of heat content of air, measured in degrees Celsius (°C).

Closely linked to temperature, dew point temperature is defined in the European standard (EN 16242) as “the temperature to which air is cooled at constant pressure and constant water vapor content in order for saturation to occur” (CEN, 2012). Another definition, by the University of Nebraska, describes it as the temperature below which moisture will condense out of the air. “Air that is holding as much water vapor as possible is saturated or at its dew point” (Shelton, 2008). From a different perspective, a company specializing in humidity control defines dew point temperature as the point of saturation. “Dew point is always less than or equal to the actual air temperature” (DST, 2019). For the context of this thesis, dew point temperature is defined as the temperature at which air reaches saturation, causing water vapor to condense. It is measured in degrees Celsius (°C).

Relative air humidity is defined in the European standard (EN 15757) as the ratio of the actual water vapor pressure of the air to the saturation vapor pressure (CEN, 2008). The University of Nebraska provides another perspective, describing it as the measure of how much moisture is present relative to the maximum moisture the air could hold at a given temperature (Shelton, 2008). Furthermore, in a recent study on sorption properties of clay materials, relative humidity was defined as the ratio of the
Partial pressure (or density) of water vapor in the air to the saturated partial pressure (or density) of water vapor at a given temperature and total pressure (Dvěš, 2021). In this thesis, relative humidity is defined as the percentage (%) of water vapor in the air relative to the maximum water vapor that the air may contain at a specific temperature.

Lastly, specific air humidity is defined differently in various contexts. According to a health-related study, specific humidity is described as a mass-based atmospheric moisture variable (mass of moisture per mass of air) that is less influenced by changes in air temperature (Klompmaker et al., 2023). Another definition is from a company specializing in humidity control which characterized it as the ratio of water vapor to the total air (dry air plus the water vapor) in a particular volume of air (DST, 2019). For the purposes of this thesis, specific humidity is defined as the absolute amount of water in grams per kilogram of dry air (g/kg_{dry air}) at a defined pressure.

### 2.3 Basic Requirements for Optimal Environment

The pursuit of identifying the ideal environmental conditions for the conservation of architectural and artistic heritage has been an evolving task. This section outlines the suggested optimal environment based on available literature, emphasizing temperature, relative humidity, and specific humidity levels. It covers the necessary conditions for both buildings in general and specific materials such as stone, wooden elements, metallic elements, paintings, and paper.

- **Built Heritage:**

  According to EN 15757, one method to determine the best environmental conditions for historic buildings is by assessing their historical climate. This pertains to the temperature and relative humidity to which the materials have already adapted. The standard suggests maintaining these established parameters if they have been proven not harmful over time. Specifically, regarding relative humidity, EN 15757 proposes setting the optimal condition target at the 50th percentile of the recorded relative humidity readings (CEN, 2008).

  In a study that analyzed the impact of external climate on church internal microclimate, optimal environmental conditions were recommended: 18°C to 20°C for the temperature, 50% to 60% for relative humidity, and 6.5 g/kg_{dry air} to 8.9 g/kg_{dry air} for specific humidity (Balík et al., 2020).

  Another study that focused on the environmental conditions for collection preservation suggested optimal ranges of 16°C to 25°C for the temperature and 40% to 60% for the relative humidity (Kirby Atkinson, 2014).

  Additionally, research on sorption properties of clay materials proposed optimal conditions for buildings in Czech Republic of 18°C to 20°C for winter air temperature, 20°C to 28°C for summer, and 40% to 60% relative humidity (Dvěš, 2021).
Internal microclimate of the space of a sacred building

- **Stone:**
  A literature on microclimate monitoring at the Milan Cathedral in Italy recommended that maintaining temperatures between 15°C and 25°C and relative humidity between 20% to 60%, with fluctuations not exceeding 10%, is optimal for the conservation of stones (Aste et al., 2019).

- **Wooden elements:**
  The same study on Milan Cathedral outlined optimal conditions for the preservation of wooden elements: temperature range from 19°C to 24°C with daily fluctuations not exceeding 1.5°C and relative humidity maintained between 45% to 65% with maximum fluctuations kept within 4% to 6% (Aste et al., 2019).
  In another study that analyzed the impacts of climate change on the preservation of heritage elements in historic buildings, recommended conditions for the conservation of wooden elements included temperatures between 19°C to 24°C and relative humidity of 50% to 60% (Bienvenido-Huertas et al., 2021).

- **Metallic elements:**
  In the context of the microclimate studies at the Milan Cathedral, the suggested optimal conditions for the preservation of metallic elements were determined based solely on relative humidity, which should be kept below 50%. Temperature was deemed irrelevant for this type of material (Aste et al., 2019).

- **Paintings:**
  A study that focused on the impact of climate change on heritage preservation recommended maintaining paintings at temperature of 19°C to 24°C and relative humidity between 45% to 55% (Bienvenido-Huertas et al., 2021).
  Another study advised somewhat comparable optimal conditions: similar temperatures of 19°C to 24°C with a little higher relative humidity range of 50% to 65% (Alcántara, 2002).
  Furthermore, in research focusing on the influence of indoor microclimate on thermal comfort and conservation of artworks in the Cathedral of Matera in Italy, optimal conditions for artwork conservation were suggested as 16°C to 22°C for temperature and 45% to 55% for relative humidity (Cardinale et al., 2014).

- **Paper:**
  The recommended optimal conditions for preserving papers include maintaining a temperature range of 18°C to 20°C and relative humidity level of 65% (Camuffo, n.d.).
  The optimal ranges vary according to location as they are influenced by external environmental factors. Each material also has its own unique and specific requirements for its preservation. For an overview of the mentioned optimal conditions, refer to Table 1.
Table 1: List of optimal environmental conditions according to different sources.

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature (°C)</th>
<th>Relative Humidity (%)</th>
<th>Specific Humidity (g/kg\text{dry air})</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Built heritage</td>
<td>18-20°C</td>
<td>50-60%</td>
<td>6.5-8.9 (g/kg\text{dry air})</td>
<td>Balík et al., 2020</td>
</tr>
<tr>
<td></td>
<td>16-25°C</td>
<td>40-60%</td>
<td>-</td>
<td>Kirby Atkinson, 2014</td>
</tr>
<tr>
<td></td>
<td>18-20°C (Winter)</td>
<td>40-60%</td>
<td>-</td>
<td>Diviš, 2021</td>
</tr>
<tr>
<td></td>
<td>20-28°C (Summer)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stone</td>
<td>15-25°C</td>
<td>20-60%</td>
<td>-</td>
<td>Aste et al., 2019</td>
</tr>
<tr>
<td>Wood</td>
<td>19-24°C (+/- 1.5°C)</td>
<td>45-65%</td>
<td>-</td>
<td>Aste et al., 2019</td>
</tr>
<tr>
<td></td>
<td>19-24°C (+/- 4-6%)</td>
<td></td>
<td></td>
<td>Bienvenido-Huertas et al., 2021</td>
</tr>
<tr>
<td>Metal</td>
<td>-</td>
<td>&lt; 50%</td>
<td>-</td>
<td>Aste et al., 2019</td>
</tr>
<tr>
<td>Paintings</td>
<td>19-24°C</td>
<td>45-55%</td>
<td>-</td>
<td>Bienvenido-Huertas et al., 2021</td>
</tr>
<tr>
<td></td>
<td>19-24°C</td>
<td>50-65%</td>
<td>-</td>
<td>Alcántara, 2002</td>
</tr>
<tr>
<td></td>
<td>16-22°C</td>
<td>45-55%</td>
<td>-</td>
<td>Cardinale et al., 2014</td>
</tr>
<tr>
<td>Paper</td>
<td>18-20°C</td>
<td>65%</td>
<td>-</td>
<td>Camuffo, n.d.</td>
</tr>
</tbody>
</table>

Considering the recommended limits identified in the literature, it is important to highlight that while various limits have been discussed, none have specifically addressed the optimal specific humidity levels necessary for the conservation of different materials. This aspect is particularly crucial given its significant influence on the sorption properties of materials, impacting their ability to absorb moisture from the surrounding environment. Specific humidity quantifies the absolute moisture content in the air, whereas relative humidity only dictates the capacity of air to hold water at specific temperatures. Thus, understanding specific humidity is essential for effectively managing environmental conditions to safeguard the preservation of diverse materials.
2.4 Impact of Microclimate to Materials

This section explores current literature and established norms concerning the influence of microclimate on materials commonly found and used in sacred buildings. Furthermore, it details how certain microclimate parameters contribute to the deterioration process of these materials over time, potentially compromising their cultural heritage value.

According to European standards EN 15757, hygroscopic materials like wooden artefacts, paints, books, bones, leather, and textiles are particularly vulnerable to wide relative humidity fluctuations as it can cause fractures and deformations. These variations in humidity levels lead to the Equilibrium Moisture Content (EMC) of the materials to be unstable, resulting to dimensional changes, internal strain-stress cycles, and risk of failure. Extreme humidity levels, whether high or low, should also be avoided as it contributes to the disruption of the materials’ EMC (CEN, 2008).

In another established norm, European standard EN 15759-1 stresses that rapid fluctuations in relative humidity create moisture content gradient within materials which in turn result in dimensional changes and stress. The standard also emphasizes that excessively high relative humidity fosters biodeterioration, such as mold, rot, and insect infestation, while overly low levels can result to some materials to become brittle – especially for fragile elements. Furthermore, high relative humidity paired with high temperatures speeds up chemical degradation, including corrosion and oxidation, highlighting the preference for cooler indoor microclimates to avoid such risks. Lastly, in terms of the air movement, heating systems can accelerate the rate of deposition of particles and increase the likelihood of damage from salt crystallization on surfaces (CEN, 2011).

In studies on bone preservation, research indicated that low specific humidity could harm artefacts while high specific humidity leads to water absorption into the material. Additionally, surface condensation on cold surfaces like walls, tiles, and vaults, promotes the formation of molds and algae growth, as well as it accelerates the natural degradation process of materials such as plasters, mortars, stones, and bricks (Balík et al., 2020).

In a study focusing on thermal comfort within a historic stone religious building, researchers identified that high relative humidity values significantly affects both the building and its artworks in a negative way. The study’s findings underscore the mutual relationship between microclimate conditions and the materials used in construction. For instance, the paper highlighted that the usage of thick walls and porous materials in historic buildings contribute to stabilizing internal environmental fluctuations. These architectural features not only enhance thermal regulation but also play a crucial role in managing humidity levels within acceptable ranges (Martinez-Molina et al., 2022).

A study of microclimate monitoring at the Milan Cathedral in Italy concluded that relative humidity stands out as the most critical parameter affecting material conservation, primarily due to its significant and
frequent fluctuations. The research also specifies the impact of microclimate parameters to wooden elements, stones, and metals. For wood, higher temperatures and relative humidity were found to cause the growth of bio-colonization, whereas low temperatures and relative humidity can cause organic materials to be less flexible and overly rigid. Furthermore, fluctuating relative humidity levels were observed to induce compression-expansion stresses in wood, potentially leading to internal mechanical damage and crack formation. Regarding stones, the study noted that high relative humidity fosters the growth of bio-organisms and increases the risk of corrosion for certain minerals within the stone which can result in the formation of stains. Additionally, wide fluctuations in relative humidity can trigger condensation-evaporation cycles on the surface of stones, promoting the movement and accumulation of salts, which in turn leads to efflorescence. If these surfaces are contaminated with pollutants, water can aggravate chemical degradation processes such as carbonation and sulfation. Lastly, the study highlighted that relative humidity exceeding 50% accelerates corrosion processes in metallic elements (Aste et al., 2019).

In a study aimed at identifying optimal indoor air parameters for historical buildings, researchers explored the relationship between materials and relative humidity using sorption isotherms. The study showed that as relative humidity rises, the moisture content of materials also increases. Figure 2 displays a sample sorption isotherm illustrating these findings for wood and brick (Tabunshchikov et al., 2020).

![Figure 2: Sorption isotherm for wood (left) and brick (right) (Tabunshchikov et al., 2020).](image)

Another study on sorption isotherms highlighted that surface moisture reaching an equilibrium moisture content of 80% relative humidity is conducive for the development of molds. The study also discussed common moisture transport mechanisms, noting that moisture can infiltrate structures in both liquid and vapor forms, but it can only escape as vapor. Vapor penetration implies condensation, while in liquid form, water can enter masonry through capillaries from the ground or directly from rainfall (Karoglou et al., 2005).
Finally, in another study that dealt with the sorption characteristics of clay materials, it was found that high humidity levels promote the growth of mold, bacteria, and mites, and can lead to condensation issues on cold surfaces. The research also explored how certain materials can absorb and release moisture (desorption), which contributes to regulate the indoor humidity by accumulating moisture during dry periods. Clay minerals were cited as an example of materials that effectively tore indoor humidity due to their composition. The study defined moisture sorption as the process whereby a gaseous or liquid substance binds to the surface of another substance. Figures 3 and 4 illustrate the processes of absorption and desorption (Diviš, 2021).

![Moisture transport phenomena in capillary porous mineral building materials](image1)

Figure 3: Moisture transport phenomena in capillary porous building materials (Diviš, 2021).

![Moisture states and phase change processes](image2)

Figure 4: Moisture states and phase change processes (Diviš, 2021).
The study emphasized that absorption involves purely physical forces without inducing chemical changes, making it a reversible process. In contrast, desorption necessitates enough energy to break the bond between the absorbate and the absorbent. Furthermore, the research highlighted that the materials can significantly impact the microclimate by affecting the moisture content, which directly influences the relative humidity in their environment. This relationship is illustrated in the sorption isotherm of common building materials (Figure 5). The study defined sorption isotherm as the relationship between the equilibrium moisture of a material and the relative humidity at a constant temperature (Diviš, 2021).

![Figure 5: Absorption and desorption isotherm of tested materials (Diviš, 2021).](image)

In summary, this section highlights the mutual relationship between microclimate and building materials, as well as the impact of microclimate parameters temperature, relative humidity, and specific humidity fluctuations on material degradation processes. The literature reviewed stresses that rapid and extreme fluctuations in these environmental factors contribute significantly to the deterioration of building materials. Continuous wide fluctuations over short periods of time induce internal stresses in materials due to their changing moisture content levels. Moreover, high humidity levels promote bio-colonization, while low humidity levels can dry out materials, potentially leading to the formation of cracks. These findings underscore the importance of stable environmental conditions in the conservation of historic buildings and their elements.
2.5 General Measures to Achieve Optimal Environment

In conclusion to the theoretical component of this study, this section delves into the recommendations derived from existing literature and norms pertaining to the general measures necessary for achieving an optimal environment conducive to the conservation of sacred buildings and their building materials.

One microclimate monitoring study suggested that mitigating moisture within walls and minimizing surface condensation are crucial in achieving an optimal environmental condition. The study underscored the importance of stabilizing the internal microclimate by regulating parameters, particularly relative humidity and specific humidity. A practical approach involves creating ideal conditions to facilitate natural drying of residual structural moisture. In cases where natural drying proves ineffective or inadequate, installation of appliances such as dehumidifiers or air dryers presents a feasible alternative (Balík et al., 2020).

Another study supported the previous findings regarding the importance of controlling moisture levels within walls to ensure effective conservation practices. This study highlighted that preventing moisture from evaporating from damp walls helps mitigate the risk of condensation, thereby preventing the transport of salts in walls. Furthermore, the study emphasized the current standards advocating for the removal of outdated centralized hot air convection systems due to their significant impact on the internal microclimate. In instances where removal is not feasible, practical alternatives include maintaining a substantial presence of people within the space, adjusting the system’s operational schedule to limit heating during specific times, and implementing ventilation on the upper areas (Varas-Muriel & Fort, 2018).

In a study on the preservation methodologies for architectural monuments, it was proposed that modern HVAC systems within these environments should be installed. These systems are encouraged to incorporate complex algorithm controls for regulating both temperature and relative humidity values. Additionally, they should integrate mechanisms designed for air drying, moistening, heating, and cooling purposes. Furthermore, the research highlighted the necessity of implementing specific measures and targeted strategies aimed at protecting the surfaces of paintings housed within these types of structures. As an example, it was suggested that periods after the opening hours necessitate enhanced ventilation, which can be achieved through the installation of exhaust fans at upper windows (Dorokhov & Pintelin, 2018).

According to EN 15759-1, optimizing the indoor climate for conservation purposes of sacred spaces such as churches, begins with the decision regarding the necessity of heating system. The need to implement a heating system depends on several factors, notably the presence of efflorescence and soiling on walls and other interior surfaces. Structures afflicted with such conditions may not benefit from heating, as it could potentially aggravate risks. Conversely, in environments where dampness and bio-colonization are prevalent, conservation heating is recommended. Its objective is twofold: first,
stabilize relative humidity levels and prevent fluctuations. For instance, even during summer periods, conservation heating might still be necessary to maintain relative humidity values below the limits to mitigate the growth of bio-colonization. Secondly, conservation heating aims to maintain interior temperatures sufficiently warm to avoid the occurrence of condensation or frost on surfaces. In addressing these issues, the control system should consider the dew point temperatures, particularly during winter months, where setting a minimum temperature threshold is essential to prevent freezing (CEN, 2011).

The implementation of conservation heating strategies must be designed according to the specific spatial requirements and operational schedule of a space. This can be achieved through either general heating encompassing an entire space or localized heating targeting specific areas only. Localized heating though can lead to cold surfaces which may result in condensation when large groups of people are present. Moreover, heating can also be applied either continuously or intermittently. A common problem with continuous heating is particle deposition and thermal stratification while intermittent heating on the other hand, can facilitate damaging cycles such as the formation of efflorescence or allow walls to become colder than the ambient air, thereby even aggravating particle deposition and condensation risks (CEN, 2011).

All the aforementioned measures demonstrate the range of approaches aimed at achieving optimal environmental conditions. They emphasize the importance of considering the distinct microclimatic characteristics inherent to each space. Therefore, strategies must be carefully customized to address the specific conservation requirements of such buildings. EN 15759-1 provides a systematic approach (Figure 6) to effectively improve the indoor microclimate of sacred spaces such as churches.
Internal microclimate of the space of a sacred building

Figure 6: Overview of the EN 15759-1.
3. PRACTICAL PART

The practical component of this study is dedicated to the actual application of the theories and concepts outlined in the theoretical part. A heritage sacred building has been selected as the case study for this purpose. This section provides a brief background of the chosen building, details the methodology implemented for the microclimate monitoring process, discusses the findings and their analyses. Moreover, it includes an assessment of the impact of microclimate on the materials within the selected space, along with an evaluation of the factors influencing the microclimate. Finally, the section concludes with a design proposal aimed at improving microclimate conditions to promote the conservation of the space and its elements.

3.1 Case Study: Sedlec Cathedral

This study examines the internal microclimatic conditions within the Treasury of the Cathedral at Sedlec, also known as the Cathedral of the Assumption of Our Lady (Figure 7). A long-term monitoring program has been conducted, focusing on key parameters such as temperature, dew point, and relative humidity.

Figure 7: Exterior of Sedlec Cathedral (The Roman Catholic Parish of Kutná hora - Sedlec, n.d.).

The church forms an integral part of the UNESCO-inscribed World Heritage Site known as “Kutná Hora: Historical Town Centre with the Church of St. Barbara and the Cathedral of Our Lady at Sedlec” (UNESCO WHC, n.d.). Its history dates to the late 13th and early 14th centuries. However, a significant event occurred in 1421 leaving it in ruins for nearly three centuries. Despite its dilapidated condition, it
was still recognized by Bohuslav Balbín as the most magnificent basilica – Splendissima Basilica. The church underwent extensive reconstruction during the late 17th and early 18th centuries under the stewardship of Abbot Jindřich Snopek. This reconstruction was characterized by a unique architectural style known as Baroque Gothic. In the 20th century, the cathedral suffered from neglect and decay, but in 1995 it was inscribed on the UNESCO World Heritage List, inspiring renewed interest in its preservation. Subsequently, a restoration initiative was undertaken, culminating in its reopening to the public in 2009 (The Roman Catholic Parish of Kutná hora - Sedlec, n.d.).

In this thesis, the focus is on the detailed examination of two distinct spaces within the cathedral: the *Klenotnice* (Figure 8), referred to as the “Treasury” in this study, and the adjacent Chapel of the Fourteen Holy Helpers in Need located beside it, hereafter referred to simply as the “chapel.” For context, the Treasury is a secluded space enclosed with doors, and is equipped with mechanical systems including a dryer and humidifier, thus maintaining a controlled environment. The technical specifications of these appliances are listed in Table 2. In contrast, the adjacent chapel is directly open and connected to the church, with no such systems in place, leaving its environment uncontrolled. The floor plan shown in Figure 9 identifies the locations of both the Treasury and the chapel. Part of this research focuses on comparing the microclimatic conditions of these two neighboring spaces that are under different environmental conditions.
Table 2: Technical specifications of the installed appliances inside the Treasury.

<table>
<thead>
<tr>
<th>Appliances</th>
<th>Brand &amp; Model</th>
<th>Maximum performance rate</th>
<th>Room area</th>
<th>Tank capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dryer (dehumidifier)</td>
<td>Wood’s DS28</td>
<td>17.50 L / 24h</td>
<td>140 m²</td>
<td>10.40 L</td>
</tr>
<tr>
<td>Humidifier</td>
<td>Brune B300</td>
<td>1.4 L / h</td>
<td>600 m³</td>
<td>25 L</td>
</tr>
</tbody>
</table>

3.2 Monitoring Methodology

To monitor the microclimate within the Treasury and the chapel, multiple probes were strategically placed at various locations and heights. Specifically, three (3) probes were installed in the Treasury: Probe 1 just above the floor, Probe 2 at a height of 2.50 meters above the floor, and Probe 3 near the ceiling or under the vault. In the chapel, a single probe (probe 4) was positioned immediately above the floor. The figure below indicates the specific locations of these probes within the church.
Measurements of fundamental internal microclimate parameters were conducted from May 6, 2022 to November 14, 2023. Each of the four probes was equipped with data loggers to record temperature, dew point temperature, and relative humidity. The specifications of these monitoring devices are listed in Table 3. Additionally, exterior temperature data was incorporated into the study, sourced from the meteorological station named Slávinka which is around 2 kilometers away from the cathedral (Meteostanice-Slávinka, n.d.). Since there is no installed equipment right outside the cathedral, there can be minor differences (maximum of 2 °C) with the actual external temperature outside the cathedral and the monitored temperature at the weather station.

Table 3: Technical specifications of the dataloggers used in the monitoring procedure.

<table>
<thead>
<tr>
<th>Brand &amp; Model</th>
<th>Specifications</th>
<th>Temperature Sensor</th>
<th>Dew Point Temperature</th>
<th>Relative Humidity Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comet S3631</td>
<td>Range: -30 to 70 °C, ± 0.4 °C</td>
<td>-60 to 70 °C, ± 1.5 °C</td>
<td>0 to 100%, ± 2.5%</td>
<td></td>
</tr>
</tbody>
</table>

### 3.3 Monitoring Results

This section is dedicated to a detailed discussion of the results obtained from the long-term monitoring phase. The data collected during the period of the study is presented through several graphs and tables to facilitate a clearer understanding of the results. These include the monitored temperatures and relative humidity, alongside the computed specific humidity values.
As depicted in Figure 11, the exterior temperatures recorded throughout the monitoring period exhibit higher values than the interior temperatures during the summer season, and conversely, lower values compared to the interior temperatures in winter. This observation indicates that exterior temperatures demonstrate greater variability or extremes in comparison to interior temperatures. Moreover, the graph also illustrates that exterior temperatures closely correspond to interior temperatures during the summer season, whereas they diverge more significantly during the winter season.

Comparing the interior temperatures of probes 1, 2, and 3 with probe 4, it becomes evident that the chapel consistently recorded lower values compared to those observed in the Treasury. Additionally, the correlation between probe 4 and the exterior temperature reveals a stronger influence of external conditions on the chapel’s interior temperature. Conversely, the correlation between the probes within the Treasury and the exterior temperature indicates that the installed appliances in the Treasury effectively influence the internal microclimate.

Lastly, the analysis of the three probes located within the Treasury reveals that temperatures within the space exhibit similarity during the summer months, whereas they demonstrate wider variations during the winter season. The findings also indicate a direct relationship between the location of the probes and the monitored temperatures as lower spaces exhibit lower temperatures, while higher spaces tend to have higher temperatures.
Figure 12: Relative air humidity from probes 1, 2, 3, and 4.

Figure 12 exhibits notable distinctions in relative air humidity between the chapel and the Treasury. Throughout the monitoring period, the probe positioned in the chapel consistently registered higher values compared to those deployed within the Treasury. These differences can be attributed to the contrasting environmental conditions of the two spaces; the Treasury operates within a controlled microclimate, regulated with appliances, whereas the chapel remains uncontrolled and is subject to the conditions of the entire church. Additionally, variations in their internal temperatures further contribute to the observed differences in relative humidity levels. Typically, the Treasury experiences warmer conditions than the chapel, influencing the relative humidity monitored by the probes. It is important to note that temperature plays a pivotal role in determining relative humidity levels, given the dependency of relative humidity on temperature variations.

Analyzing the relative humidity levels monitored by the probes inside the Treasury, the data depicted in the graph indicates a pattern: lower areas (ex. Probe 1) generally exhibit slightly higher relative humidity levels compared to higher regions. Moreover, over the course of monitoring, these readings tend to converge during the summer season, suggesting similar humidity trends. In contrast, during the winter season, the readings exhibit more differences, indicating varying humidity levels across the different heights of the room.
Aside from the microclimate parameters gathered during the monitoring campaign, another crucial factor considered in this study is the specific humidity. This can be computed using temperature and relative humidity values, utilizing the following equation (Balík et al., 2020):

\[
a = 23.58 - \frac{4004.2}{2235.5 + T}
\]
\[
b = 2.7183^a
\]
\[
c = \frac{0.622 \times RH \times 0.01 \times b}{100000 - (RH \times 0.01 \times b)}
\]

\[
SH = c \times 1000
\]

where:
- \(a, b, \& c\) = required variables
- \(T\) = temperature
- \(RH\) = relative air humidity
- \(SH\) = specific air humidity

This parameter provides insights into the actual amount of moisture present in the air. As mentioned in the Section 2.2 of this study, specific air humidity is defined as the absolute amount of water in grams per kilogram of dry air (g/kg\text{dry air}) at a defined temperature (DST, 2019). Moreover, specific humidity has an important influence on the sorption properties of materials as it quantitatively describes the amount of moisture available in the air that materials can absorb. Unlike relative humidity, specific humidity is independent of temperature. This distinction highlights specific humidity's function as a reliable indicator the overall humidity level of an environment, whether humid or dry. Furthermore, relative humidity, in contrast, depends on temperature, making it less suitable for standalone analysis. For instance, high relative humidity can coexist with low specific humidity when temperatures are low, and vice versa. Therefore, relying solely on relative humidity for analysis may not provide a complete understanding of moisture conditions. By incorporating specific humidity with other monitored variables, a more comprehensive analysis of the microclimate behavior within the chapel and the treasury can be achieved.

Upon analyzing the computed specific humidity values, the results depicted in Figure 13 illustrate seasonal patterns within both the chapel and the Treasury. Generally, both spaces exhibit higher specific humidity levels during summer and lower levels during winter. An observation also is that the chapel consistently maintains higher specific humidity levels compared to the Treasury during the summer months, while their values converge more closely during the winter.
Additionally, within the Treasury, a comparison among the three probes reveals that during summer, lower areas exhibit higher humidity levels while higher areas show lower humidity levels. In contrast, during winter, this pattern reverses, with lower areas experiencing lower specific humidity and higher areas experiencing higher specific humidity, although the differences are relatively minor.

![Figure 13: Specific air humidity from probes 1, 2, 3, and 4.](image)

Another approach for analyzing and characterizing the microclimate behavior within the chapel and the Treasury involves identifying the average, median, minimum, and maximum readings of various parameters. This provides insights into the patterns and trends in temperature, dew point temperature, relative humidity, specific humidity, and specific humidity fluctuations over the duration of the monitoring period. This study considers these parameters across monthly (Table 4) and hourly (Table 5) intervals to have a detailed understanding how environmental conditions vary over time.

Table 4 provides an overview of the monthly exterior temperatures, resulting an average of 13 °C and a median of 14 °C. The lowest recorded monthly average of 2 °C occurred in December, while the highest, 22 °C, was observed in July. Regarding the interior temperatures, the data indicates that the chapel experiences lower temperatures than the Treasury. The chapel maintained an average temperature of 15°C, whereas temperatures in the Treasury ranged between 18 °C to 20 °C. In August, the chapel reached its maximum temperature of 22 °C while probe 2 inside the Treasury recorded the highest temperature among probes 1 to 3 with 25 °C during the same month. Moreover, the lowest
temperature obtained inside the chapel was 7°C in February while probe 1 registered the lowest temperature inside the Treasury with 11 °C also in the month of February.

Regarding the relative humidity, the average level in the chapel was observed to be significantly higher compared to the Treasury, averaging around 68% and 53% to 55% respectively. The peak relative humidity recorded in the chapel occurred in September at 86%, while probe 1 inside the Treasury recorded its highest relative humidity of 65% in August. Conversely, the lowest relative humidity observed inside the chapel was 58% in December, while among the three probes inside the Treasury, probe 2 recorded lowest at 44% during the same month.

For the specific humidity, probes 1 and 2 registered an average of 7.5 g/kg\textsubscript{dry air} while probes 3 and 4 obtained higher values of 8.2 g/kg\textsubscript{dry air} and 8.1 g/kg\textsubscript{dry air}. The maximum specific humidity value that the chapel obtained was 12.8 g/kg\textsubscript{dry air} in August while the probe 2 registered the highest in the treasury with 11.4 g/kg\textsubscript{dry air} during the same month. The lowest specific humidity value for the chapel was 3.9 g/kg\textsubscript{dry air} in December while probe 1 registered the lowest of 4.2 g/kg\textsubscript{dry air} also in the same month. In terms of the fluctuations in specific humidity, the differences between the probes in the chapel and the treasury are not that significant as probe 2 recorded 1.1 g/kg\textsubscript{dry air}, probes 1 and 3 had 1.2 g/kg\textsubscript{dry air}, and the chapel recorded 1.4 g/kg\textsubscript{dry air}. The highest fluctuation in the chapel was recorded at 2.5 g/kg\textsubscript{dry air} in September to October, while probes 1 and 2 both recorded the highest fluctuations inside the Treasury in September to October also. Lastly, the lowest fluctuations for the chapel were observed at 0.1 g/kg\textsubscript{dry air} in June to July, while probes 1 and 2 recorded the lowest fluctuations inside the Treasury at 0.4 g/kg\textsubscript{dry air} during the same months.

Table 4: Monthly average, minimum, maximum, and median values of temperature, dew point temperature, relative humidity, specific humidity, and specific humidity fluctuations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Exterior</th>
<th>Probe 1</th>
<th>Probe 2</th>
<th>Probe 3</th>
<th>Probe 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave. T</td>
<td>13 °C</td>
<td>18 °C</td>
<td>19 °C</td>
<td>20 °C</td>
<td>15 °C</td>
</tr>
<tr>
<td>Med T.</td>
<td>14 °C</td>
<td>17 °C</td>
<td>18 °C</td>
<td>20 °C</td>
<td>16 °C</td>
</tr>
<tr>
<td>Min. T</td>
<td>2 °C (Dec)</td>
<td>11 °C (Feb)</td>
<td>12 °C (Feb)</td>
<td>16 °C (Apr)</td>
<td>7 °C (Feb)</td>
</tr>
<tr>
<td>Max T</td>
<td>22 °C (Jul)</td>
<td>24 °C (Aug)</td>
<td>25 °C (Aug)</td>
<td>23 °C (Jul/Aug)</td>
<td>22 °C (Aug)</td>
</tr>
<tr>
<td>Ave. DP</td>
<td>9 °C</td>
<td>9 °C</td>
<td>11 °C</td>
<td>10 °C</td>
<td>10 °C</td>
</tr>
<tr>
<td>Med. DP</td>
<td>9 °C</td>
<td>9 °C</td>
<td>10 °C</td>
<td>10 °C</td>
<td>10 °C</td>
</tr>
<tr>
<td>Min. DP</td>
<td>1 °C (Feb/Dec)</td>
<td>1 °C (Dec)</td>
<td>6 °C (Apr)</td>
<td>0 °C (Feb/Dec)</td>
<td></td>
</tr>
<tr>
<td>Max. DP</td>
<td>15 °C (Aug)</td>
<td>16 °C (Aug)</td>
<td>15 °C (Aug)</td>
<td>18 °C (Sept)</td>
<td></td>
</tr>
<tr>
<td>Ave. RH</td>
<td>55 %</td>
<td>53 %</td>
<td>54 %</td>
<td>69 %</td>
<td>69 %</td>
</tr>
<tr>
<td>Med. RH</td>
<td>54 %</td>
<td>53 %</td>
<td>53 %</td>
<td>68 %</td>
<td>68 %</td>
</tr>
<tr>
<td>Min. RH</td>
<td>47 % (Dec)</td>
<td>44 % (Dec)</td>
<td>49 % (Nov)</td>
<td>58 % (Dec)</td>
<td></td>
</tr>
<tr>
<td>Max. RH</td>
<td>65 % (Aug)</td>
<td>64 % (Aug)</td>
<td>61 % (Aug)</td>
<td>86 % (Sept)</td>
<td></td>
</tr>
</tbody>
</table>
Table 5, on the other hand, provides a detailed breakdown of exterior temperatures. First, the hourly exterior temperatures averaged 13 °C with a median of 14 °C. The lowest hourly average was at -9 °C while the highest was recorded at 30 °C. Same as the monthly data, the chapel maintained lower temperatures compared to the Treasury, averaging 15 °C against 18 °C to 20 °C respectively. The chapel reached its highest temperature at 23 °C, whereas probes 2 and 3 registered the highest temperatures inside the Treasury at 26 °C. Conversely, the lowest interior temperature recorded was 5 °C for the chapel, and 6 °C for probe 1 inside the Treasury.

Regarding relative humidity, the hourly averages of the data obtained from the chapel and the Treasury are almost similar with those from the monthly averages. The highest relative humidity observed in the chapel was 91%, while probe 1 inside the Treasury recorded its peak at 65%. Conversely, the lowest relative humidity in the chapel was noted at 41%, whereas probe 2 within the Treasury registered the lowest at 33%.

In terms of specific humidity, probes 1 and 2 averaged 7.5 g/kg\textsubscript{dry air} and 7.6 g/kg\textsubscript{dry air} respectively, while probes 3 and 4 resulted to higher values at 8.4 g/kg\textsubscript{dry air} and 8.1 g/kg\textsubscript{dry air} respectively. The chapel recorded its maximum specific humidity at 14.4 g/kg\textsubscript{dry air}, whereas probe 2 in the Treasury peaked at 14.5 g/kg\textsubscript{dry air}. The lowest specific humidity values were 2.4 g/kg\textsubscript{dry air} for the chapel, and 2.5 g/kg\textsubscript{dry air} for probe 1 in the Treasury.

Fluctuations in specific humidity exhibited minimal differences between probes in the chapel and the Treasury across the average, median, and minimum values. However, the chapel recorded its highest fluctuation at 1.5 g/kg\textsubscript{dry air}, while probe 1 inside the Treasury registered its highest fluctuation at 2.2 g/kg\textsubscript{dry air}. 
Table 5: Hourly average, minimum, maximum, and median values of temperature, dew point temperature, relative humidity, specific humidity, and specific humidity fluctuations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Exterior</th>
<th>Probe 1</th>
<th>Probe 2</th>
<th>Probe 3</th>
<th>Probe 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave. T</td>
<td>13 °C</td>
<td>18 °C</td>
<td>19 °C</td>
<td>20 °C</td>
<td>15 °C</td>
</tr>
<tr>
<td>Med T.</td>
<td>14 °C</td>
<td>18 °C</td>
<td>19 °C</td>
<td>21 °C</td>
<td>16 °C</td>
</tr>
<tr>
<td>Min. T</td>
<td>-9 °C</td>
<td>6 °C</td>
<td>9 °C</td>
<td>14 °C</td>
<td>5 °C</td>
</tr>
<tr>
<td>Max T</td>
<td>30 °C</td>
<td>25 °C</td>
<td>26 °C</td>
<td>26 °C</td>
<td>23 °C</td>
</tr>
<tr>
<td>Ave. DP</td>
<td>9 °C</td>
<td>9 °C</td>
<td>11 °C</td>
<td>10 °C</td>
<td></td>
</tr>
<tr>
<td>Med. DP</td>
<td>9 °C</td>
<td>9 °C</td>
<td>11 °C</td>
<td>11 °C</td>
<td></td>
</tr>
<tr>
<td>Min. DP</td>
<td>-5 °C</td>
<td>-5 °C</td>
<td>-1 °C</td>
<td>-6 °C</td>
<td></td>
</tr>
<tr>
<td>Max. DP</td>
<td>19 °C</td>
<td>20 °C</td>
<td>19 °C</td>
<td>19 °C</td>
<td></td>
</tr>
<tr>
<td>Ave. RH</td>
<td>55 %</td>
<td>54 %</td>
<td>55 %</td>
<td>69 %</td>
<td></td>
</tr>
<tr>
<td>Med. RH</td>
<td>56 %</td>
<td>54 %</td>
<td>54 %</td>
<td>69 %</td>
<td></td>
</tr>
<tr>
<td>Min. RH</td>
<td>34 %</td>
<td>33 %</td>
<td>37 %</td>
<td>41 %</td>
<td></td>
</tr>
<tr>
<td>Max. RH</td>
<td>76 %</td>
<td>75 %</td>
<td>72 %</td>
<td>91 %</td>
<td></td>
</tr>
<tr>
<td>Ave. SH</td>
<td>7.5 g/kg</td>
<td>7.6 g/kg</td>
<td>8.4 g/kg</td>
<td>8.1 g/kg</td>
<td></td>
</tr>
<tr>
<td>Med. SH</td>
<td>7.4 g/kg</td>
<td>7.4 g/kg</td>
<td>8.4 g/kg</td>
<td>8.0 g/kg</td>
<td></td>
</tr>
<tr>
<td>Min. SH</td>
<td>2.5 g/kg</td>
<td>2.6 g/kg</td>
<td>3.7 g/kg</td>
<td>2.4 g/kg</td>
<td></td>
</tr>
<tr>
<td>Max. SH</td>
<td>14.3 g/kg</td>
<td>14.5 g/kg</td>
<td>14.1 g/kg</td>
<td>14.4 g/kg</td>
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</tr>
<tr>
<td>Ave. SH FL</td>
<td>0.1 g/kg</td>
<td>0.1 g/kg</td>
<td>0.1 g/kg</td>
<td>0.1 g/kg</td>
<td></td>
</tr>
<tr>
<td>Med. SH FL</td>
<td>0.1 g/kg</td>
<td>0.0 g/kg</td>
<td>0.1 g/kg</td>
<td>0.0 g/kg</td>
<td></td>
</tr>
<tr>
<td>Min. SH FL</td>
<td>0.0 g/kg</td>
<td>0.0 g/kg</td>
<td>0.0 g/kg</td>
<td>0.0 g/kg</td>
<td></td>
</tr>
<tr>
<td>Max. SH FL</td>
<td>2.2 g/kg</td>
<td>1.8 g/kg</td>
<td>2.1 g/kg</td>
<td>1.5 g/kg</td>
<td></td>
</tr>
</tbody>
</table>

3.4 Analysis of Gathered Data

Based on the results outlined earlier, this section provides a detailed analysis. This covers trends, critical periods, the potential impact of microclimate to the materials inside the Treasury and examines the factors influencing the microclimate inside both the Treasury and the chapel.

3.4.1 Trends

In this section, several observed trends observed from the data are to be discussed, namely seasonal trends, vertical gradients, and hourly behavior.

- **Seasonal Trend**

Looking across all probes, it is evident that both the chapel and the Treasury exhibit their highest internal temperatures in August and their lowest in February. This pattern closely aligns with the exterior
temperature, suggesting a direct influence of external conditions on the Treasury and chapel's internal microclimate.

In terms of the humidity levels, both relative air humidity and specific air humidity levels measured from all probes reach their peak in August and drop to their lowest levels in December. This indicates that the Treasury and the chapel experience excessively humid conditions in August and overly dry conditions in December. Tables 6 and 7 support this observation by illustrating that during summer and winter months, there are numerous days per month when the specific humidity values were extremely low or high. According to a study which discussed the optimal range of specific humidity for the conservation of sacred buildings, the lower limit is 6.5 g/kg_dry air, and the upper limit is 8.9 g/kg_dry air (Balík et al., 2020). The monitored values from the Treasury and the chapel consistently exceeded these limits.

Table 6: Number of days with specific humidity values lower than 6.5 g/kg_dry air.

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sept</th>
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<td>Probe 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>31</td>
</tr>
<tr>
<td>2022</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>2023</td>
<td></td>
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<td></td>
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<td>Probe 2</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>31</td>
</tr>
<tr>
<td>2022</td>
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<td>31</td>
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<td>0</td>
<td>7</td>
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<tr>
<td>2023</td>
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<td></td>
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<tr>
<td>Probe 3</td>
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<td></td>
<td>-</td>
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<td>-</td>
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<td>-</td>
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<td>-</td>
</tr>
<tr>
<td>2022</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
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<tr>
<td>2023</td>
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<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Probe 4</td>
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<td>29</td>
<td></td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2023</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Number of days with specific humidity values higher than 8.9 g/kg_dry air.

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sept</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
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<tr>
<td>Probe 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td>16</td>
<td>30</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2022</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>29</td>
<td>30</td>
<td>30</td>
<td>8</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>2023</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probe 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td>16</td>
<td>30</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2022</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>9</td>
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<tr>
<td>2023</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
To assess the differences of various parameters at different heights within the Treasury, understanding the vertical gradient is crucial. Analysis of the data from the probes reveals a distinct pattern: lower areas consistently exhibit cooler temperatures, whereas higher areas display higher temperatures. The analysis of relative humidity levels across different heights of the Treasury reveals a lack of discernible pattern, with minimal and insignificant variations observed. In contrast, specific humidity exhibits a clear trend: lower elevations generally feature lower specific humidity values, while higher elevations tend to display higher moisture levels. This behavior emphasizes the vertical distribution of moisture and highlights how specific humidity levels vary vertically within different elevations of the Treasury. Figure 14 visually represents this description. Furthermore, this observation highlights the importance of specific humidity measurements, as discussed in Section 3.3 of this study. It emphasizes that relying solely on relative humidity reading may overlook crucial variations in the actual moisture content of the air, where specific humidity levels can change even when relative humidity levels appear similar. Therefore, a comprehensive understanding of the vertical distribution of moisture in a space requires integrating relative humidity measurements alongside specific humidity data.

![Figure 14: Vertical gradient along the height of the Treasury based on hourly measurements.](image-url)
Hourly Behavior

Lastly, this discussion focuses on understanding the hourly patterns that influence the daily microclimate inside the Treasury. Focusing on relative air humidity and specific air humidity as the parameters, the average hourly data obtained from Probe 1 inside the Treasury from August and December are analyzed. These months were selected as they best represent the summer and winter months of the year as they exhibited the highest and lowest values of humidity among the other months.

Figure 15 illustrates that in August, relative humidity begins to rise at 7:00 in the morning, peaks at approximately 10:00, and starts declining from 18:00 onwards. While during the month of December, the increase in relative humidity starts later at 10:00 in the morning, reaches its peak by 11:00, and begins to decrease at 17:00. The graph also reveals that hourly fluctuations in relative humidity shows greater amplitude in December in contrast to August. This distinction can be attributed to the temperature variance between these two months, given that the relative humidity is significantly influenced by temperature levels.

In terms of specific humidity values, Figure 16 shows that the specific humidity in August observes the same hourly behavior as that of the relative humidity. However, in December, specific humidity values begin to decline at 9:00 in the morning, reach their lowest point at 11:00, and then starts increasing again by 17:00.

![Relative Humidity Hourly Behavior](Figure 15: Treasury's Probe 1 relative humidity hourly behavior.)
3.4.2 Critical periods

Building upon the identified trends, this section delves into the critical periods. Specifically, this includes the discussion on the risk of condensation, significant fluctuations, and periods when relative humidity and specific humidity levels exceed optimal environmental conditions for the conservation of sacred buildings and its elements.

- Risk of surface condensation

This irregularity is assessed by evaluating the relationships between air temperature, dew point temperature, and surface temperature. In the case of the chapel, analysis of the data reveals a possible risk of condensation from August to October (Figure 17). During these months, the recorded difference between the interior temperatures and the dew point temperatures is merely 2 °C. This slight margin is already considered to produce risk of surface condensation as this small difference falls within the accuracy range of the dataloggers used for monitoring. Surface temperature, although not directly measured in this study, is inferred to maintain close values to air temperature, typically within a variance of no more than 0.5 °C, as indicated by studies similar to this kind of spaces.
On the other side of the wall, the Treasury showed no condensation risk throughout the monitoring period, attributed to its controlled environment conditions. The monitored temperatures from the probes inside the Treasury are shown on Figures 18 to 20. This contrast highlights the effectiveness of the appliances installed in the Treasury, specifically the dryer and humidifier, in maintaining optimal environmental conditions.
Internal microclimate of the space of a sacred building

Figure 19: Exterior, interior, and dew point temperatures of probe 2 showing no risk of condensation throughout the monitoring period.

Figure 20: Exterior, interior, and dew point temperatures of probe 3 showing no risk of condensation throughout the monitoring period.
Significant fluctuations

Another important aspect influencing the microclimate of the Treasury occurs during the period of significant fluctuations of specific humidity on a monthly, daily, and hourly scale. These abrupt changes in environmental conditions, specifically on the amount of moisture in the air, impose internal stress on the building materials and artefacts within the Treasury, potentially compromising their general conditions.

Interpreting the monthly microclimatic behavior of the treasury through the specific humidity fluctuations, it can be observed that during the summer months, the space experiences heightened fluctuations and increased humidity levels, hence greater instability of environmental condition. Conversely, winter brings about fewer fluctuations and lesser humidity levels, resulting to drier conditions. Figure 21 shows these fluctuations across all probes inside the Treasury.

Furthermore, upon comparing the fluctuation patterns monitored in both the chapel and the Treasury, it can be observed that the chapel generally exhibited more pronounced fluctuations throughout the entire monitoring period (Figure 22). This is expected due to the difference in their environment. However, an incident occurred in August 2023 when the appliance (dryer) in the Treasury did not function, worsening its environmental conditions in contrast to those of the chapel. This problem was intensified by the Treasury’s enclosed environment, which restricted natural ventilation and air circulation.
In addition, it is also evident that fluctuations in both spaces tend to reach higher values during the summer months compared to the relatively more stable observed during winter.

![Specific Humidity Monthly Fluctuations](image)

Figure 22: Comparison of specific humidity monthly fluctuations between the chapel and the Treasury.

Zooming into a smaller scale, the specific humidity daily fluctuations highlight two critical observations. First, there are higher values on the vertical axis at 10.0 g/kg dry air, contributing to the disparity between the fluctuations within the chapel and the Treasury. And secondly, the microclimate conditions inside the Treasury exhibit weekly patterns, pinpointing specific days when major fluctuations occur.

In Figure 23, the chapel shows greater daily variations compared to its monthly averages, whereas the Treasury maintains the same ranges. Additionally, it emphasizes the substantial influence of the appliances installed in the Treasury, which accounts for the significant discrepancy in specific humidity fluctuations observed between the two spaces.
Figure 23: Comparison of specific humidity daily fluctuations between the chapel and the Treasury.

Analysis shown in Table 8 reveals that fluctuations within the Treasury predominantly occur during weekends (Saturday and Sunday) and the first days of the week (Monday and Tuesday). This suggests that these days likely experience activities within the Treasury that significantly alter its microclimate such as increased public visitation, maintenance operations, or appliance usage.

Table 8: Calendar days which exhibited significant specific humidity daily fluctuations inside the Treasury.

<table>
<thead>
<tr>
<th></th>
<th>Mon</th>
<th>Tue</th>
<th>Wed</th>
<th>Thu</th>
<th>Fri</th>
<th>Sat</th>
<th>Sun</th>
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<td>19</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>21</td>
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Lastly, delving into a finer scale, the analysis of hourly fluctuations in specific humidity within the Treasury indicated how the daily schedule of the space influences its microclimate conditions throughout the day. Figure 24 illustrates that during the summer season (represented by August), fluctuations commence at 7:00 in the morning and 18:00 in the afternoon. Conversely, in winter (represented by December), fluctuations begin at 9:00 in the morning and 17:00 in the afternoon. This pattern suggests that hourly variations in specific humidity are tied to the opening and closing hours of the Treasury or the cathedral itself.

During summer, fewer number of visitors contribute to drier air, while increased foot traffic results in higher humidity levels. On the other hand, in winter, the data indicated that the Treasury becomes drier during operational hours. This observation implies that the appliances (dryer and humidifier), may not be appropriately programmed to align with the microclimatic conditions of the Treasury at this period of the year and may require necessary adjustments.

![Figure 24: Hourly fluctuations of specific humidity within the Treasury, illustrating seasonal trends during summer and winter seasons.](image)

- Periods exceeding optimal environmental conditions

Another critical aspect of the Treasury’s microclimate is the occurrence of relative humidity and specific humidity values that exceed optimal environmental conditions. Various studies in the conservation of built heritage propose different humidity thresholds, but this study adopts limits recently established for the Sedlec Cathedral. For the relative humidity, the limits are suggested at 50% to 60% (Balík et al.,...
2020). As depicted in Figure 25, the relative humidity levels within the Treasury frequently exceed the recommended lower and upper thresholds, particularly during the summer and winter season.

![Relative Humidity Chart](image)

Figure 25: Relative humidity values with the thresholds of 50% and 60%.

For specific humidity, the suggested limits are 6.5 g/kg$_{\text{dry air}}$ and 8.9 g/kg$_{\text{dry air}}$ (Balík et al., 2020). Similarly, Figure 26 reveals that specific humidity values within the Treasury repeatedly exceed the lower and upper limits throughout the year, with extreme values occurring during summer and winter.

![Specific Humidity Chart](image)

Figure 26: Specific humidity values with the thresholds of 6.5 g/kg$_{\text{dry air}}$ and 8.9 g/kg$_{\text{dry air}}$. 
3.4.3 Impact of microclimate to materials

The issues discussed in the previous section significantly impact the state of the materials housed within the Treasury. These materials include various building components such as stones, plaster, and paints, as well as historical artefacts like the gilded silver monstrance and a replica of the Virgin Mary painting by the Master of Třeboň Altar from the late 14th century (painted on wood), along with foundational documents of the monastery. These materials are particularly vulnerable to major fluctuations and extreme humidity and dryness. Hence, mitigating these environmental factors are crucial to the preservation of the integrity and longevity of these invaluable cultural and historical assets.

Wide fluctuations in both relative humidity and specific humidity levels can lead to rapid changes in the moisture content of these materials, therefore altering their equilibrium moisture content. With increasing humidity, the moisture content within these materials tends to rise, and conversely, it decreases as humidity levels drop. These rapid fluctuations contribute to possible dimensional changes, such as expansion and contraction, which can lead to internal stresses that may manifest as cracks. Specifically for stones, wide fluctuations in humidity can lead to the formation of efflorescence due to the accumulation of salts caused by condensation and evaporation cycles. Paintings are similarly vulnerable, with such fluctuations potentially causing fractures and deformations.

Excessive levels of specific humidity also accelerates the degradation process of these materials. Too humid conditions may facilitate the absorption of moisture into these materials. For stones, high humidity levels foster the development of bio-organisms, and it also increases the risk of corrosion for certain minerals, leading to the formation of stains. Conversely, overly dry environments can render materials brittle, particularly affecting paintings, and contribute to overall drying out of the materials. These scenarios increase the materials’ vulnerability to cracking.

The Treasury exhibits no evidence of surface condensation, whereas data from the adjacent chapel indicates recurring instances across the monitoring period. This contrast highlights the effectiveness and the importance of implementing measures to regulate the microclimate within a space to promote its preservation.

To summarize this section, the materials housed within the Treasury are particularly vulnerable to wide fluctuations in both relative and specific humidity levels, as well as to extreme levels of both parameters. Importantly, there is no observed susceptibility against surface condensation.
3.4.4 Basic influences that affect the microclimate

Based on the analysis of all the data, three primary factors have been identified that significantly affect the internal microclimate behavior of the Treasury: exterior temperature, operations, and internal environmental setting.

The exterior temperature dictates the internal temperature within the Treasury. This relationship is clearly illustrated in Figure 27, where a strong correlation between external and internal temperatures is evident based on weekly average readings.

Another significant factor influencing specific humidity levels is the operational dynamics of the Treasury, which is closely tied to the functioning of the cathedral. Analysis of Table 8 and Figure 24, depicting daily and hourly specific humidity fluctuations respectively, indicates a correlation between potential shifts in operational conditions and changes in specific humidity levels. Specifically, observations from Table 8 highlight distinct fluctuations in daily specific humidity levels during weekends, coinciding with potential alterations in Treasury operations, such as opening its doors to the rest of the cathedral for increased accessibility to visitors. Similarly, Figure 24 further illustrates fluctuations in specific humidity corresponding to presumed opening and closing hours of the Treasury, suggesting a direct relationship between operational schedules and environmental moisture levels.

It should be noted, however, that this study does not investigate whether human presence directly influences the observed fluctuations in specific humidity values. This aspect presents a potential area
for future research endeavors, as investigating the impact of visitor activities on microclimatic conditions could provide valuable insights for the management and conservation of the Treasury and its artefacts.

Moreover, another important factor is the internal environmental setup of the Treasury itself. This aspect encompasses controlled conditions maintained through appliances such as dryer and humidifier. The comparative analysis on the specific humidity fluctuations between the Treasury and the chapel highlights the contrast between controlled and uncontrolled environment (see Figure 23). Factors like natural ventilation and air circulation are integral components within this context.

Exterior temperature, operations, and environmental setting are critical considerations to mitigate their adverse effects on the internal microclimate of the Treasury. Implementing effective climate control measures should be considered to sustain an optimal environment conducive to the preservation of the Treasury and its elements.

### 3.5 Practical Design Proposal

As a core objective of this study, this section discusses the recommendations and practical measures aimed to enhance the internal microclimate of the Treasury. This study primarily proposes that a switching control system be implemented to address the issues related to wide fluctuations and extreme humidity levels. The proposed system aims to effectively regulate the operation of dryers and humidifiers within the Treasury. It functions by dynamically determining the activation and deactivation times of these appliances based on real-time specific humidity levels. The main goal is to maintain specific humidity values within the predetermined upper and lower thresholds, as illustrated in Figure 26. This regulatory framework mainly requires setting limits on fluctuations in specific humidity levels to ensure stability and preservation of the Treasury and the materials housed within.

In practice, the switching control system is envisioned to manage fluctuations across different time scales – weekly, daily, and hourly. This approach aims to impose specific limits on these fluctuations: 1.2 g/kg$_{dry}$ air for weekly fluctuations, 0.6 g/kg$_{dry}$ air for daily fluctuations, and 0.2 g/kg$_{dry}$ air for hourly fluctuations. These stabilization thresholds are identified based on the analysis of specific humidity data, with each limit designed to encompass approximately 10% of the dataset exhibiting the most significant fluctuations. Visual representations of these thresholds can be found in Figures 28 to 30. For example, the weekly limit of 1.2 g/kg$_{dry}$ air corresponds to the top 10% (rounded off for simplicity) of the data points that display the highest weekly fluctuations. This translates to about 13 readings out of 97, highlighting instances where humidity fluctuations exceed the specified threshold. Similar principles are suggested to be applied to daily and hourly fluctuations.
Figure 28: Specific humidity weekly fluctuations with stabilization threshold of 1.2 g/kg dry air.

Figure 29: Specific humidity daily fluctuations with stabilization threshold of 0.6 g/kg dry air.
Considering the observed trends within the Treasury’s microclimate behavior, the following operational guidelines are additionally recommended:

- During winter, where the space is characterized by excessively dry conditions, it is advised to put the humidifier in use. This aims to elevate humidity levels within the acceptable limits. Despite an existing humidifier installed in the Treasury, the study suggests adding or replacing it with a more advanced model, as current data still shows humidity levels below the lower threshold of 6.5 g/kg dry air, suggesting the current humidifier’s inefficiency.

- Conversely, in summer, when conditions tend to be overly humid, utilizing dryers is recommended to lower humidity levels within the acceptable limits. Like the humidifier, upgrading the current dryer in place or adding an additional unit is advised due to persistent humidity levels exceeding the upper limit of 8.9 g/kg dry air.

Despite the generally stable conditions indicated by Figures 28 to 30, which that there are no rapid changes, there remains room for improvement in the environmental stability, particularly concerning specific humidity levels that do not consistently meet the defined upper (8.9 g/kg dry air) and lower (6.5 g/kg dry air) limits. The proposed fluctuation thresholds of 1.2 g/kg dry air, 0.6 g/kg dry air, and 0.2 g/kg dry air are stringent but these are designed to establish and maintain a stabilized environment. The objective is to
reduce instances where specific humidity levels fall outside the upper and lower bounds, thereby enhancing the overall internal microclimate of the Treasury.

Finally, in addressing maintenance and remediation strategies, it is advisable to enhance ventilation and air circulation within the Treasury during periods of appliance inactivity to mitigate potential increases in humidity levels and wide fluctuations. However, this approach must be implemented cautiously, especially considering that air exchange with the cathedral environment could impact the microclimate within the Treasury. Real-time monitoring under such circumstances is crucial, as it ensures that adjustments to ventilation methods are beneficial rather than detrimental to the conservation of the Treasury and its artefacts.

By implementing these strategies, the study aims to improve the internal microclimate of the Treasury, thereby enhancing the sustainability and longevity of its cultural heritage. These measures are crucial for safeguarding the space against the detrimental effects of both extreme and fluctuating humidity levels over time.
4. CONCLUSION

The findings of this study highlight the significance of studying internal microclimate within the context of heritage conservation. Central to this understanding is the important role of monitoring, which serves as the foundational step necessary to establish a comprehensive database. This database, in turn, forms the basis upon which enhancements to the microclimate conditions of historical structures can be effectively planned and implemented.

Specifically, the analysis of the microclimate behaviors of the Treasury and the adjacent chapel reveals that environmental setting has a significant impact on a space’s internal microclimate condition. The Treasury being in a controlled environment as an enclosed space equipped with appliances such as the dryer and humidifier shows better microclimate behavior than the chapel which is an uncontrolled one as it is directly open to the rest of the area of the church. The chapel experiences more extreme relative and specific values and wider fluctuations compared to the Treasury. The chapel also experiences risk of surface condensation, whereas the Treasury does not.

However, even if the Treasury is exhibiting better microclimate conditions, the data still shows that the Treasury is experiencing pronounced fluctuations and extreme humidity levels throughout the year, with peaks occurring in August and December. The fluctuations observed in specific humidity levels have significant implications to the preservation of the materials housed within the Treasury. This includes not only the architectural components such as stones and plasters but also the artefacts contained inside the Treasury. While the immediate effects on these materials may not be apparent, long-term deterioration can manifest due to internal stresses induced by changes in their equilibrium moisture content, leading to cycles of expansion and contraction.

The current humidifier and dryer systems installed in the Treasury are inadequate, and further aggravated by ineffective operational schedules that do not sufficiently regulate humidity fluctuations. As a result, supplementary measures are necessary to be employed. Addressing these challenges requires the implementation of a specialized switching control system tailored to the specific microclimate characteristics and behavior observed within the Treasury.

To improve the internal microclimate conditions of the Treasury, a proposed strategy involves implementing stringent controls on specific humidity fluctuations across weekly, daily, and hourly time frames. These limits are particularly designed and calibrated based on the monitored specific humidity levels. The implementation of this control mechanism hinges on specific humidity thresholds, tailored to stabilize the internal environment of the Treasury. Additionally, this specific humidity-dependent strategy aims to establish a responsive control system that effectively regulates the use of the appliances within the Treasury, thereby mitigating the detrimental effects associated with humidity extremes and fluctuations. This proactive approach is essential for the conservation of the Treasury’s architectural and historical integrity for future generations.
Internal microclimate of the space of a sacred building
5. REFERENCES


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