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

Keywords: church typology; humidity

1. Introduction

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

In the study of the microclimate of seven Latvian churches, possible risks of condensation on the inner surfaces of external walls and ceilings were calculated at three different room temperatures and three different indoor relative humidities, where the materials and dimensions of the enclosing structures were taken from the Krimulda (LV) church [1]. Such a calculation does not give a complete picture of the possible formation of condensation risks in churches, because each church could have different materials and dimensions of the surrounding structures. In order to determine the risks of condensation on the internal walls and ceilings of buildings during periods of low temperature, it is necessary to take into account both the outdoor and indoor air temperatures, as well as the types and thicknesses of the enclosing construction materials. In Latvia, one of the three leading denominations—Lutheran—has 337 religious buildings [4–7]. There are several types of materials for the enclosing structures of these cult buildings, and their thicknesses are also different. Houses of worship in Latvia have been built since 1198, and accordingly, the construction technologies of these buildings have changed over the course of several hundred
years. Cultural and historical heritage cult buildings often have a specially protected status according to the Latvian Law of 1992 “On the Protection of Cultural Monuments”, as a result of which the exterior doors or windows of the cult building can only be restored and replaced with new ones that are more energy-efficient and air-tight is not allowed.

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

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

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

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

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

2. Literature Review

Historical buildings, such as castles, mosques and churches, require careful handling to preserve their cultural and historical value. The methodology of historical building analyses is complicated by the usage of ancient materials, the presence of artworks and a lack of documentation [15]. An important conservation factor is the indoor environmental parameters. Most of them comprise temperature and humidity. High humidity and temper-
ature will cause biodeterioration—a material destruction process caused by microbes [16] and fungi [17].

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

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

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

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

3. Materials and Methods

3.1. Creation of a Typology of Cult Buildings

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

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

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

- From 13 October 2021 to 27 December 2021 and from 10 January 2022 to 7 July 2022—Krimulda church, with exterior masonry walls and both brick and wooden vaulted ceilings. The Krimulda Church is a popular tourist attraction in Latvia, and its doors are open to tourists 24 h a day, 7 days a week, 365 days a year, which could give complete assurance about the influence of outdoor air humidity on the indoor climate. The church is located 45 km from Riga to the East.
• From 10 January 2022 to 7 July 2022—the Turaida church, with exterior walls of wooden logs and a wooden covered ceiling, is located in the territory of the Turaida Museum Reserve and is open six days a week for museum visitors from 10:00 a.m. to 6:00 p.m. The church is located 47 km from Riga to the East.

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

![Image of HOBO MX Temp/RH/Light/Ext-Temp Kit](image1.png)

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

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

![Image of HOBO MX instruments on the outer wall](image2.png)

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

![Image of HOBO MX instruments on the ceiling arch](image3.png)

**Figure 3.** Example of mounting HOBO MX measuring instruments on the ceiling arch.
In the Turaidas church, one measuring device was placed in the middle of the room on a chandelier at a height of 2.7 m from the floor shown in Figure 6.

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

$$\Delta_v = v_i - v_e$$

(1)

where $v_i$ is the humidity by volume of indoor air (g/m$^3$) and $v_e$ is the humidity by volume of outdoor air (g/m$^3$) [9].
From the thirty-minute interval data, the average moisture excess was calculated for each hour, so the hourly moisture excess data was used in the analysis. To analyze the dependency of moisture excess on the outdoor climate and to eventually determine the critical moisture excess values, the data for each place were sorted separately—according to the outdoor air temperature, using a 0.1 °C increment of the outdoor temperature. From these sorted values, maximum, minimum, mean and 10% critical levels (90% percentile and 10% percentile) for each place and temperature were determined.

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

4. Results and Discussion
4.1. Typology of Cult Buildings

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

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

<table>
<thead>
<tr>
<th>Churches Building Period</th>
<th>Total</th>
<th>13 c.</th>
<th>14 c.</th>
<th>15 c.</th>
<th>16 c.</th>
<th>17 c.</th>
<th>18 c.</th>
<th>19 c.</th>
<th>20 c.</th>
<th>21 c.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single span</td>
<td>238</td>
<td>7</td>
<td>1</td>
<td>4</td>
<td>8</td>
<td>41</td>
<td>52</td>
<td>85</td>
<td>37</td>
<td>3</td>
</tr>
<tr>
<td>Two-span</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Three-span</td>
<td>23</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>7</td>
<td>3</td>
<td>7</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Cross</td>
<td>8</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Central</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Incl. wooden</td>
<td>26</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Churches Building Period</th>
<th>Separating Wall with Arch</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 c.</td>
<td>6</td>
</tr>
<tr>
<td>14 c.</td>
<td>-</td>
</tr>
<tr>
<td>15 c.</td>
<td>2</td>
</tr>
<tr>
<td>16 c.</td>
<td>5</td>
</tr>
<tr>
<td>17 c.</td>
<td>13</td>
</tr>
<tr>
<td>18 c.</td>
<td>2</td>
</tr>
<tr>
<td>19 c.</td>
<td>1</td>
</tr>
</tbody>
</table>
• The construction period; since the 13th and 14th centuries, wall thicknesses for masonry churches are greater than for 19th century buildings. In the 19th century, brick was more widely used (see Table 3). The thermal conductivity $\lambda$ of the enclosing structures was determined in accordance with the building code of Latvia [28]. The types of enclosing structures in churches of the 20th and 21st centuries are very numerous and different, but none of the churches of this period have the status of cultural and historical heritage, and therefore were not included in this study;

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

<table>
<thead>
<tr>
<th>Churches Building Period</th>
<th>Brick/Stone (Homogeneous)</th>
<th>Wood (Homogeneous)</th>
<th>Wood (Inhomogeneous)</th>
<th>Brick Vault (Homogeneous)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.gs.</td>
<td>1.5 m–2 m</td>
<td>0.87 (W/m·K)</td>
<td>0.2 m</td>
<td>0.15 m</td>
</tr>
<tr>
<td></td>
<td>0.87 (W/m·K)</td>
<td>-</td>
<td>0.2 m</td>
<td>0.15 m</td>
</tr>
<tr>
<td>14.gs.</td>
<td>1.5 m–2 m</td>
<td>0.87 (W/m·K)</td>
<td>0.2 m</td>
<td>0.15 m</td>
</tr>
<tr>
<td></td>
<td>0.87 (W/m·K)</td>
<td>-</td>
<td>0.2 m</td>
<td>0.15 m</td>
</tr>
<tr>
<td>15.gs.</td>
<td>1.5 m–2 m</td>
<td>0.87 (W/m·K)</td>
<td>0.1–0.3 (W/m·K)</td>
<td>0.14 m</td>
</tr>
<tr>
<td></td>
<td>0.87 (W/m·K)</td>
<td>-</td>
<td>0.1–0.3 (W/m·K)</td>
<td>0.14 m</td>
</tr>
<tr>
<td>16.gs.</td>
<td>1.5 m–2 m</td>
<td>0.87 (W/m·K)</td>
<td>0.14 m</td>
<td>0.14 m</td>
</tr>
<tr>
<td></td>
<td>0.87 (W/m·K)</td>
<td>-</td>
<td>0.1–0.3 (W/m·K)</td>
<td>0.14 m</td>
</tr>
<tr>
<td>17.gs.</td>
<td>0.87 (W/m·K)</td>
<td>0.2 m</td>
<td>0.13 (W/m·K)</td>
<td>0.14 m</td>
</tr>
<tr>
<td>18.gs.</td>
<td>0.87 (W/m·K)</td>
<td>0.13 (W/m·K)</td>
<td>0.2 m</td>
<td>0.13 m</td>
</tr>
<tr>
<td>19.gs.</td>
<td>0.87 (W/m·K)</td>
<td>0.13 (W/m·K)</td>
<td>0.2 m</td>
<td>0.12 m</td>
</tr>
<tr>
<td>20.gs.</td>
<td>different</td>
<td>different</td>
<td>different</td>
<td>different</td>
</tr>
<tr>
<td>21.gs.</td>
<td>different</td>
<td>different</td>
<td>different</td>
<td>different</td>
</tr>
</tbody>
</table>

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

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

<table>
<thead>
<tr>
<th>Room</th>
<th>Ceilings from Wood Construction Vault</th>
<th>Ceilings from Brick Vault</th>
<th>Straight Wooden Ceiling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altar room</td>
<td>103</td>
<td>43</td>
<td>129</td>
</tr>
<tr>
<td>Parish room</td>
<td>107</td>
<td>29</td>
<td>139</td>
</tr>
</tbody>
</table>

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

4.2. Moisture

Relative humidity and temperature measurements in Krimluda church were made with two measuring devices, taking into account the high ceiling, $h = 7$ m, and the orienting air flow on the hall and balcony ceilings found in the previous study [1]. Therefore, one measuring device was installed in the arch of the balcony, which separates the ceiling of the balcony and the hall, and the other measuring device was installed at the outer wall of the hall, where the firewood heating tap is located. 13 m away. The temperature increases shown in the graph in Figure 7 are related to the heating of the room once a week on Sundays (for example: 17 October 2021 01:30 p.m.), when the temperature
differences (+5.366 °C) on the outer wall (+15.697 °C) are also expressed, as well as on
the balcony (+21.063 °C), which confirms the flow of warm air and the large heat losses
found in the tower part of the balcony. On the other hand, there are differences in relative
humidity fluctuations also at these same moments of the temperature fluctuations and
when comparing the specific data in each of these measurements. For example: 17 October
2021 01:30 p.m.—on the balcony relative humidity 44.9638% temperature 21.063 °C and on
the grass wall relative humidity 62.36% temperature 15.697 °C; putting these measurements
on the Mollier diagram, it can be established that the absolute air humidity g/kg is the
same. Accordingly. we can conclude from this that relative humidity fluctuations affect
large temperature fluctuations. and in order to be able to analyze and evaluate humidity
fluctuations, it is necessary to compare the effect of the actual moisture content of the
outdoor air on the indoor air.

![Plot showing humidity and temperature measurements in Krimulda church.](image)

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

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

Indoor temperature and relative humidity measurements were collected and statis-
tically analyzed. Outdoor air parameters were taken from the “Latvian Environment.
Geology and Meteorology Center” database station in Sigulda, 10 km away from both
druches. As you can see in Figures 9 and 10, the distribution density of the measurement
points is very different, so in Figures 11–13, 10–90% data filtering is used for the minimum,
maximum, and average, as well as 10 and 90% excess humidity between the rooms and outside, depending on the temperature.

As it can be seen in Figures 8–10, the excess moisture in relation to the outdoor air temperature from −10 to +15 °C is hardly noticeable. But in the outdoor air temperature range from +15 to 30 °C, there is visible moisture increase. The excess outdoor air humidity for 90% values in the temperature range from −10 to +15 is from 0 to 3 g/m³, while in the temperature range from +15 to 30 °C it is from 0 to 6 g/m³. Looking at and comparing all three in Figures 11–13, we did not see any significant difference in these fluctuations of excess moisture from the outdoor air temperatures, and all three graphs are very similar, since the measurements were made in the same time period. The similarity of these graphs confirms that the increase and fluctuation of excess moisture is not related to local moisture release that could be brought to these two different sites by the different number of tourist visitors. Additionally, the similarity of these graphs confirms that there is a large natural infiltration of outdoor air. Moisture is not related to the local moisture release that could be brought to these two different sites by the different number of tourist visitors. Additionally, the similarity of these graphs confirms that there is a large natural infiltration of outdoor air.
Figure 10. Moisture excess in Turaida church on the lamp.

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

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

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

5. Conclusions

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

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

Author Contributions: Conceptualization, A.L. and A.B.; methodology, A.L.; software, A.B.; validation, M.M. and A.P.; formal analysis, M.M.; investigation, M.M. and A.B.; resources, A.B.; data curation, M.M. and A.P.; writing—original draft preparation, M.M. and A.P.; writing—review and editing, A.L. and A.B.; visualization, M.M.; supervision, A.L. and A.B.; project administration, A.B.; funding acquisition, A.B. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the European Social Fund within the Project No 8.2.2.0/20/I/008 «Strengthening of PhD students and academic personnel of Riga Technical University and BA School of Business and Finance in the strategic fields of specialization» of the Specific Objective 8.2.2 «To Strengthen Academic Staff of Higher Education Institutions in Strategic Specialization Areas» of the Operational Programme «Growth and Employment».

Institutional Review Board Statement: The study did not involve humans or animals.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.