Microclimate Conditions in the SS. Salvatore Church of Bologna

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Abstract

This paper analyses the microclimate conditions in the Church of Santissimo Salvatore in Bologna and their influence on the acoustics of the Church and the sound of the pipe organ. It is commonly acknowledged that the variation of air temperature, median radiant temperature, relative and absolute humidity could provoke thermal expansions of metals which are used for the organ pipes. This paper analyses a monitoring campaign which lasted one year in which temperature and relative humidity were stored with a data logger. Moreover, the paper shows the effect in the variation of the microclimate conditions in the church by simulating different numbers of people in the church and different thermal conditions outdoor. Finally, the paper reports the variations of the acoustic parameters simulating the new values of temperature, relative humidity and air velocity.

1. Introduction

While historical buildings are extremely valuable, managing their environs may be difficult. This is mostly because restoring them can be expensive and complex, especially when it comes to major buildings like churches. Visible areas are typically given priority in current restoration projects, leaving many older materials unrepaired or only partially restored. This leads to a lack of progress in confronting invisible parts of indoor environmental control. Many churches experience rapid temperature variations as a result of overheating, and severe effects on their interiors are also a result of lack of control over external factors. This creates problems for both the preservation of these areas' valuable cultural heritage and the proper use of their cultural value. Microclimate investigations in Italian churches have been reported in several studies (Aste et al., 2019; Poljak & Ponechal, 2023; Aste et al., 2016). However, it can be said that there is still insufficient information to discuss practical measures for appropriate operation and preservation effectively.

Organ tuning is typically influenced by temperature. Metal pipes not only expand with environmental changes but also, as the air temperature inside the pipes fluctuates, the speed of sound changes significantly, affecting the pitch of the organ pipes. A temperature variation of 10 degrees can result in approximately a one-third semitone change. It might be argued that discussing the appropriate preservation and best use of historical organs is difficult without first managing interior settings properly.

Thermo-hygrometric variables are one of the various variables that influence acoustic parameters. The impact of temperature and humidity has been examined in the realm of voice alarm systems (Gomez-Agustina et al., 2014), and in voice reproduction systems (Yang & Moon 2018). Their findings indicated that higher temperatures and humidity levels led to an increase in reverberation time, particularly at high frequencies (Yan & Tronchin, 2025). Consequently, parameters associated with speech were observed to decrease as temperatures and humidity values rose. In our previous research, experimental and statistical analysis was conducted on the influence of temperature, humidity, and air velocity to room acoustic parameters and showed the formulas for calculating each acoustic parameter (Tronchin, 2021).

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2. A Brief History and Case Study Overview

Italian churches are rich cultural assets, but investigations trying to identify and best use their distinctive worth remain behind due to their complexity. Not every place can recreate the music of that era on-site. Though Bologna is the only place in Italy with a significant concentration of Renaissance to early Baroque organs, there have been almost no recent studies on organs, acoustics, churches as musical surroundings, and microclimates for preservation.

The Santissimo Salvatore Church (via Cesare Battisti, 18, 40123 Bologna) originated as the Canonici Regolari monastery in the fourteenth century. It developed into a large monastery with a bell tower, a church, a theater, an extensive library, and three courtyards in the fifteenth century. The church was fully renovated in the early years of the 17th century, constructing the current building. Magnificent works of art from the 12th to the 16th centuries, including works by Guercino and others, are housed inside the church (Fini, 2007). Designed between 1605 and 1623 by architect Tommaso Martelli with assistance from Padre Giovanni Ambrogio Mazenta, who also worked on Bologna's San Pietro Cathedral, the present church edifice is one of the city's largest and is distinguished by its early Baroque style (Zaccanti, 1995). The church's main construction was damaged by lightning and battle in the 18th and 19th centuries, but it has since undergone multiple renovations to return to its former shape as his masterwork. The church underwent its most recent restoration in 2000. Without the dome, the church's interior measurements are roughly 60 meters long, 28 meters wide, and 26 meters tall. Inside, there is a single, spacious nave with eight side chapels, massive pillars, a large number of windows, and four raised balconies for music, as well as two antique organs from that era.

This church's importance stems from the fact that it is Bologna's oldest originally intact musical setting, created in the early Baroque era especially for separated choirs. In fact, it produces a reverberant ambiance that provides a rich background for religious music.

3. Methods and Tools

3.1 Measurements of the Microclimate

To better understand the real environment in which the organ is located, the temperature and relative humidity in the church were observed using small data loggers (RC-51H by Elitech, London, UK) at intervals of 10-15 minutes throughout the year 2023. On the front of one organ (in cornu epistolae: 9.3 meters above floor level on the eastern wall of the southern transept) long-term measurements were made. The outside condition was derived from data from the Arpae (https://www.arpae.it/) regional weather station located in the heart of Bologna.

Fig. 1 – Data logger on the front of organ

3.2 Indoor and Outdoor Thermal Simulation Conditions

The program IES.VE (www.iesve.com/) was used to simulate the church's interior setting. The most recent weather data for Bologna was obtained from climate.onebuilding.org; it was last updated in 2021. A simplified internal structure model of the church was created in IES.VE, all internal environmental parameters were computed based on the external condition. Using Apache, the temperature and humidity for the entire year were computed, and at specific periods, MicroFlo-CFD was used to simulate air velocity. Due to variations in the population (0, 10, 100, and 500), the daily hours were fixed from 8:00 to 18:00. The output data for each parameter from the simulation was obtained hourly.

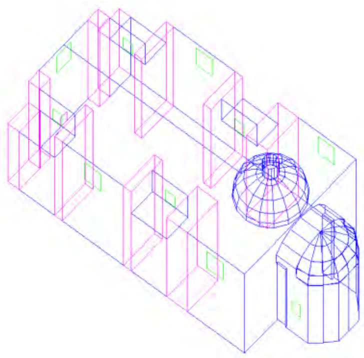

Fig. 2 – Simulation 3D model of the church in IES.VE software

3.3 Modelling of Acoustic Parameters

Regression equations derived from prior study data on the link between temperature, relative humidity, and air velocity and acoustic parameters were used to do this (Tronchin, 2021). Every octave band has a different coefficient value. Temperature readings of 26.88 to 31.77 degrees Celsius (mean 30.28), humidity values of 37.8 to 54.7 % (mean 43.52 %), and air velocity values of 0 to 0.56 m/s (mean 0.15 m/s) were the range of measurement data used in this formula. The values of the input variables match the variation in the mean values.

$$y = A + B_1(\Delta t) + B_2(\Delta t)^2 + B_3(\Delta t)^3 + C_1(\Delta u) + C_2(\Delta u)^2 + C_3(\Delta u)^3 + D_1(\Delta v) + D_2(\Delta v)^2 + D_3(\Delta v)^3 \quad (1)$$

Using Apache data, the acoustic parameters for the full year were calculated without taking into account the values D1 to D3, which presuppose a zero-air velocity. Air velocity measurements ranging from D1 to D3 were included in order to evaluate the impact of occupancy.

Table 1 – Regression Coefficient for Reverberation Time T30

Input variable	-	Δt	Δt2	Δt3	Δu	Δu2	Δu3	Δv	Δv2	Δv3
Coefficients	A	B_1	B_2	B_3	C_1	C_2	C_3	D_1	D_2	D_3
125Hz	2.417				-0.018					
250Hz	2.95			-0.006	0	-0.003				
500Hz	2.813									4.437
1000Hz	2.891	-0.033		0.001	-0.005			0.244	-0.684	
2000Hz	2.737	-0.012	-0.007				0	0.116		-0.604
4000Hz	2.152			0.002	0.006	0		0.076	-0.24	

4. Results and Discussion

4.1 Measurement and Simulation of Both Indoor and Outdoor Environments

It seems that 2021 was marginally colder than 2023 based on a comparison of the meteorological data from both years (Table 2). But beyond this discrepancy, it becomes clear that the simulations and the real observations diverge significantly.

Table 2 – Annual Air Temperature and Relative Humidity of Indoor and Outdoor

	Air Temperature (°C)			
	Average	Min	Max	Range
Meas. Church interior 2023	19.7	9.8	28.7	18.9
Meas. Exterior 2023	17.1	-1.2	40.1	41.3
Calc. Church interior 2021	16.8	0.11	34.4	34.29
Meas. Exterior 2021	14.8	-5	36	41

	Relative Humidity (%)			
	Average	Min	Max	Range
Meas. Church interior 2023	56.1	35.5	70.2	34.7
Meas. Exterior 2023	62.3	11	99	88
Calc. Church interior 2021	60.7	13.79	99.94	86.15
Meas. Exterior 2021	69.6	14	100	86

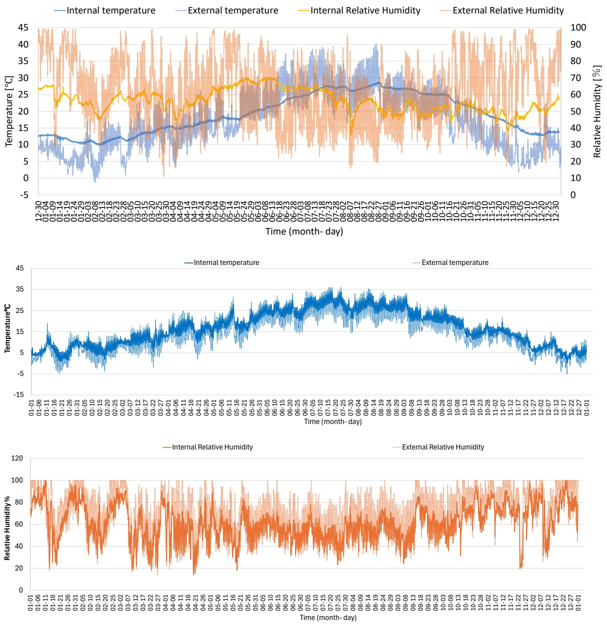

Fig. 3 – Microclimate measured and simulated: Temperature and relative humidity (a) measured in the church with the regional weather station data (Bologna idrografico in 2023) (b)(c) Simulation in IES.VE software with the weather station data (Bologna Marconi in 2021)

While the sensors placed within the actual church show relatively mild movements, the simulated temperature and humidity fluctuations nearly match those outside (Fig. 3). While the simulations displayed data from the room's centre, the actual measurements were made at the organ's location.

4.2 Variations with People Occupancy

The simulated annual temperature and relative humidity are displayed here under the influence of population occupancy, and their patterns were nearly constant throughout the year. With 500 participants, the larger results revealed a few minor variations (Fig. 4). While seasonal variations in humidity occur, the amplitude of temperature swings stayed largely stable year-round at a maximum of 1.6 degrees. The simulation indicated that during the winter, the impact of human presence on humidity was larger.

Table 3 – Difference between no people and 500 people

	Average	Min	Max	Range
Difference of Air Temperature (℃)	0.83	0.28	1.64	1.36
Difference of Relative Humidity (%)	**-0.46**	**-4.01**	**11.91**	**15.92**

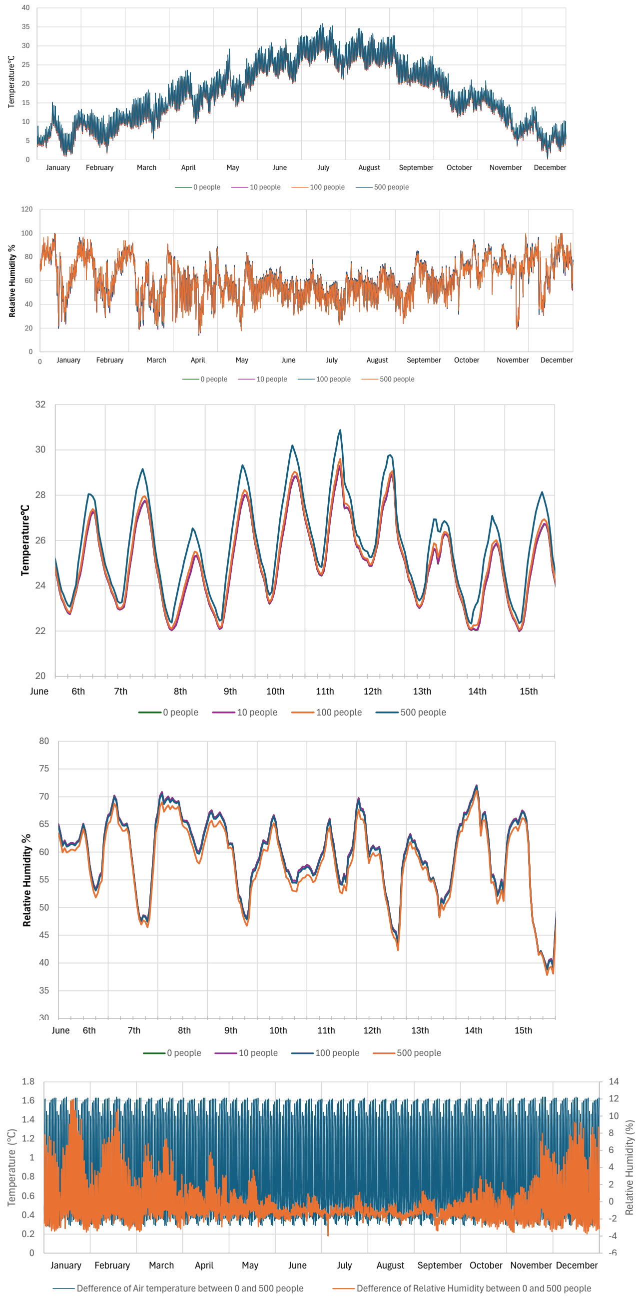

Fig. 4 – Temperature and relative humidity simulated in IES.VE, and Enlargements

4.3 Analysis of Indoor Acoustics

The acoustic parameter T30 (Reverberation Time) variation for entire data and particular chosen times for examining the impact of occupancy were computed (Fig. 5), as it happens for simulations on theatres (Bevilaqua et al., 2024). Depending on frequency, the annual variances showed notably different tendencies. Even though the church is much larger than it was in the previous report, two of the six values—roughly ranging from two to 3.5—were deemed appropriate for the reverberation value (Fig. 5a). The other four values, however, fluctuated over a very wide range (Fig. 5b–c).

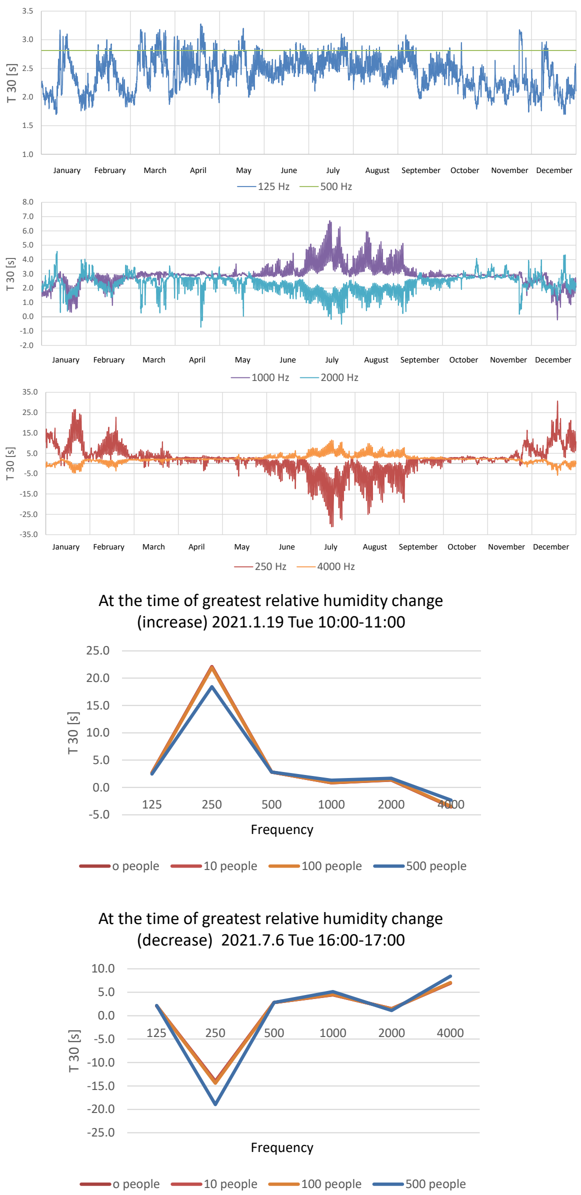

Fig. 5 – Acoustic parameter T30 calculated from the simulation data. (a)(b)(c) thought one-year, (d)(e) Variations with people occupancy

In several timings depicting the greatest temperature change and the greatest relative humidity between zero people and 500 people, the simulated variations of the T30 value were shown (Fig. 5d-e). When compared to annual variations, the range of value changes caused by occupancy was not very great.

5. Conclusions

For the purpose of preserving cultural heritage, it is necessary to evaluate the impact of interior environmental variables on acoustic parameters because air stratification and thermo-hygrometric conditions in tall historical structures are challenging to model. This study shed new light on the intricate relationships that exist between old churches' interior microclimate, organ pipe acoustics, and cultural heritage preservation. More real-world thermo-hygrometric behaviors were recorded than in prior modeling attempts thanks to long-term observation of temperature and humidity distributions in the Church of Santissimo Salvatore in Bologna. A greater knowledge of how underlying physical elements like temperature and humidity affect acoustic characteristics was attained by the integrated approach that combined field data with thermal and acoustic simulations. The real measurements and the modeling simulation showed noticeably different trends for the indoor temperature and humidity over the course of the year. The year-round changes in the acoustic parameters, which were computed, were extraordinarily broad. Overall, the findings show that in order to properly evaluate the effects on cultural heritage assets that are sensitive to indoor environmental conditions, such as pipe organs, and are housed in locations with limited capacity to regulate temperature, like tall historical buildings, detailed measured microclimate data are necessary. The preservation of both tangible and intangible cultural assets could be advanced by more research using this methodology on other case studies.

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