

On-Site Measurements and Whole-Building Thermal Dynamic Simulation of a Semi-Confined Prefabricated Building for Heritage Conservation

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Abstract

In this study the capability of a BDFWall model (IDA Indoor Climate and Energy software) is assessed in a semi-confined site for the conservation of works of art. The case under study is the paleontological deposit of “La Polledrara di Cecanibbio” (Rome, Italy), where many valuable faunal remains from the Middle Pleistocene are preserved. The thermo-hygrometric data collected from 2009 to 2013 have allowed for a thorough investigation of the environmental conditions of the site. The calibration of the simulation-building model was performed in two phases. First, a sensitivity analysis was conducted to identify which input parameters significantly affect the discrepancy, if any, between measured and modelled hourly indoor temperature (T) data (from September to December 2013). Second, the calibration of the model was carried out by taking into account the most effective parameters. The dual approach, given by both experimental and simulation data, can support the preventive measures of risk analysis for artworks in the case of retrofit solutions of a building used for conservation purposes.

1. Introduction

Recently, the whole-building dynamic simulation has become a useful tool in preventive climate control actions in buildings which preserve cultural artefacts. However, the existing software has been developed to model the indoor climate of modern buildings having regular geometries and for which the thermo-physical properties of building materials are well known.

In historical and archaeological buildings, the libraries of the simulation codes do not include the materials of these structures and, in the case of semi-confined sites, strongly affected by external factors and/or boundary constraints, the performance of these codes has not been thoroughly investigated.

The possibility to know in advance the effect of a retrofit in buildings with conservation purposes is fundamental in order to assess the optimal solutions taking into account both conservation needs and people’s thermal comfort requirements.

This paper describes how the dynamic simulation software, IDA Indoor Climate and Energy, applied to a semi-confined site such as the paleontological deposit of “La Polledrara di Cecanibbio” in Rome (Italy) was used.

The aim was to investigate the thermal behaviour of the case under study by using both on-site measurements and simulated values. This allows a better understanding of the object/environment and building/environment interaction. This study pays particular attention to the calibration of the whole-building dynamic model using only the features of the building envelope, since the variations of the geometry and of the thermo-physical properties of the building components and boundaries do not affect the model in the same way.

2. The Case Study

“La Polledrara di Cecanibbio” (Lat. 41.9°, Long. 12.3°) is a paleontological deposit located about 15 km NW of Rome (Italy) in a rural area. Several

valuable faunal remains from the Middle Pleistocene are preserved, such as large mammals (*Palaeloxodon antiquus* and *Bos primigenius*). The largest faunal remains are held by cineritic tuffite fluvial sediments (Fig. 1). The faunal remains placed in the north side of the site suffer from biological degradation because they are directly exposed to soil hygro-metric conditions.



Fig. 1 – La Polledrara di Cecanibbio, Rome (Italy)

The deposit was discovered in 1984 within a survey supported by the Soprintendenza Speciale per i Beni Archeologici di Roma (SSBAR) and was kept un-earthed in the following years. In 2000, a prefabricated building was built with the main purpose to preserve the fossils from meteorological conditions and to make it a public museum.

The building covers an excavated area of 900 m² (30x30 m per side) and is placed directly on the soil. The maximum height of the building is 8 m (east side), while the minimum is 6.5 m (west side). The windows (i.e. double-pane clear glazing with aluminium frame without thermal-break) are along the north and south walls covering an area of about 1900 m² with a solar factor of 0.79 and a heat transmittance (U-value) of 5.80 W/(m²K). There are internal white PVC roller blinds which are usually never opened.

The external walls are double skin panels insulated by polyurethane with a nominal thickness of 6 cm and a U-value=0.60 W/(m²K).

The roof is a trapezoidal sheet for concrete slabs with a nominal thickness of 12 cm, a slope of 30 cm and a U-value=1.09 W/(m²K).

3. Measurement and Simulation

An on-site monitoring campaign and whole-building dynamic simulation software were used with the double purpose to investigate the thermal behaviour of “La Polledrara di Cecanibbio” and to optimize the semi-automatic calibration of the simulation model in the case of a semi-confined site.

3.1 On-Site Monitoring Campaign

Sensors for the measurement of indoor temperature (T), relative humidity (RH), and cracks (FO) parameters were installed in June 2008. The analysis was carried out taking into account data from January 2009 to December 2013. The outdoor T and RH sensors were installed in June 2013 in the south corner of the building, accurately shaded from direct solar radiation, and protected from meteorological events. T sensor is a platinum resistance thermometer Pt100 1/3 DIN (accuracy = 0.3 °C), whereas RH sensor is a film capacitor “Rotronic” C94 (accuracy = 1.5 %). The metrological features of T and RH sensors are in accordance with the European Standards EN 15758:2010 and EN 16242:2012, respectively.

FO sensor is a capacitor (accuracy = 0.25 %) and is installed on the crack of a cinerite that holds a fang of a *Palaeloxodon antiquus*.

All the sensors were connected to a datalogger CR 1000 distributed by Tecno.el S.r.l. (Italy), with acquisition and recording time set to 30 minutes.

The monitoring campaign is still in operation.

3.2 Analysis of Microclimatic Data Series

Before performing the exploratory data analysis (EDA), the quality of the T-RH data series was assessed using the Continuity Index (CI) and the Completeness Index (CoI) (Frasca et al., 2016). Both indexes range between 0 (poor quality) and unity (high quality, i.e. no missing values).

Assuming any distribution of the data, the Spearman’s rank correlation coefficient (ρ) was computed to assess whether there was a monotonic relationship between the T-RH parameters and the cracks, in order to define an empirical relationship among parameters. This relationship is useful, in combination with the simulation results, to support

preventive measures concerning risk analysis for artworks in the case of retrofit solutions of a building used for conservation purposes.

3.3 Simulation Environment

3.3.1 IDA ICE setting

A dynamic building simulation for indoor climate analysis was performed using the software tool IDA Indoor Climate and Energy (IDA ICE) 4.7.1 developed and distributed by EQUA simulation AB. The BDFWall model (finite differences model of a multi-layer component) was used to carry out the simulation of the thermal behaviour of the building.

We created the geometry of the building model of “La Polledrara di Cecanibbio” was created starting from the architectural survey provided by the SSBAR and using the thermo-physical properties reported in UNI 10351:2015 for opaque components and in EN 673:2011 and EN 410:2011 for glass components. The first guess building model was assumed as an unconditioned large area, only affected by external climate and directly placed on soil.

The soil layer was modelled according to model ICE 3, which computes the soil temperature as the mean of T of the selected climate file without 2D or 3D modelled effects.

The air infiltrations were modelled according to wind driven flow and considering air tightness at 0.5 ACH (Air Change per Hour) at a pressure difference of 50 Pa.

Lighting, equipment and people were not included, since the site has a limited number of visitors in the selected period.

A climate file was built to run the model for calibration using outdoor T and RH measured at “La Polledrara”. Wind direction and speed intensity, direct and diffuse (sky) radiation on a horizontal surface, measured at ESTER station (Energia Solare TEst e Ricerca), belonging to the Tor Vergata University of Rome (Lat. 41.9°, Long. 12.6°), were also included in the climate file.

3.3.2 Method

In this study, MatLab 2014a was used to set the configuration parameters of the building model to carry out the Sensitivity Analysis (SA) and the calibration of the simulation model, based only on the parameters that describe the building envelope.

First, the SA was carried out to identify the most effective parameters of the model. Then, the calibration based on these selected parameters was performed to minimize the difference between modelled and measured data. The aim was to identify the best settings of the thermal-physical properties of building components and boundaries.

After that, the model was validated in a different period (January 2016) given the availability of measured indoor and outdoor temperature data.

3.3.3 Sensitivity analysis

In this study, the Elementary Effects method (EEs) was applied using modelled hourly indoor T from September to December 2013 and based on the Morris random sampling method of the set of parameters (Morris, 1991) that defined the building model. The experimental plan is built by taking into account the number of EEs (r) for each parameter and the number of levels (p) in which the parameters range. In this study, we computed $r=10$ for each parameter using only $p=4$ discretized levels in the experimental plan. We selected 24 parameters (k) for screening, and defined the ranges according to a fixed uncertainty at $\pm 10\%$ from the initial value, as listed in Table 1.

In this way, the resulting computational effort was 250 runs (N) which corresponds to:

$$N = r * (k + 1) \quad (1)$$

The input set parameter matrix given by Morris sampling is N -by- k . The N -models were run in batch mode in IDA ICE. The error between simulated T and T from the first guess model was expressed in terms of the mean absolute error (MAE) that was used as a target function for the calculation of the EEs.

The EEs ascribed to each parameter are defined as the difference in the output between two following simulations divided by the variation of the input parameter (Saltelli et al., 2004). The EEs were computed according to eq. 2:

$$EEs(x) = \frac{y(x_1, x_2, \dots, x_i + \Delta x_i, \dots, x_k) - y(x)}{\Delta x} \quad (2)$$

where x is the set of parameters, y is the target function and Δx is the variation of the input parameter. Finally, the mean (μ^*) of the absolute values of the EEs associated with each parameter, the standard deviation (σ) and the ratio σ/μ^* were calculated. μ^*

provides a measure of the parameter relevance (Campolongo et al., 2011), in the rank order. The ratio σ/μ^* is an indicator of linearity of each parameter effect ($\sigma/\mu^* < 0.1$) with respect to other parameters and to the whole modelled building (Garcia

Sanchez et al., 2014). In EEs scatter plot (σ vs μ^*) four areas delimited by $\sigma/\mu^* < 0.1$, $0.1 \leq \sigma/\mu^* < 0.5$, $0.5 \leq \sigma/\mu^* < 1$ and $\sigma/\mu^* \geq 1$, allows highlighting if outcomes from SA are physically consistent.

Table 1 – Modelling parameter values used in the first guess model (initial value) and parameter ranges value used in Morris sampling for SA

Component	Parameter	Initial Value	Range for SA
External Wall - Steel	λ [W/(m K)]	52	47-57
	s [m]	0.001	0.001-0.005
	d [kg/m ³]	7800	7000-8600
	c [J/(kg K)]	550	490-600
External Wall - Polyurethane	λ [W/(m K)]	0.034	0.029-0.040
	s [m]	0.15	0.13-0.17
	d [kg/m ³]	25	22-28
	c [J/(kg K)]	1.464	1.320-1.610
Roof - Concrete	λ [W/(m K)]	0.21	0.18-0.25
	s [m]	0.15	0.14-0.17
	d [kg/m ³]	700	630-770
	c [J/(kg K)]	1050	1000-1150
Soil	λ [W/(m K)]	1.5	1.3-1.7
	s [m]	1	0.9-1.1
	d [kg/m ³]	1200	1080-1320
Window	c [J/(kg K)]	840	765-925
	U [W/(m ² K)]	3.052	2.950-3.500
	ExtW-Slab [W/(m K)]	0.05	0.04-0.06
Thermal Bridges	ExtW-IntW [W/(m K)]	0.03	0.02-0.04
	ExtW- ExtW [W/(m K)]	0.08	0.07-0.09
	WinPerim [W/(m K)]	0.03	0.02-0.04
	DoorPerim [W/(m K)]	0.03	0.02-0.04
	Roof [W/(m K)]	0.09	0.08-0.10
	Slab [W/(m K)]	0.14	0.13-0.15

Note: λ =thermal conductance; s=thickness; d=density; c=specific heat; U=heat transmittance; ExtW-Slab=external wall-internal slab; ExtW-IntW=external wall-internal wall; ExtW-ExtW= external wall-external wall; WinPerim = external window perimeter; DoorPerim = external door perimeter; Roof=roof-external wall; Slab=external slab-external wall.

3.3.4 Calibration

The simulation model was calibrated using hourly indoor T measurements from September till December 2013. The model was initialized at a start-up period from August 18, 2013 to August 31, 2013. The calibration was carried out taking into account

only the most effective parameters with the aim to minimize the root-mean-square-difference (RMSD) and the CV-RMSD (Coefficient of Variation of the RMSD) between modelled and measured indoor T. They were used to assess the quality of the changes to calibrate the building model (Cornaro et al.,

2016). The most effective parameters were ranged within the interval reported in Table 1, using a major number of levels with respect to the Morris sampling.

The modelled and measured indoor T were compared using the Taylor Diagram (Taylor, 2001). It summarizes the agreement between observed data (a) and modelled data (b) using three statistical quantities: standard deviation (SD), correlation coefficient (R), and the centred RMSD (E'), the relationship of which is given by the following equation:

$$E' = \sqrt{SD_a^2 + SD_b^2 - 2\cos(SD_a SD_b R)} \quad (3)$$

4. Results and Discussion

4.1 Microclimate Analysis

Both the T and RH data series are of high quality (CI=1.00 and CoI=0.96) and hence suitable for exploratory data analysis.

Fig. 2 shows the box-and-whiskers plots of RH data. Several outliers (indicated as circles in the figure) are observed in winter, spring, and fall. A detailed

study of RH outliers has shown that they occurred mainly in the hourly intervals between 13:00 UTC and 20:00 UTC, i.e. after the maximum solar exposure of the building.

The box plots for T (figure not shown), do not show any anomalous values, and there is no significant difference among seasons over the selected period. The mean yearly value is 17.7 °C ranging between 12.4 °C (25th percentile) and 23.1 °C (75th percentile). It was found that in summer the indoor environmental conditions were too warm and too humid, while in winter, they were too cold and humid, especially in morning. These conditions provoked thermal discomfort, as communicated by staff and visitors, and might have favoured the biological degradation in the north side of building.

The behaviour of T and RH daily span (difference between the maximum and minimum values) allows studying their short-term variability. A similar behaviour among season (except in summer) was observed: $\Delta T_{daily}=1-7$ °C and $\Delta RH_{daily}=3-40$ %. In summer, the daily span of T and RH range as follows: $\Delta T_{daily}=5-6$ °C and $\Delta RH_{daily}=20-40$ %, showing that the period is mostly characterized by large fluctuations.

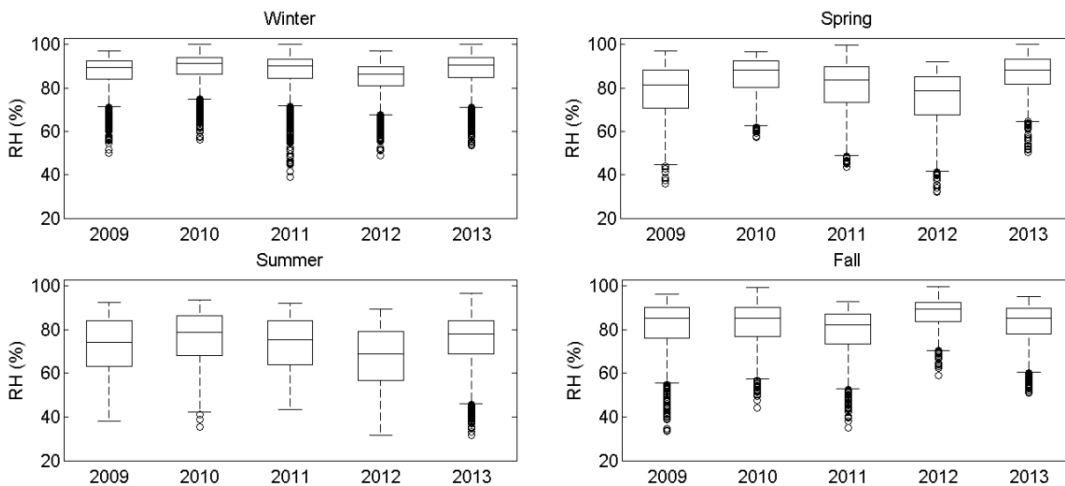


Fig. 2 – Box and-whiskers plots of indoor relative humidity (RH) for each season over the period 2009-2013. The line inside the box is the median value, with the 25th and 75th percentiles as lower and upper sides of the box, respectively. The lowest and the highest value of the data set are plotted as whiskers when they are not outliers, indicated as circles (i.e. above or below 1.5*IQR, IQR interquartile range)

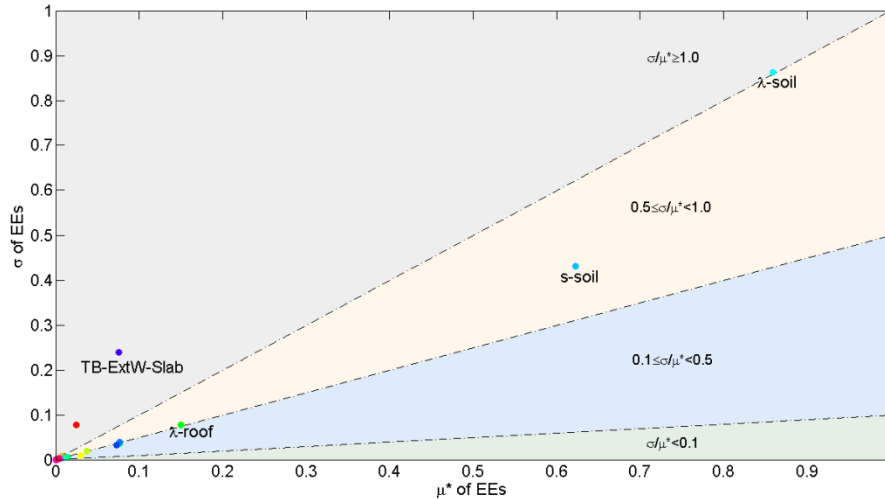


Fig. 3 – Scatter plot (σ vs μ^*) of Elementary Effects method for 250 runs by taking into account 24 input parameters (indicated as colored dots) of building envelope. Four areas delimited by the ratio σ/μ^* indicate the effect of parameter on model: light green ($\sigma/\mu^* < 0.1$, linear effect), light blue ($0.1 \leq \sigma/\mu^* < 0.5$, monotonic effect), pink ($0.5 \leq \sigma/\mu^* < 1$, almost monotonic effect), and grey ($\sigma/\mu^* \geq 1$, non-linear and/or non-monotonic effect)

Finally, T-RH parameters affect the evolution cracks measured on the cinerite that holds a fang: the correlation with T is $\rho=0.62$ whereas with UR is $\rho=-0.68$. An empirical relationship was found:

$$FO = b_1 * RH^{b_2} * T^{b_3} \tag{4}$$

where $b_1 = 6.76$, $b_2 = -0.09$ and $b_3 = 0.01$. Modelled FO data deviate from measured FO of at most 5 %.

4.2 Simulation

Fig. 3 shows the results of the EEs computed taking into account 24 parameters (see Table 1). The most effective parameters corresponding with the high values of μ^* and σ are: the thermal conductance (λ_s) and thickness (s_s) of the soil, the thermal conductance of the roof (λ_r), and the thermal bridge related to the external walls and slab ($TD_{ExtW-Slab}$).

The scatter plot shows that the effects of λ_s and $TD_{ExtW-Slab}$ are non-linear and/or non-monotonic (indicated as the grey area in figure ($\sigma/\mu^* \geq 1$)), while the effects of λ_r and s_s are almost monotonic (indicated as the pink area in the figure ($0.5 \leq \sigma/\mu^* < 1$)).

The significant influence of the soil on indoor T is due to its low resistance at heat transfer. It is controlled by several factors such as porosity and soil temperature. Further studies will be carried out taking into account the actual temperature of the soil.

The other parameters form a cluster with low μ^* and σ , which means that they have a limited influence

on the model and could be neglected in the model calibration.

Fig. 4 shows the Taylor Diagram for a comparison among modelled hourly indoor T (indicated as coloured dots) and measured hourly indoor T (indicated as A) by running several simulations varying the first two effective parameters as described above (subsection 3.3.4).

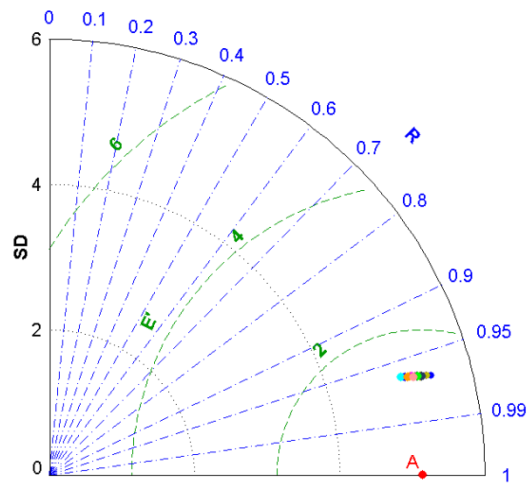


Fig. 4 – Taylor Diagram displaying a statistical comparison among observations (A) and 15 run models (clustered coloured dots). Black dotted circles are standard deviation (SD), green dashed circles are the centred root-mean-square-difference (E') and, finally, blue dash-dotted lines are the correlation coefficient (R)

Modelled indoor T data are strongly clustered showing that, even though λ_s and s_s are the most effective parameters, their variation does not play a key role in minimizing the error among modelled

and measured T. Data series are highly correlated ($R > 0.95$), the E' ranges within 1.32 °C and 1.39 °C, and the SD is between 5.0 °C and 5.5 °C.

In Table 2, the RMSD and the CV-RMSD of the indoor T over the calibration period for the first guess model and the calibrated model are reported with respect to the observations. The RMSD and the CV-RMSD of the calibrated model are quite lower than in the first guess model. Even though the most effective parameters were identified, the calibration procedure did not improve the capability of the model to well simulate the building. This would confirm that an accurate monitoring of the soil temperature should be performed and included in the analysis.

Table 2 – The RMSD and the CV-RMSD for the first guess model and the calibrated model are reported

	First Guess Model	Calibrated Model
RMSD	1.38 °C	1.32 °C
CV-RMSD	8.0 %	7.8 %

Fig. 5 shows the temporal behaviour of bias (%) calculated between measured and calibrated modelled indoor T. The mean bias is 0.6 % (indicated as a dashed blue line), while the 7th and 93rd percentile are -9.0 % and 14.5 %, respectively (indicated as dashed red lines). The calibrated modelled T usually overcomes the measured T, mainly from the end of November, when a sudden drop of outdoor T occurs.

The RMSD and the CV-RMSD of the indoor air T over the validation period (January 2016) are 1.92 °C and 20.0 %, respectively. In general, the modelled T overestimates the measured T.

The increase in RMSD and CV-RMSD can be due to a different behaviour in the heat transfer of the soil during meteorological events. Over the validation period, the amount of precipitations was about 18 mm/day, while in the calibration period heavy rainfall (about 230 mm/day), although sporadic, was recorded.

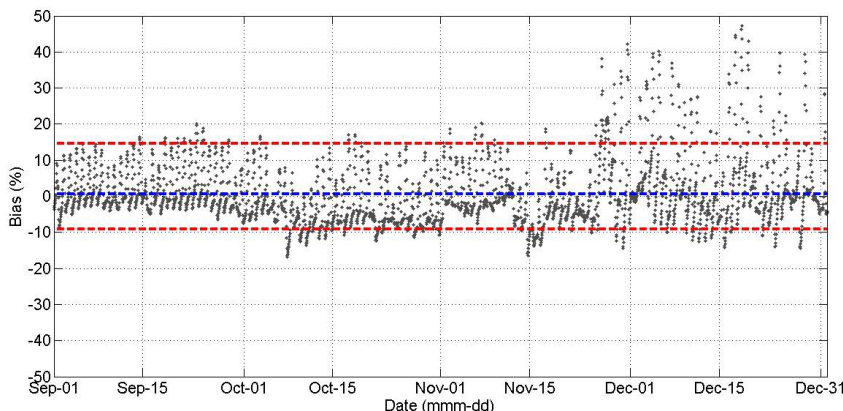


Fig. 5 – Time plot of bias (%) computed between measured indoor T and calibrated modelled indoor T data from September to December 2013. Blue line is the mean of bias (0.6 %), while red lines are 7th (-9.0 %) and 93rd (14.5 %) percentile of bias respectively

5. Conclusion

The temporal behaviour of indoor thermo-hygrometric parameters seems to be related to the solar exposure of the building and its capability to transfer the heat thorough external walls (i.e. thin double skin insulated panels). This has favoured an indoor environment unsuitable for the conservation purpose of faunal remains. The empirical relationship between cracks and T-RH (eq. 4) will be used for

preventive measures after an accurate calibration of the building dynamic simulation model.

The Elementary Effects (EEs) method allowed us to identify the most effective parameters, then used in the calibration. In this case study, the most effective parameters are the thermal conductance and the thickness of the soil. Nevertheless, the use of these parameters does not allow to minimize the error between calibrated modelled and measured indoor temperature, suggesting that other parameters, such

as the air infiltration rate, should be taken into account.

Further studies will be conducted considering the measured soil temperature and humidity, and by using the HAMWall model implemented into the IDA ICE environment. The HAMWall allows the simultaneous simulation of the transfer of heat, air mass, and moisture. In this way, it will be possible to find the most adequate thermo-hygrometric conditions to consider in the building retrofit for the conservation of faunal remains.

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