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Energy Procedia 133 (2017) 257–267

Energy Procedia

www.elsevier.com/locate/procedia

Climamed 2017 – Mediterranean Conference of HVAC; Historical buildings retrofit in the Mediterranean area, 12-13 May 2017, Matera, Italy

Assessment of the indoor environmental conditions of a baroque library in Portugal

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Abstract

This paper presents the preliminary results of the study of the indoor environmental conditions in a Baroque building of a XVIII century library, located in the heights of the historic centre of the University of Coimbra (UC), which was established 727 years ago. Since these conditions play a very important role in the conservation of the books and the wood bookshelves, experimental surveys based on permanent measurements of the hygrothermal air conditions and of particulate matter concentrations are being carried out since early October 2016. Some early results of this short term study are presented and discussed.

Peer-review under responsibility of the scientific committee of the Climamed 2017 – Mediterranean Conference of HVAC; Historical buildings retrofit in the Mediterranean area

Keywords: Microclimate; Conservation; Indoor Air Quality, Particulate Matter, Heritage buildings.

1. Introduction

As stated in [1], *'contaminants levels must be maintained at low concentrations for human health and to guarantee the correct preservation of works of art and cultural heritage'*. Besides the building itself – the XVIII century Baroque library of the University of Coimbra –, the books kept inside are also part of this heritage, and due to its organic characteristics, these are vulnerable to hygrothermal variations and contaminants. At the same time, the deposition of dust, e.g. in the shelves and painted woods, results in a negative visual effect, such as the loss of brightness and "opacity" of colours, due to their accumulation and cementation in works of art [2], [3], also

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1876-6102
Peer-review under responsibility of the scientific committee of the Climamed 2017 – Mediterranean Conference of HVAC; Historical buildings retrofit in the Mediterranean area
10.1016/j.egypro.2017.09.385

contributing to deterioration processes [2], [4], [5].

The first studies dedicated to the indoor environmental conditions of this Baroque library were conducted at the end of last century, at a time when it was still used as a traditional library, though with a small number of users (by this time, the university community was already served by the General Library, built in the 1960s).

In 2013, the buildings of 'University of Coimbra – Alta and Sofia' were declared a World Heritage Site by UNESCO [6], turning the *Baroque Library* into part of an important tourist circuit in Portugal. Currently, it closes only 5 days a year, receiving up to 60 visitors every 20 minutes - over 400,000 tourists in 2015, becoming the third most visited monument in Portugal. Similarly to other contemporary libraries, such as the *Old Library* of the Trinity College in Dublin (Scotland) [7], the *Baroque Library* in Coimbra is daily open for visits: 7h/day in winter and 11h/day in summer time.

In face of this new reality, the Rectorate of the University has been very concerned about the heritage preservation and started a research project focused on the accurate characterization of the indoor environmental conditions within the Baroque library and on the assessment of risk situations, both for heritage and health issues.

Since the indoor conditions play a very important role in the conservation of the books and the wood bookshelves, experimental surveys based on permanent measurements of the hygrothermal air conditions and of particulate matter concentrations are being carried out since early October 2016, in order: (i) to assess the current indoor environmental conditions (IEC) of the library; (ii) to investigate whether the risky IEC are mainly caused or not by the increased occupancy / visiting rate; (iii) to propose mitigating interventions and alternative strategies.

The measuring campaign included the monitoring of the following parameters: indoor air temperature (Ta, ºC), relative humidity (RH, %), carbon dioxide concentration values (CO_2, ppm) and particulate matter (PM, $\mu g/m^3$). These were registered every ten minutes during the entire monitoring period, during day and night time. Indoor/outdoor relations were established and collected data were compared with different guidelines – national and international standards. Some early results of this short term study are presented and discussed.

2. Method and object of study

The case study is located in the heights of the historic centre of the University of Coimbra (UC), at the southwest end of the university courtyard, 120 m above the sea level, as shown in Fig. 1, a). In terms of climatological data, the average monthly rainfall (AMR) varies between 10.9 mm in July and 126.2 mm in December, the rainiest month. Additionally, the average monthly mean (AMM) temperature values vary between 10.4ºC in December and 20.4º in August, the hottest month [8]. The Baroque Library was built between 1717 and 1725, and the decoration works lasted for another three years [9], [10]. The library is composed of *'three floors: the Noble floor, richly decorated space, the most emblematic face of the House of the Library; Intermediate Floor, workplace and acted as the guard house; the Academic Prison, which worked here from 1773 until 1834'*[11].

The library is exclusively naturally ventilated. Some of the external walls are more than 2.0 m thickness and internally, the Noble floor walls are integrally covered by wood shelves. Herein are comprised circa 40,000 volumes [11]. The Intermediate floor has always been the deposit of the Library; nowadays it is open to the public and it also hosts small exhibitions.

It is daily open to visitors: (a) winter (31/10/2016 to 1/3/2017): 9h00 − 13h00 & 14h00 −17h00; summer (16/3 to 30/10/2016): 9h00 − 20h00.

2.1. The monitoring campaigns

Between October and December 2016, several parameters were monitored, namely: indoor air temperature (Ta, ºC), relative humidity (RH, %), carbon dioxide concentration values (CO_2, ppm) and particulate matter (PM, $\mu g/m^3$). Table 1 presents a list of the equipment used during the monitoring campaigns: October and November/December 2016, as well as the interval between records. During the first monitoring campaign the Library was open to public according to the summer schedule (9h00 − 20h00) and during the second campaign visits were possible according to winter time (9h00 − 13h00 & 14h00 −17h00).

2.2. The available guidelines and recommendations

In terms of particulate matter, the authors have been following the criteria presented by Pinheiro *et al* (2014) – one of most recent studies on the concentration and distribution of particulate matter (PM) in Portuguese archives. These authors recall the studies Nazaroff (2004) or Ryhl-Svendsen (2006), alerting to the hazard properties of PM, namely showing that the inadequate exposure to PM can lead to health problems as well as to the degradation of material and artistic objects.

Particle matter exposure values are suggested by several entities: (i) EPA (US Environmental Protection Agency); (ii) WHO [15]; (iii) US National Bureau of Standards (1983) *in* Blades et al. (2000); (iv) or ASHRAE 2015. Of all these values, the recommended maximum value of PM_{10} for Museums by the US National Bureau of Standards – 75 $\mu g/m^3$ is highlighted, a value in accordance with category C defined in Table 2.

Table 1. List of the equipment used in the monitoring campaigns.

Parameter	Equipment	Monitoring period [(1), (2)]	Monitoring interval
Particles (PM, $\mu g/m^3$)	Lighthouse 3016 IAQ	4 Oct – 19 Oct 11 Nov – 30 Nov	Every 10 min - six records/hour, covering the 3 hourly visits (group entry of tourists every 20 min)
Temperature (T, ºC)	PS32 SENSOTRON	4 Oct – 19 Oct	Every 10 min
Relative Humidity (HR, %)	HOBO MX1102 Data Logger	6 Oct – 19 Oct 7 Nov – 16 Dec	Every 60 sec Every 5 min
Cabon dioxide (CO_2, ppm)	HT 2000 data logger *(intermediate floor)*	11 Oct – 17 Oct 7 Nov – 23 Nov 28 Nov – 16 Dec	Every 5 min

Notes: (1) Oct = October; Nov = November; Dec = December: min = minutes; sec = seconds. (2) The values presented ahead in the Results section, correspond to a daily average < 24h: the average of the totality of the records since the equipment turned on (early in the morning) until the moment it turned off, due to battery exhaustion (typically between 00h30 and 01h30).

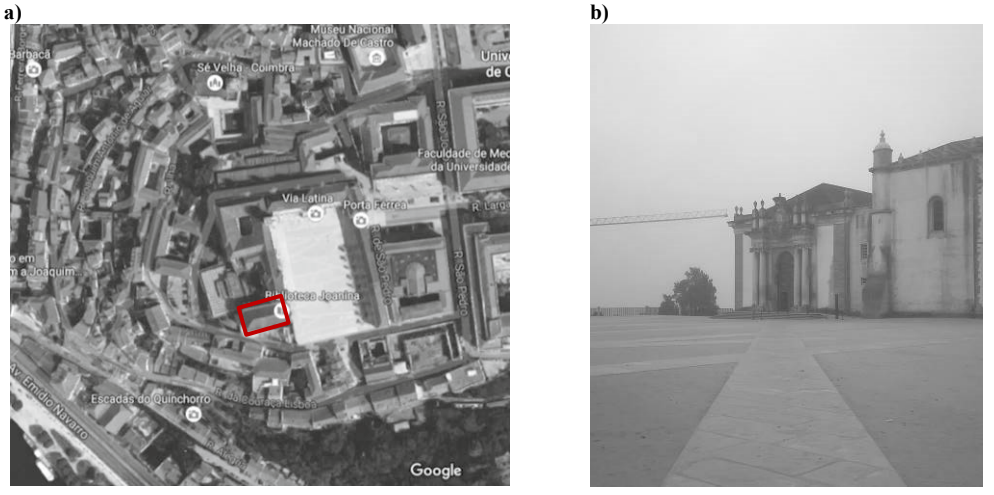

Fig. 1. a) Location of the Library [Google Maps (2016)]; b) external view of the Library East façade.

Table 2. Rating IAQ categories for the conservation of indoor environment, proposed in [18] and [1], defined by the average concentration values of PM_{10} and $PM_{2.5}$.

Type	Conservation categories and concentration intervals (μg/m^3)			
	A	B	C	D
$PM_{2.5}$	< 1	1 − 5	5 – 10	> 10
PM_{10}	< 10	10 – 30	30 – 75	> 75

CO_2 concentration levels were assessed according to the national legislation, which currently defines a threshold limit for CO_2 in the indoor air equal to 2250 mg/m^3 (1250 ppm), average concentration value during the various occupancy periods.

Relating air temperature and relative humidity, several norms and international recommendations have been published since 1999, on methodologies of analysis and intervals of tolerance in the context of the preservation of archives and / or artistic and cultural assets. At European level, the Italian standards stand out: *i*) UNI 10829:1999, *"Beni di Interesse Storico Artistico. Condizioni Ambientali di Conservazione. Misurazione ed Analisi"*; *ii*) UNI 10969:2002*, "Beni culturali - Principi generali per la scelta e il controllo del microclima per la conservazione dei beni culturali in ambienti interni"*, iii) UNI 15757:2010 *"Conservazione dei beni culturali - Specifiche concernenti la temperatura e l'umidità relativa per limitare i danni meccanici causati dal clima ai materiali organici igroscopici.*

In the latest, which replaced a previous standard, a significant step was taken in the face of optimum conservation conditions. Parallel to these, the climatic history of the spaces where the works are located must always be taken into account, that is, the mean values of the microclimatic parameters become as important as the analysis of their fluctuations around the mean value. In other words, this standard has proposed that the acceptable microclimatic variability and the risk limit for an artefact, whose fragility is controlled by hygroscopicity, depends on its climatic history, during which an adaptation to "normal variability" has been developed. It is also noticeable that this standard has been translated into English and assumed at European level as UNI EN 17757 of November 2010. More recently, it was published ISO 11799: 2015 *Information and documentation - Document storage requirements for archive and library materials*, mainly dedicated to the storage of long-term materials in repositories and libraries.

Given its current use, the Baroque library under study has a significant human occupancy (due to regular visits by tourists), for which it can be framed into the typology of museum space, where acceptable values of indoor air temperature and relative humidity are greater than those recommended for the restrict conservation of books. In [19], the author presented a significant table summarizing the latest normative guidelines on the hygrothermal conditions of the indoor environment in museums. Notwithstanding the differences between the various normative documents, it can be concluded that more important than the T or RH indoor air reference ranges, it is the amplitude and frequency of their variations. Evaluating the set of recommendations, and considering the current use of the Library, the authors considered the following values as reference in the analysis of the monitoring of its interior environment:

- Annual average values:

Air temperature (T): 15 ºC − 25 ºC;
Relative Humidity (RH): 50 % − 60 %;

- Acceptable values for short-term fluctuations[†]:

± 5 ºC; ± 10 % RH (ASHRAE (2015) *Class B*) [‡].

[†]In this context, a 'short period' may be one to two weeks.

[‡]According to ASHRAE 2015, Class B corresponds to *'a very small risk for most artifacts, paintings, photographs and books; No risk to many artifacts and to most books'* and *'Classes B and C are useful and feasible for many medium and small institutions, and are the best that can be done in most historic buildings'.*

3. Results and data analysis

Since during both monitoring campaigns CO_2 levels were always within the recommended values, it is herein stated beforehand that no special attention was driven towards this parameter in the current paper.

3.1. Particulate matter

Particles were only monitored on the Noble floor. Fig. 2 presents the time evolution of the daily mean PM_{10} concentrations in the indoor air, resulting of the monitoring campaign carried out between 4 and 18 October 2016. Black and grey solid lines refer to daily averages during the period of visits and to the total measurement period, respectively. The dashed grey curve, accumulated precipitation (mm), evidences the direct effect of rainfall on the sharp decrease in the concentration of particles within the Library, although mean values remain high, in category D (> 75 µg / m3, Table 2).

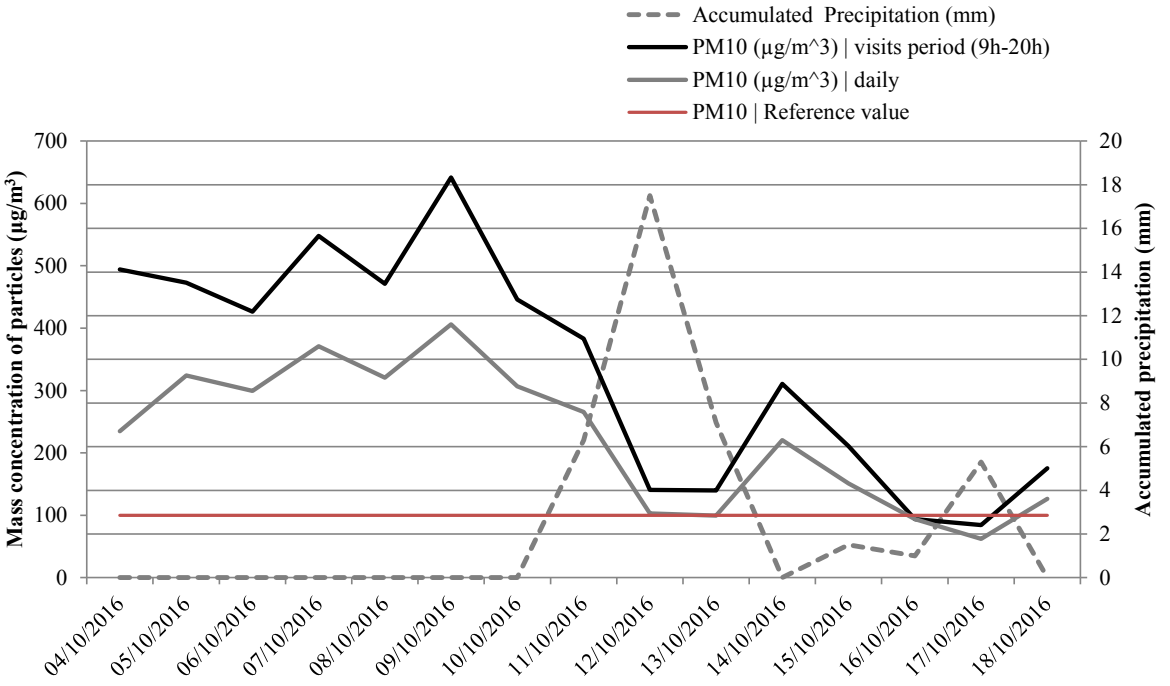

Fig. 2. Time evolution of the daily mean values of mass concentration of particles (µg/m^3) on the Noble floor, between 4 &18 October 2016. The maximum reference value, according to the national regulations in force for IAQ in buildings, is represented by the red line (reference value: 50 µg/m^3, added a 100% tolerance).

Overall, the daily PM_{10} average concentration during the visiting period is about 50% higher than the daily average entire measurement period – this aspect gains greater highlight in dry weather days. A summary of all the measured particle concentration values during both monitoring campaigns, both PM_{10} and $PM_{2.5}$, is given in Table 3.

Fig. 3 shows the distribution of the totality of the recorded values of PM_{10} and $PM_{2.5}$, distributed over the conservation categories presented in Table 2. During the first monitoring campaign, for both PM classes, there was a predominance of category D, the one presenting the highest risk of degradation. During the second monitoring campaign, these values slightly improved, but they were still far from a 'safe' preservation target: more than 50% of the values fell into category C and D.

Table 3. Summary table of all registered PM values (µg/m^3).

Period	PM	Minimum value	Maximum value	Average + St Dev
4 - 18 October	PM 10	19.01 (visit period) [1]	1234.77 (visit period) [5]	11.76 ± 5.68
		3.39 (daily) [2]	1234.77 (daily) [5]	
	PM 2.5	3.64 (visit period) [3]	44.42 (visit period) [6]	228.76 ± 239.00
		0.85 (daily) [4]	44.42 (daily) [6]	
11 - 30 November	PM 10	6.70 (visit period) [7]	856.98 (visit period) [11]	8.08 ± 5.45
		0.88 (daily) [8]	856.98 (daily) [11]	
	PM 2.5	1.34 (visit period) [9]	35.47 (visit period) [12]	54.50 ± 61.01
		0.25 (daily) [10]	35.47 (daily) [12]	

Notes – values recorded at:[1] 18h40m, 16/10/2016; [2] 01h12m, 12/10/2016; [3] 17h05m, 13/10/2016; [4] 01h32m, 12/10/2016; [5] 15h58m, 07/10/2016; [6] 12h05m, 08/10/2016; [7] 14h23m, 27/11/2016; [8] 02h14m, 25/11/2016; [9] 11h32m, 25/11/2016; [10] 08h00m, 25/11/2016; [11] 14h23m, 27/11/2016; [12] 16h10m, 17/11/2016.

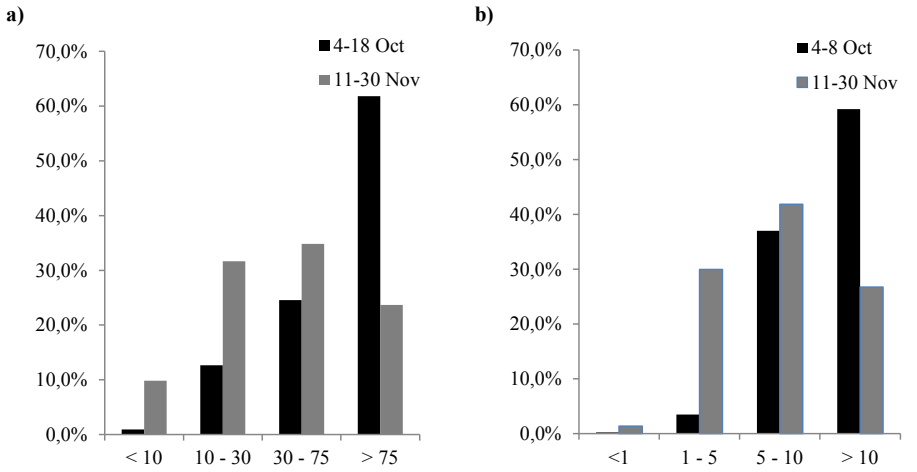

Fig. 3. Distribution of all record values of PM10 and PM2.5 according to the concentration ranges defining the conservation categories A, B, C and D, as indicated in Table 2. a) PM 10; b) PM 2.5.

Briefly, from the analysis of all recorded data, several inferences were drawn: (i) the particles of largest dimension (between 2.5 and 10 µm) were predominant, as it is typical of atmospheric dust (> 5 µm); (ii) the concentration of particles was much higher during the period of visits, when the maximum values were registered. The entrance/presence of the particles is mainly due to the transport of dust adhering to the visitors' shoes, more than a result of the frequent openings of the main door for access or exit of tourists; (iii) these factors are intensified by the type of lining material of the courtyard, a sand of calcareous nature, which, as a result of the dozens of tourists waiting for their visit, is an abundant source of dust; (iv) in the absence of a significant change in the number of visitors on 11, 12 and 13 October, the marked drop in PM values was exclusively due to the occurrence of rainfall, with the consequent reduction of the concentration of PM (both outdoors and indoors). Fig. 2 shows the immediate rise in PM_{10} concentration in October 14th, when there was no precipitation.

In the literature on the subject, values of the I/O (indoor/outdoor) ratio are frequently lower than 1 (or just slightly above 1) for the different physicochemical pollutants. When I/O<1, it means that the concentrations of pollutants are higher in the exterior, which is more easily verified in museums located in demarcated urban environments. Nevertheless, the I/O ratio values obtained from the PM_{10} measurements were much higher than 1, which clearly means that the suspended particles are due to action within this space.

3.2. Indoor air temperature and relative humidity on the Noble floor

Concerning the indoor air temperature (T, ºC) and relative humidity (RH, %), data from the HOBO equipment were chosen. These values were recorded every minute, over 24h-periods, allowing the diurnal variation assessment of the hygrothermal behaviour of the building. Since this equipment was placed in the Library only on the 6th October, the analysis of the first period is focused between 7-18 October. Fig. 4 shows the simultaneous representation of T and RH inside and outside the Library. It was verified that the variation of the RH was almost symmetric of T, this relation is stronger in the parameters registered indoors. This relationship of practically inverse variation of the RH with the T, suggests that the absolute humidity on the noble floor has varied little during this measurement period.

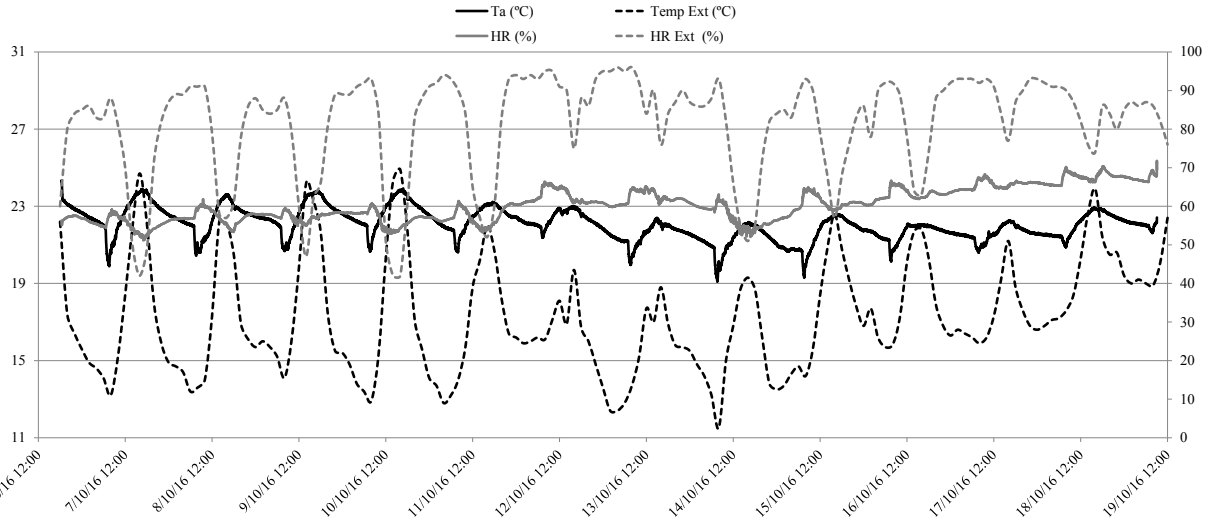

Fig. 4. Time evolution of air temperature (T) and relative humidity (RH) inside the Library Noble floor between 6 and 19 October 2016[§].

From data presented in Fig. 4, complemented with the totality of the collected data, the following may be highlighted: (i) since the case-study is not provided of any HVAC system, it was observed that the building naturally responded to the external temperature variations, in a relatively smooth and typical way of a building with relatively high thermal inertia; (ii) within the 1st monitoring period, daily temperature fluctuations were lower than 3.5 ºC (excepting on October 7, when it reached 4ºC); (iii) during the 2nd monitoring campaign, only in 10% of the days the daily fluctuation was above 4ºC, but always below 5.6 ºC; (iv) concerning relative humidity (RH, %), the situation showed to be more concerning. On the one hand, during the 12-day period in October, the mean value oscillated between 55% and 65% (only on October 18 this figure was higher), which could be stated to be acceptable. However, the minimum RH value was 51% and the maximum value was 70%. In summary, there was a variation of almost 20% of RH in a short period of time, being within the limit of the value considered acceptable for fluctuations of RH (±10%). During the 2nd monitoring, though RH daily fluctuation was not very high (always <11%), it reached absolute values higher than 65% during 67% of the days.

[§] The meteorological data were obtained from the nearest stations, installed in the Laboratory of Industrial Aerodynamics (LIA) and in the Department of Mechanical Engineering of the Faculty of Sciences and Technology of the University, namely: ADAI@LAI: https://www.wunderground.com/personal-weather-station/dashboard?ID=ICOIMBRA14#history; and, ADAI@DEM.UC: https://www.wunderground.com/personal-weather-station/dashboard?ID=ICOIMBRA27

3.3. Indoor air temperature and relative humidity on the Intermediate floor

Table 4 shows a summary of the recorded data and in Fig. A.1 (Annex) the time evolution of the recorded values in the intermediate floor with those obtained in the noble floor (NF) are compared during the second monitoring campaign.

The following observations stand out: (i) relating the hygrothermal behaviour of the intermediate floor of the library it was found that the temperature in this floor is less dependent on the external conditions than those registered on the noble floor (Fig. A.1); (ii) the temperatures recorded on the intermediate floor were always higher (3 to 4ºC, on average) than those on the upper floor; (iii) in turn, RH values were more similar on both floors during the 1st monitoring campaign. In Nov-Dec, RH fluctuations were lower on this floor; (iv) generally, the T recorded on the intermediate floor presented a greater concern factor than the RH, not for the amplitude of the fluctuations recorded, but for its higher absolute recorded values – the average value was 24.5 ºC during the 7-day period in October and, 21,6 ºC in Nov-December; (v) except for October 14th, daily RH fluctuations recorded on the intermediate floor during the 1st period were lower than 9%, and in Nov-December, only in 9% of the days, daily variation was slightly higher than 10%, which can be considered as acceptable.

Table 4. Summary table of all registered values on the intermediate floor.

Period	Parameter	Minimum value	Average value (average + St dev)	Maximum value	External (min – average - max)
4 - 18 Oct	T (ºC)	23.2	24.5 ± 0.5	25.3	11.5 – 16.7 – 22.6
	RH (%)	51.8	58.8 ± 2.9	64.8	51 – 84 – 96
7 Nov - 16 Dec (except 24-278 Nov & 6-8 Dec)	T (ºC)	18.7	21.6 ± 1.1	23.9	2.3 – 12.7 – 20.4
	RH (%)	44.0	57.2 ± 3.4	64.6	47 – 81 – 98

In summary, the preliminary analysis unveils relatively acceptable hygrothermal conditions within the Baroque Library. However, it should be noted that this measurements: (i) refer to a relatively short period of time, (ii) a single sampling point on each floor and (iii) mild and relatively stable climatic conditions. For a comprehensive assessment of the hygrothermal conditions on the indoor environment of the library, a comprehensive monitoring, both in terms of time and in sufficient number of sampling points, is mandatory. Therefore, on December 16th 2016, a new monitoring campaign was initialized, comprehending 12 measurement points in the Noble floor and some other on the intermediate one.

4. Conclusions and outlook

From the preliminary assessment of the environmental conditions in the Baroque Library of the University of Coimbra, based on the measurement campaigns carried out during the months of October, November and December 2016, it can be stated that:

1) Among all the monitored parameters, the very high concentration of suspended particles (PM) recorded in the Noble floor represents the highest risk for the book collection and the remaining heritage site;

2) The consistently high levels of PM concentration, especially during the visits' period, can also compromise the health of users, especially for the Library personnel, who remain in this space for an extended period of time (workday);

3) From the comparison of recorded values during day and night periods, it was observed that the high PM values were mainly due to: (i) the high number of visitors, (ii) the high dust load - generated and adhered to footwear, as visitors walk through the sanded courtyard, carrying the sand indoors, and (iii) the frequent main door

opening exposing the indoor environment directly to the outside. This finding was in accordance to the studies of [21] and [22];

4) Although in an informal way, the excessive amount of dust perceived by the visitors, associated to the high number of tourists diminishes the aesthetic experience that the space promotes;

5) Although the recorded values of indoor air temperature (T) and relative humidity (RH) were not elevated during the studied monitoring period, this deserves further attention, given that the current conservation standards that point at the historical temporal analysis of these parameters – A permanent evaluation is therefore required;

6) At the same time, the interdependence of T and HR in the Noble and intermediate floors, as shown in Fig. A.1, raises questions regarding the hygrothermal conditions of the interior environment in severe climatic conditions.

In view of the obtained results and the observations set out above, a list of possible measures to resolve some of the issues identified in this first study can be pointed: (i) protection of the architectural and exhibition heritage through the protection of visitors' footwear (a practice that is recommended in [23], and is applied in several museums/exhibition spaces); (ii) limitation of the number of visitors; (iii) protection of dust deposition over books through application of dust falls between shelves [24]; (iv) changing the main access to the public.

In summary, the conclusions obtained from this preliminary analysis, point at the existence of relatively acceptable hygrothermal conditions within the Baroque Library. However, it is noted that these are based on measurements taken in a limited period of time, at a single sampling site on each floor of the Library and during non–extreme climatic conditions, for which further investigations are forthcoming.

Acknowledgements

This work was supported by the University of Coimbra under project grant BJUC-AHT – "Avaliação Higrotérmica do Ambiente Interior na Biblioteca Joanina da Universidade de Coimbra".

Appendix A.

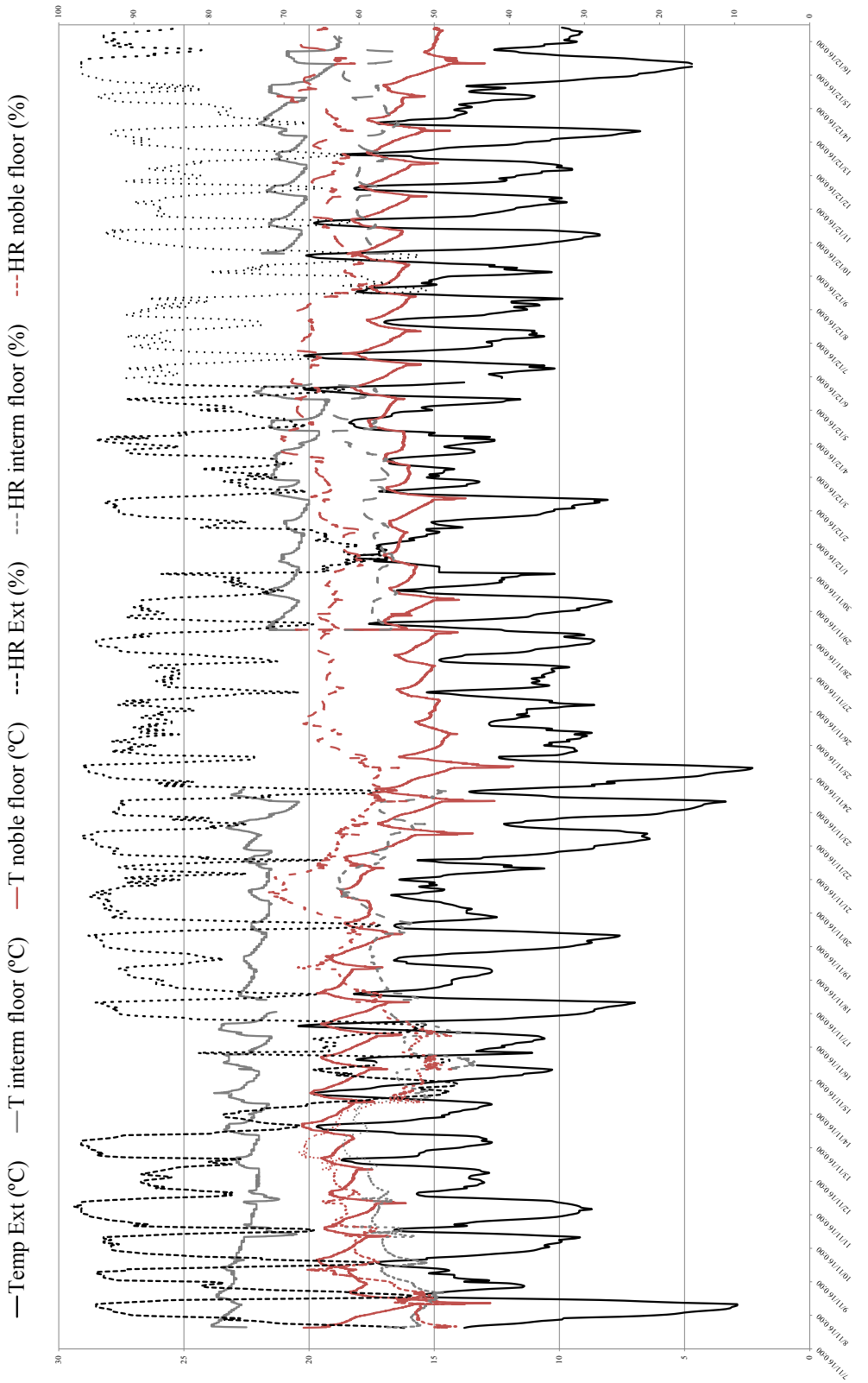

Fig.A.1. Variations of air temperature (Temp) and relative humidity (RH) on the intermediate floor of the Library, between November 7 and December 16, 2016: comparison with the environmental conditions and measurements on the Noble floor during the same period.

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