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Relationship between indoor thermal comfort conditions and the Time Weighted Preservation Index (TWPI) in three Brazilian archives

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ABSTRACT

There are many factors that affect paper degradation in archives, but air temperature and humidity under inadequate storage conditions are among the most important ones. Such inadequate conditions will trigger biological, chemical and physical processes that may enhance the degradation of papers. On the other hand, users of libraries and archives, where documents are stored, require adequate indoor conditions for carrying out diverse activities. In this paper we analyze the performance of archives with regard to paper and document storage conditions, also given in terms of the Time Weighted Preservation Index (TWPI), against overall comfort conditions, according to ISO 7730 and to the Building Bioclimatic Chart. For that purpose, five different settings were chosen, corresponding to indoor and outdoor conditions of three Brazilian archives, located in diverse climatic regions (Curitiba, 25°25′S 49°16′W, Belo Horizonte, 19°56′S 43°56′W and Rio de Janeiro, 22°50′S 43°10′W). The monitoring period comprehended 12 months, with a mid-term data collection. Results showed that there is a significant difference in storage conditions among different locations, even though there is a similarity in indoor thermal comfort conditions. A compromise solution should be sought between storage conditions and human thermal comfort parameters.

1. Introduction

Depending on the type of material to be stored in a given archive, an object can undergo alterations and, as a consequence, degradation, in three different manners: changes in dimensions, chemical reactions and biological degradation. The physical phenomena causing dimensional alterations are the expansion and contraction of organic materials, due to air temperature and humidity variations. Moisture absorbing materials, such as wood, bone, ivory, parchment, textiles, basketry and adhesives, swell in high ambient relative humidity of the air, consequently suffering deformation, movements of parts, cracks, rupture of fibers and under low relative humidity, such objects suffer a contraction. The phenomena resulting from chemical reactions originate from elevated temperature and moisture content of indoor air, causing corrosion of metals, oxidation, discoloring of paintings, acid hydrolysis of cellulose in papers, weakening of textiles, etc. Biological phenomena, however, are responsible for biological activities in all organic materials, as the result of a lack of ventilation and air changes in the presence of high temperatures and humidities. Humidity is the basis for the growth of microorganisms.

Particularly temperature and humidity conditions have a direct effect on stored materials, requiring a set of actions to meet the collection's requirements, with the aim of preserving Cultural Heritage. Considering the high costs of permanently running HVAC systems, a viable and less costly alternative could be the implementation of passive strategies, eliminating or at least reducing the need of a permanent air-conditioning of the indoor space.

The purpose of this research was twofold: on one hand, to evaluate different Brazilian archives located under diversified climatic conditions by means of indoor and outdoor air temperature and humidity measurements, when compared to recommended standards of the field of Preventive Conservation and, on the other hand, to verify whether for a limited monitoring paper degradation would take place. The initial idea was to observe paper degradation as an aid to check the applicability of the recommended standards under natural aging conditions, considering that most of the traditional recommendations for paper storage, including the Time Weighted Preservation Index (TWPI), were developed from controlled, artificial aging experiments. Since aging of paper under ambient conditions is a very slow process, it is rather difficult to evaluate and predict with absolute certainty the effect of storage conditions based on the accelerated aging results. The motivation for carrying out this research was to find ways to make international standards more flexible and suitable for archives situated in tropical and subtropical regions.

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Nomenclature

PI	relative permanence of given paper or Permanence Index (non-dimensional)
T	air temperature (°C)
RH	relative humidity (%)
ΔH	activation energy (kcal)
TWPI	Time Weighted Preservation Index (non-dimensional)
PMV	predicted mean vote (non-dimensional, according to a 7 point-scale)
M	metabolic rate (W)
DF	decrement factor (non-dimensional)

In recent years, there has been a considerable effort in Brazil from research centers and governmental programs to promote energy conservation measures in many sectors. The *PROCEL Edifica* initiative is one of the main programs, funded by the National Government, aiming at the rational use of electricity in buildings. More recently, in 2009, a technical regulation focusing on energy efficiency was developed for commercial, services and public buildings (*Regulamento Técnico da Qualidade do Nível de Eficiência Energética de Edifícios Comerciais, de Serviços e Públicos – RTQ-C*). Although Brazil's energy generation comes from renewable sources (about 45% of total energy production), there has been a trend over the last decade that non-renewable sources take hold of the bulk of the country's energy production [1]. In this sense, such initiatives contribute to reduce energy demand in the building sector, thus the determination of more appropriate storage conditions in archives can have an impact on the demand for air-conditioning and be also part of this context.

On the other hand, the evaluation of such spaces from the point of view of human thermal comfort is justified, considering the human occupancy of storage places (keepers and visitors). Under tropical conditions, it is not unusual that indoor conditions of libraries and archives will trigger respiratory diseases in occupants, in some cases due to fungi formation linked to inadequate storage conditions. In other cases, indoor thermal conditions may be too uncomfortable for users and a cause of absenteeism (keepers).

Recently spread information concerning fungi contamination in the Manguinhos Library [2,3], which belongs to the distinguished Brazilian institute Fundação Oswaldo Cruz, located in Rio de Janeiro, depicts an episode that lead to an interdiction of the building during several months of 2006–2007. Professionals and experts gathered thereafter to define strategies for improving indoor conditions, considering three different approaches: storage adequacy, hygienic measures and maintenance, and measures related to human health. Among the causes that lead to the fungi spread in the archive are: combination of high air temperatures and humidities following a rainy week, high daily indoor fluctuations of the indoor air temperature and concurrent repairs and interruptions in the existent HVAC system. The episode exemplifies the interaction between storage conditions and their impacts on occupants.

Considering the combined effect of air temperature and humidity in such spaces, the present paper investigates whether compatibility solutions are possible, from the aspects of human thermal comfort and paper storage conditions. Thus, the objective of this study is to monitor the change in storage conditions of archives located in three different climatic regions in Brazil and assess its impact on the overall thermal performance of each building and on human thermal comfort levels according to ISO 7730 [4]. A follow-up of this study is being carried out in university libraries, where paper (books, magazines, journals) and people share the same space.

2. Materials and methods

As aforementioned, one of the purposes of the research was to evaluate the adequacy of three different Brazilian archives in storing paper samples, by means of thermal monitoring inside and outside those archives. As a relevant aid for analysis, paper samples, which were bought commercially, were exposed to ambient and indoor conditions of the chosen archives for a given period of time and the physical and chemical decay rates were assessed. The detailed analysis of the observed paper decay rates after natural exposure is not part of the present analysis and will therefore not be discussed in this paper. In order to preserve the anonymity of the evaluated national and regional archives, they are termed in this paper "Archive 1", "Archive 2" and "Archive 3".

Paper samples were accommodated in small acrylic containers and exposed to different conditions of temperature and relative humidity in three Brazilian climate types: CFa (Curitiba, 25°25′S 49°16′W, 910 m above sea level), Cwa (Belo Horizonte, 19°56′S 43°56′W, 860 m above sea level) and Aw (Rio de Janeiro, 22°50′S 43°10′W, on the east coast), according to Koeppen–Geiger's climate classification [5].

Six different settings were originally chosen for exposing the paper samples, corresponding to indoor and outdoor conditions in each location. The period for the natural aging of the paper samples at such locations comprehended 12 months, with a mid-term data collection. In this paper we analyze the performance of such archives with regard to paper and document storage conditions, also given in terms of the Time Weighted Preservation Index (TWPI), against overall thermal comfort conditions, according to the Building Bioclimatic Chart and to ISO 7730 (PMV).

2.1. The box container

The small-sized container used for storing and exposing the paper samples consists of an acrylic box (41 × 41 × 16 cm, 4 mm thickness), naturally ventilated but provided with activated carbon filters on its openings (Fig. 1). Thomson [6] recommends the use of such filters as an efficient measure to control main pollutants, such as sulfur dioxide (SO_2), nitrogen dioxide (NO_2) and ozone (O_3). The acrylic walls have also been covered by a Solar Gard LX 70 film in

Fig. 1. The box container with datalogger outside the box.

order to block most of the UV (99%) and 95% of the infrared radiation.

The external boxes were provided with a ventilated roof structure, white painted, built with MDF, blocking direct radiation while allowing cross ventilation through the box openings (Fig. 2).

Inside such containers, dataloggers were placed for measuring temperature and humidity conditions to which the paper samples would be exposed during monitoring. The paper samples were hung on parallel strings and set aside from each other.

The paper samples were bought in a local stationery store. As a whole, 39 A4 paper sheets have been bought. Such sheets were then cut to fit the sample size of 10.5 × 29.7 cm. Seventy-eight strips were then used for the various tests referring to: (1) the initial conditions, after papers had been bought; (2) after 6 months of natural exposure; (3) after 12 months of natural exposure. Thus, inside the box, from day one, 52 strips were hung until the first data collection and 26 strips remained from the very first day until the end of the complete natural aging period of 12 months.

Dataloggers (Log Box, with an accuracy of ±2% for air temperature and ±5% for relative humidity, and resolution of 0.1 °C and 0.1%) were placed inside the internal and external box containers and compared to concurrent measurements of temperature and humidity outside the box. For the external box configuration (roof covered), measurements were carried out in the local meteorological station. In that case, reference datalogger was placed in the Stevenson screen used in the meteorological station for standard measurements (Fig. 3).

Comparisons of the temperature and humidity data showed that, apart from a small time lag resulting from the negligible thermal mass of the box container, measurements inside the container were equivalent to ambient conditions.

2.2. Monitoring

For each archive two locations were defined: inside the archive and outside it. For the outdoor measurements, the space above the flat concrete roof, common to the three archives, was chosen for placing the box container with ventilated roof structure. For the indoor measurements, the box container with the samples was placed inside the archive, exposed to usual storage conditions of other documents. As one of the main purposes of the research was to evaluate the thermal adequacy of the archives with regard to local climate, different space conditioning strategies were sought: Archive 1, without air-conditioning (Curitiba); Archive 2, with pre-programmed, forced ventilation, set to operate when vapor content outdoors is lower than indoors (Belo Horizonte); Archive 3, with a central air-conditioning system (Rio de Janeiro).

Fig. 2. The box container with roof in the meteorological station.

Fig. 3. Reference datalogger in the Stevenson screen.

Curitiba has a subtropical humid climate type, with cold winters. Mean annual temperature lies around 16.5 °C, with great daily and seasonal fluctuations. Monthly average relative humidity varies between 76% in July and 82% in summer.

Belo Horizonte has a tropical altitude climate type. Summer is characterized by rainfalls and high temperatures and winter is generally dry with low temperatures. Mean annual temperature is around 21 °C, with great daily and seasonal fluctuations, although seasonal fluctuations not as less extreme as in Curitiba. Monthly average relative humidity varies between 65% in August and 79% in summer.

Rio de Janeiro has a tropical Atlantic climate type with low daily and seasonal hygrothermal fluctuations. Mean annual temperature is around 24 °C. Monthly average relative humidity varies between 77% in July and 80% in the rest of the year.

The installation of the box containers took place at the end of August 2007. Monitored data considered for analysis was from September 6th, 2007 until September 5th, 2008.

2.3. Archives

All archives are not naturally ventilated, windows are sealed. Traditional masonry of ceramic bricks, plastered and without insulation is also common to all three archives. Ceiling material consists of concrete slabs.

In Archive 1 (without air-conditioning, located in Curitiba), the indoor box container was positioned on the upper floor of the archive.

In Archive 2 (with an automated, forced ventilation system, located in Belo Horizonte), the indoor box container was placed on the first floor of the archive, where the forced ventilation system is located. The system contains a dehumidifier and inflow/exhaust fans with activated carbon filtering. The set point for relative humidity is 50% and the desired indoor temperature is 24 °C. The system operates continuously, being fully automated: forced ventilation and dehumidification only take place, when outdoor conditions are more favorable than indoors (such automation is based on sensor measurements and on PI calculations – shown in the following section of this paper).

In Archive 3 (with a central air-conditioning system, located in Rio de Janeiro), the indoor box container was placed in an air-conditioned room. It is a Central Chilled Water HVAC System with cooling power around 140–280 refrigeration tons. Maintenance of the air ducts takes place once a year. The system is set to operate continuously.

3. Scientific background

This section is concerned with the scientific background of the indices used to evaluate indoor conditions in the three archives. The TWPI refers to paper storage conditions; the PMV [4] method was used to evaluate human thermal comfort conditions offered by each archive; and Givoni's Building Bioclimatic Chart was employed in order to evaluate the overall building performance in each case.

3.1. The TWPI calculation method

The Time Weighted Preservation Index (TWPI) can be calculated from monitored temperature and humidity data according to a mathematical formula, which takes into account the Permanence Index (PI), here calculated for every monitoring hour.

The PI is an attempt to link temperature and relative humidity with the rate of chemical degradation of materials. It is based on a detailed study of the hydrolysis of cellulose acetate and it has been extended to a wide variety of museum objects [7]. The PI is thus a relevant tool to quantify the effect of the environmental factors of temperature (T) and percent relative humidity (%RH) upon the anticipated useful life expectancy of paper-based collections [8]. As pointed out by Sebera, the isoperm method should be able to provide ready answers to a large variety of questions related to environmental conditions of stored objects, including changes in storage conditions, the effect of allowing wider swings in temperature and percent relative humidity about the established set point conditions and expected preservation gains as a result of modifications of existing or construction of new storage facilities.

According to Sebera, the isoperm method is restricted to strength loss associated with the chemical reactions of cellulose hydrolysis and oxidation; conventional wisdom attributed 90% or more of paper degradation to these two mechanisms. Also, the PI is a measure of the relative rather than the absolute rate of degradation (and paper permanence). The PI gives also an indication of the permanence (in years) or longevity of a given paper.

The relative permanence of given paper or the Permanence Index (PI) is expressed by the formula:

$$\mathrm{PI} = \frac{P_2}{P_1} = \frac{\mathrm{RH}_1}{\mathrm{RH}_2} * \left[\frac{T_1 - 460}{T_2 - 460}\right] * 10^{394*\Delta H*\left[\left[\frac{1}{T_2+460}\right]-\left[\frac{1}{T_1+460}\right]\right]} \tag{1}$$

where T and RH are air temperature and relative humidity for initial conditions (1) and for a given set of conditions (2). P_1 and P_2 are degradation rates of the paper under both sets of conditions and PI is the rate of degradation (or permanence) P_2 relative to P_1. ΔH is the activation energy, a constant that quantifies the sensitivity of a specific reaction to temperature changes [8]. Sebera suggests for ΔH the range of 30–35 kcal as a good approximation for most preservation applications.

In this paper a value of 35 kcal was used for ΔH, which is used by Sebera [8] for the isoperm definition in the case of paper samples. Reference T and RH considered as initial conditions refer to isoperm 1 (PI = 1, T = 20 °C and RH = 50%), according to Sebera [9]. PI 1 corresponds to a standard lifetime of 45 years for paper samples (ordinary newspaper).

The cumulative effect of PI values over a given period is given by the Time Weighted Preservation Index (TWPI). This index was proposed by the Image Permanence Institute IPI and takes into account the time effect of variable ambient conditions [10]. The TWPI can be calculated according to the formula:

$$\mathrm{TWPI}_n = \frac{n * \mathrm{TWPI}_{n-1} * \mathrm{PI}j_n}{\mathrm{PI}_n * (n-1) + \mathrm{TWPI}_{n-1}} \tag{2}$$

where n refers to the total number of time intervals.

3.2. ISO 7730 – PMV calculation

ISO 7730 [4] presents the calculation procedures of the predicted mean vote (PMV), a thermal sensation index originally developed by Fanger [11], which is "applicable to healthy men and women exposed to indoor environments where thermal comfort is desirable". The PMV index is based on a 7-degree two-pole thermal sensation scale (from very cold = −3 to very hot = +3) and is based on the heat balance of the human body.

The PMV was calculated for the indoor conditions of each archive from monitored temperature and relative humidity using the public domain software Rayman 1.2 [12], which is a model for estimating and calculating mean radiant temperature and thermal indices within urban structures. For the indoor conditions of each archive, it was assumed that: the mean radiant temperature was the same as the air temperature (no radiant heat sources) and the air speed is low and equal to 1 m/s. Calculations were made for an "average" male individual, according to ISO 8996 [13], a person 1.75 m tall with 70 kg and 30 years of age under sedentary activities (M = 80 W). Clothing levels were assumed differently for the summer (first 6 months) and for the winter season (the rest of the monitoring period), 0.4 clo and 0.9 clo, respectively. The assumptions made had the sole purpose of simplifying greatly the input of environmental data, which was fed to Rayman as a list of measured temperature and relative humidity data in a text file.

3.3. Givoni's Building Bioclimatic Chart

A well-known method of bioclimatic analysis consists of plotting temperature and humidity data in the psychrometric chart, and then identifying comfort strategies. This procedure allows a firsthand climate data analysis, aimed at formulating building design guidelines [14].

The first method conceived for plotting climate data (ambient) on a diagram, which could be useful for building design was developed by Olgyay [15]. Later, Givoni [16] proposed the Building Bioclimatic Chart (BBCC), which is based on indoor temperature and humidity data rather than ambient conditions, plotted on a psychrometric chart. Givoni suggests that the BBCC chart is indicated for naturally ventilated buildings. A revision of the original BBCC was shown in Givoni [14] and was recently adopted by the Brazilian Thermal Performance Standard [17] for the definition of bioclimatic zones and corresponding building design guidelines for low-cost houses.

In this paper, all measured data (T and RH for the whole monitoring period of 12 months) in the three archives have been plotted separately on Givoni's Building Bioclimatic Chart with the Analysis software, developed at the Federal University of Santa Catarina, Brazil [18], which uses the revised BBCC.

4. Results

This section presents monitoring results in terms of storage conditions and indoor comfort in the three archives.

4.1. T and RH monitoring and obtained TWPI

Monitoring of temperature and relative humidity allowed the evaluation of the overall performance of each space as well as an appraisal of the HVAC system adopted in each archive. The total monitoring period consisted of one full year of natural aging in the three locations and accordingly the data should be comprised of six data sets (indoor and outdoor data for the three archives), divided into two periods (6 months and 12 months). However, a summer storm destroyed the outdoor box container in Belo Horizonte and, as a result, for Archive 2 we had T and RH measurements as well as observed paper degradation rates only for the internal conditions. In addition, the datalogger which was installed in the box container in Rio de Janeiro stopped registering during the summer period, possibly due lightning strikes. It was thus decided to use climatic data from the nearby meteorological station in each city as a reference for ambient conditions.

There were also some gaps in the outdoor data for Curitiba and in the indoor data for Archive 3 in Rio de Janeiro, which showed unrealistic values for the relative humidity in the end of the monitoring period. As a result, an average of the observed relative humidity was assumed for that time period.

Nevertheless, monitored data show a consistency with climatic features of each location (outdoor data) and with the air-conditioning system used in each archive (indoor data).

Figs. 4–6 show monitored temperatures inside and outside each archive, which correspond to the natural aging conditions the paper samples have been exposed to.

Fig. 4 shows the higher daily and seasonal temperature fluctuations, the lower average temperatures and the more defined seasons, which characterize Curitiba, where Archive 1 is located. In the same graph, the great internal fluctuations also reflect the passive operation of the building, which has no HVAC system under use.

Fig. 5 shows the intermediate outdoor climatic conditions of Belo Horizonte (Archive 2), as compared to Curitiba and Rio de Janeiro, with maximum temperatures below 35 °C and minimum temperatures usually above 10 °C. Indoor temperature conditions are more stable than in Archive 1, due to the forced ventilation strategy used.

Fig. 6 shows the effectiveness of the HVAC system of Archive 3 in lowering indoor temperatures. Although the pattern of the internal temperatures curve is not constant, due to an intermittent operation of the system (it was later observed that the HVAC system is turned off on weekends), indoor conditions will not exceed 25 °C, even though ambient conditions may reach up to 35 °C and above that in some occasions.

Table 1 presents a summary of indoor and outdoor averages as well as temperature and relative humidity amplitudes (mean diurnal swings) and observed differences between maxima and minima for both periods (mid-term: 6 months, and complete monitoring period: 12 months). It is assumed that two basic stress conditions

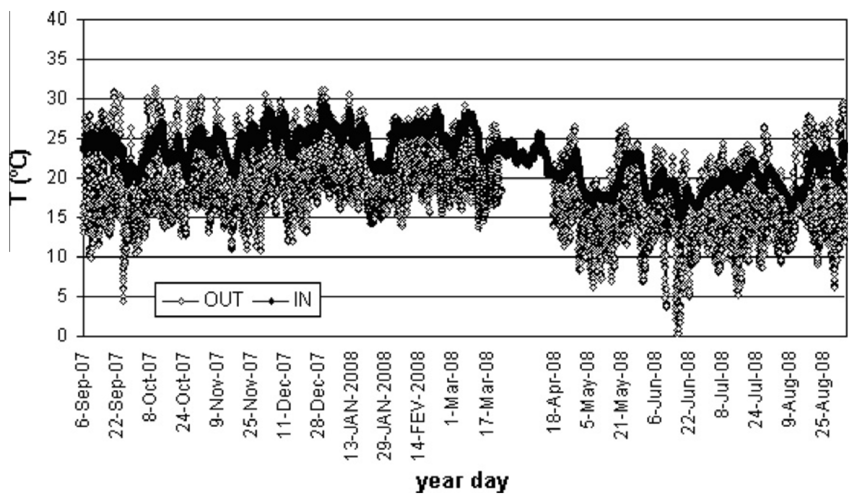

Fig. 4. Indoor and outdoor conditions in Archive 1 (Curitiba).

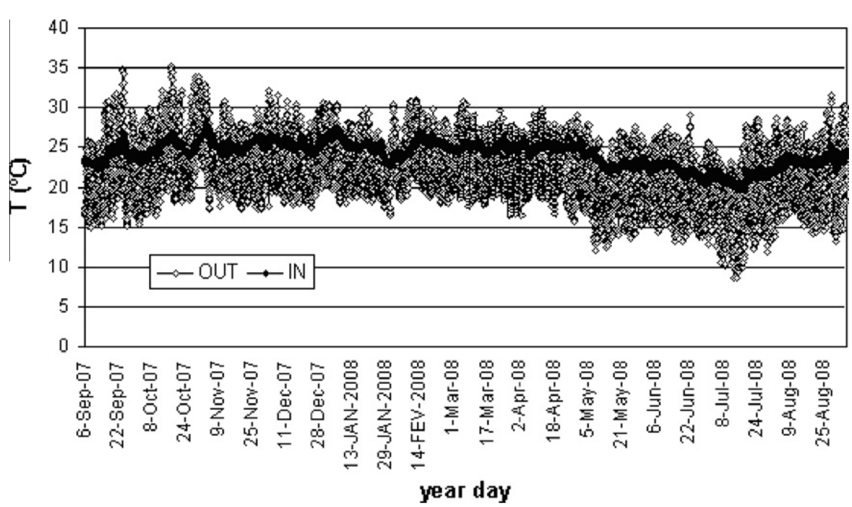

Fig. 5. Indoor and outdoor conditions in Archive 2 (Belo Horizonte).

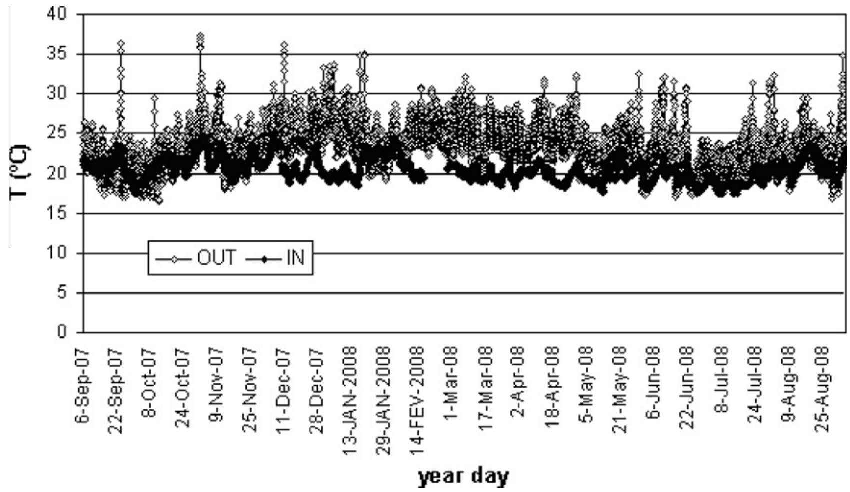

Fig. 6. Indoor and outdoor conditions in Archive 3 (Rio de Janeiro).

Table 1
Indoor and outdoor monitoring conditions.

		T_{min} (°C)	T_{max} (°C)	RH_{min} (%)	RH_{max} (%)	Average diurnal swing (°C)	Average diurnal swing (%)	Absolute fluctuation for the period (°C)	Absolute fluctuation for the period (%)
6 Months	Archive 1 (indoors)	19.0	29.4	35	73	1.4	5	10.4	38
	Archive 2 (indoors)	22.3	27.7	38	72	0.6	3	5.4	34
	Archive 3 (indoors)	17.4	25.0	63	88	0.9	4	7.6	25
	Archive 1 (outdoors)	4.4	31.4	22	95	9.5	39	27.0	73
	Archive 2 (outdoors)	15.0	35.2	15	98	9.3	38	20.2	83
	Archive 3 (outdoors)	16.4	37.3	17	96	5.6	22	20.9	79
12 Months	Archive 1 (indoors)	14.8	29.4	35	79	1.2	6	14.6	44
	Archive 2 (indoors)	19.7	27.7	38	72	0.6	3	8.0	34
	Archive 3 (indoors)	17.4	25.0	63	94	0.9	5	7.6	31
	Archive 1 (outdoors)	-0.1	31.4	21	100	9.5	40	31.5	79
	Archive 2 (outdoors)	8.6	35.2	14	98	9.7	41	26.6	84
	Archive 3 (outdoors)	16.4	37.3	17	96	5.3	23	20.9	79

will have an impact on paper degradation: the short-term indoor swings and the long-term T and RH fluctuations.

The table confirms some of the observations discussed above. Archive 1 shows greater average and absolute fluctuations of indoor temperatures and relative humidities in both periods, as a result of its free-running condition (no HVAC). Higher temperatures are observed outside Archive 3. Adopting optimal storage conditions for paper (PI = 1, T = 20 °C and RH = 50%) as a reference, it is possible to verify which percentage of time is above such limits and thus obtain another indicator for each T and RH conditions the paper samples have been exposed to (Table 2).

From the table, it is verified that some archives provide worse storage conditions than the ambient. Such is the case for Archives 1 and 2, concerning measured air temperatures. Archive 3 shows about half of the hours of the total monitoring period (12 months) not departing from recommended temperature limits, but virtually no control of internal moist.

The calculated TWPI for each archive is shown in Table 3. It should be reminded at this point that TWPI values above the unity will mean a prolonged lifetime of the expected lifespan of that given paper, values below that mean that the lifetime is shorter than under standard conditions (isoperm 1, T = 20 °C and RH = 50%). The relationship between internal and external TWPI was also obtained, showing the ability of each archive to promote better storage conditions for paper collections than under ambient T and RH conditions. In the table, it is verified that Archive 3 (air-conditioned), among all three archives, provides better storage conditions, according to the TWPI calculation procedure. The two other archives present worse conditions for paper storage than outdoors (TWPI relation below unity). Nevertheless, all archives

Table 2
Percentage of time above $T = 20$ °C and RH = 50%.

		T above recommended limits (%)	RH above recommended limits (%)
6 Months	Archive 1 (indoors)	99	87
	Archive 2 (indoors)	100	83
	Archive 3 (indoors)	72	100
	Archive 1 (outdoors)	36	90
	Archive 2 (outdoors)	76	79
	Archive 3 (outdoors)	87	98
12 Months	Archive 1 (indoors)	77	92
	Archive 2 (indoors)	100	86
	Archive 3 (indoors)	56	100
	Archive 1 (outdoors)	29	88
	Archive 2 (outdoors)	65	80
	Archive 3 (outdoors)	87	97

Table 3
Calculated TWPI and TWPI relation.

		TWPI (indoors)	TWPI (outdoors)	$TWPI_{in}/TWPI_{out}$
6 Months	Archive 1	0.33	0.68	0.49
	Archive 2	0.30	0.38	0.51
	Archive 3	0.52	0.28	1.86
12 Months	Archive 1	0.37	0.78	0.47
	Archive 2	0.32	0.41	0.78
	Archive 3	0.55	0.29	1.90

Table 4
PMV averages and estimated indoor thermal comfort/discomfort levels.

		PMV average	Cold (%)	Comfort (%)	Warm (%)
Period 1 (09–06–07 to 02–20–08)	Archive 1	−0.6	66.6	25.4	7.9
	Archive 2	−0.3	55.8	23.1	21.1
	Archive 3	−1.8	100	0	0
Period 2 (02–21–08 to 09–05–08)	Archive 1	−0.3	55.8	23.1	21.1
	Archive 2	0.3	9.6	44.0	46.4
	Archive 3	−0.5	80.4	18.3	1.3
Entire monitoring period	Archive 1	−0.4	60.7	24.2	15.1
	Archive 2	−0.06	36.3	37.2	26.5
	Archive 3	−1.09	89.4	9.9	0.7

provide worse conditions than the ideal isoperm 1, meaning that even with costly mechanical systems ideal storage conditions will not be reached.

4.2. Indoor comfort conditions (PMV calculations)

Results can be represented for the two periods, the first one characterized by higher temperatures and within a time period which spans from the fall season until close to the spring equinox, and the second half, until the end of monitoring. In addition, a summary of indoor comfort conditions is shown, so that correlations to observed TWPI, which is a cumulative preservation index, can be drawn. Table 4 presents the average PMV obtained for a male individual, under sedentary activities in each archive as well as the percentage of time (hours) below and above the recommended limits for the PMV, according to category "A" for the thermal environment [4]: $-0.2 < \text{PMV} < +0.2$.

Results indicate that the best conditions can be found for the second half of the monitoring period in Archive 2, which had a controlled, forced ventilation system. For the warmer period, the same archive had the highest rate of "hot" hours. The worse conditions with regard to human thermal comfort can be found in Archive 3, which is permanently air-conditioned. In such an archive, in summer, for the adopted clothing ensemble of 0.4 clo, virtually all hours lie within cold conditions, i.e. PMV under −0.2, thus the considerably low average value of −1.8 for that variable.

4.3. Indoor comfort conditions (BBCC)

The thermal performance conditions for each archive is given in terms of the obtained percentages of hours within the boundaries of the comfort zone in the Building Bioclimatic Chart (BBCC), which are assessed from the chart generated by the Analysis software. Solely indoor conditions are shown in Figs. 7–9.

Indoor comfort conditions vary just slightly among the archives: Archive 1 had 90% of the monitoring hours within the comfort range, Archive 2100% and Archive 383%.

5. Discussion

With regard to reducing temperature and relative humidity fluctuations in each archive (Table 1), it is noticed that Archive 2 has a similar control over diurnal and seasonal fluctuations as the permanently air-conditioned Archive 3. The relationship between the indoor and the outdoor diurnal as well as seasonal T and RH swings (given by the decrement factor DF[1]) shows in almost all cases lower values for Archive 2, which has a forced ventilation system with moist control, meaning that such an archive promotes better control of indoor fluctuations with a much less complex HVAC system and consequently a lower energy demand. Indeed, it has been noticed in previous studies that in subtropical regions forced ventilation with humidity control (operating the system selectively, according to outdoor vapor pressure levels) can improve indoor storage conditions [19,20]. However, as pointed out by Michalski [21] and other critics of tightly controlled temperature and RH set points for storage environments [22], controlling indoor fluctuations is secondary, not primary, to the preservation of records.

The observation of optimal *T* and RH parameters (Table 2), which do not exceed isoperm 1 (PI = 1, $T = 20$ °C and RH = 50%), may be relevant under the preventive conservation point of view. Best conditions for humidity control are verified in Archive 2, however at the cost of raising its indoor temperatures. Worst conditions for humidity control are noticed in Archive 3, suggesting that such the HVAC system operates according to a temperature set point, only. If we observe results for the outdoor conditions, however, it is striking that Archive 1, located at a colder region, does not take any advantage by passive means of the lower temperatures outdoors, which could be quite beneficial for paper storage.

Assuming that the TWPI (Table 3) is a relevant preservation index and looking into the TWPI relation ($TWPI_{in}/TWPI_{out}$), Archive 3 presents the most favorable conditions for storing paper and documents, for both time spans. Nevertheless, considering outdoor TWPI parameters, it is verified that external conditions in Curitiba (Archive 1) surpass by far the monitored indoor conditions and are more beneficial (from the preventive conservation perspective) than results obtained indoors in both periods in Archive 3. That fact suggests that an improved design of the building (storage place), that would take advantage of the city's colder climate, could

[1] Such 'daily swing relation' can be meaningful for evaluating the thermal performance of buildings. Once indoor temperature conditions can be stabilized around a given range, it is matter of adjusting it (by mechanical means or passively, increasing solar gains or restricting them with shading devices, controlling ventilation openings, etc.) to a comfortable temperature range. A low DF means that the building is capable of satisfyingly narrowing this range, relative to outdoors.

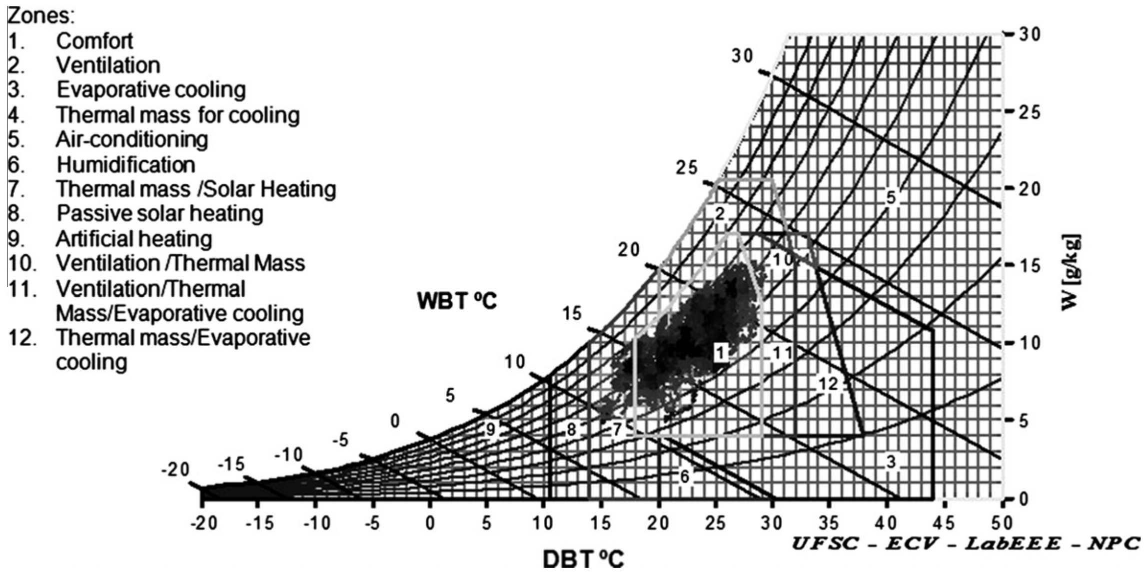

Fig. 7. Indoor comfort conditions in Archive 1 (Curitiba).

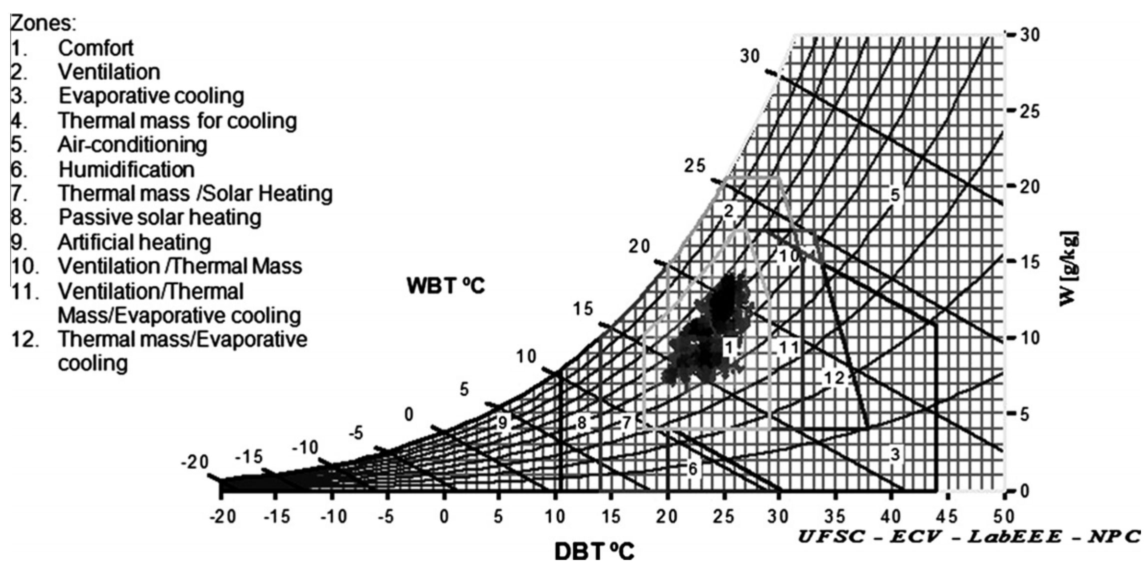

Fig. 8. Indoor comfort conditions in Archive 2 (Belo Horizonte).

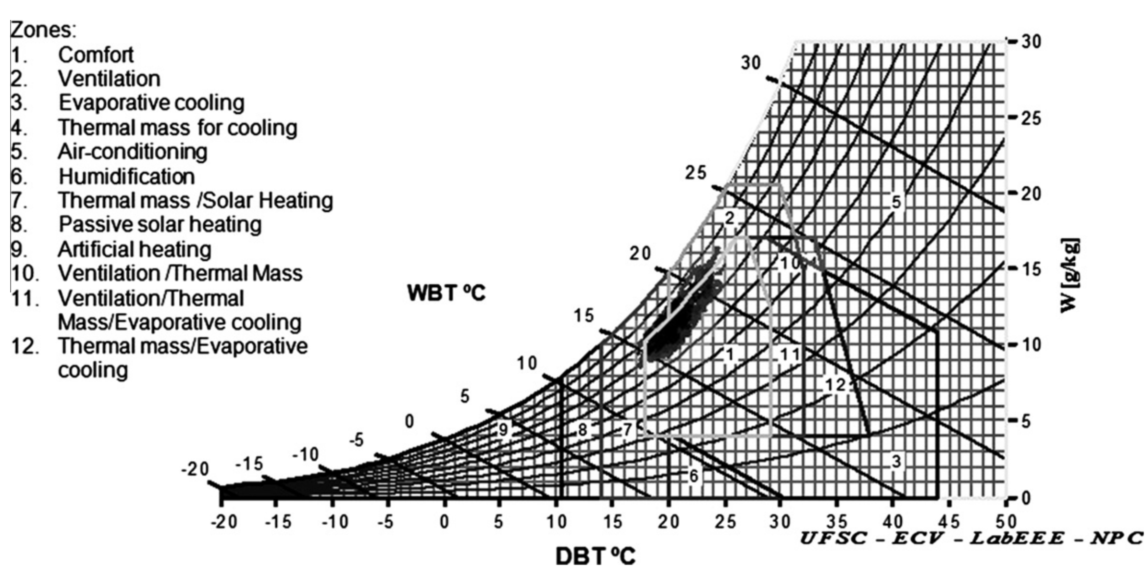

Fig. 9. Indoor comfort conditions in Archive 3 (Rio de Janeiro).

present optimal paper storage conditions while not needing HVAC strategies.

The bioclimatic charts (BBCC, Figs. 7–9) suggest that in general the archives do not present thermal discomfort. Nevertheless, the more detailed PMV analysis (PMV, Table 4) shows variations for each separate archive. The comfort analysis is in some ways contradictory to TWPI results. Whereas the best paper storage conditions are found in Archive 3, such an archive yields the lowest PMV for the complete time span (PMV −1.09). In the first 6 months, best comfort conditions are verified in Archive 1, which has a low TWPI relation.

An assessment of human thermal comfort levels in terms of the PMV indicate that this comfort index is very affected by the average indoor temperature. Warmest conditions are found in Archive 2, in both periods. On the other hand, optimal storage conditions require controlled indoor temperature below and not greater than 20 °C. Best conditions with regard to both requirements would then need a compromise solution. In the archives evaluated, Archive 1 could provide the best case. Figs. 10 and 11 show that such an archive would perhaps act as an intermediate solution for both parameters. Again, it should be stressed that this particular archive, which is located in a cold region, could be substantially improved by building design and yield better storage conditions (and possibly reduce thermal discomfort due to heat).

5.1. Human thermal comfort and paper conservation in archives: searching for a compromise solution

As stated in the introductory part of this paper, the motivation for carrying out this research was to find ways to make international standards more flexible and suitable for archives situated in tropical and subtropical regions. In this sense, not only energy efficiency issues are raised, with regard to the maintenance of excessively high standards, but also the occupant thermal condition should be considered, either as keeper or user of the indoor space.

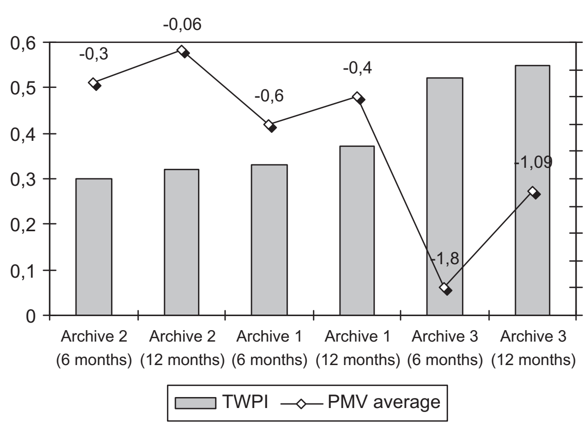

Fig. 10. Indoor storage versus comfort conditions (PMV).

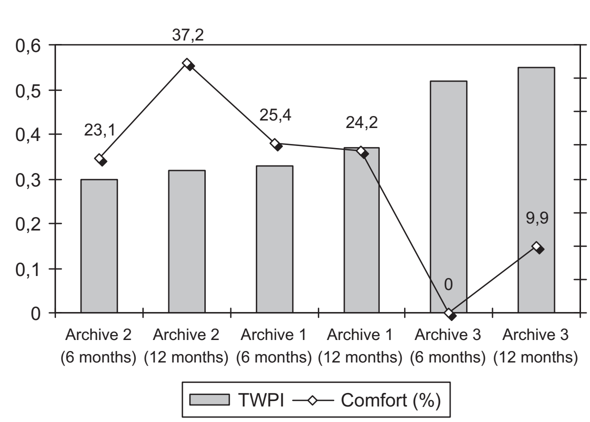

Fig. 11. Indoor storage versus comfort conditions (comfort).

The diagram of Fig. 12 shows the human thermal comfort, as defined by Givoni [14], the regions where mould growth occurs and where paper becomes too brittle, when fold endurance tests would fall, along with the respective isoperms (with isoperm 1 at 50% RH and 20 °C), which give an indication of the permanence (in years) or longevity of a given paper.

If the wide range of Givoni's comfort zone for developing countries is considered for evaluating indoor human thermal comfort conditions provided by a given archive, it can be noticed that the inferior boundary for paper storage, at 20% relative humidity, as suggested by Sebera [8], practically coincides with the lower comfort limit. According to Michalski [21], mould growth may start by 60% relative humidity (although quite slowly), although it will only speed up with higher humidities. Here we maintain Sebera's suggested limit of 65%. In the same diagram, the isoperm curves indicate that lower temperatures would yield greater paper longevity. A rule of thumb in Preventive Conservation states that for a 5 °C drop in room temperature doubles the lifetime of a paper [23,24].

If one departs from isoperm 1 downwards, indoor temperatures could vary from 25 °C to about 18 °C, under controlled, low indoor humidity levels, in order to meet human thermal comfort and paper storage requirements. It should be stressed, from new guidelines for humidity and temperature in archives [21], that there is no need of extremely rigid control of indoor temperature and humidity fluctuations. Considering that paper collections (mildly and strongly acidic papers, photographs) stored in archives can be classified as having medium to low chemical stability, with a lifetime ranging enormously from 30 to 300 years, the Canadian Conservation Institute (CCI) suggests that fluctuations of ±10% in relative humidity and of ±10 °C in air temperature would cause none to tiny damage, provided that room temperature does not exceed 30 °C and relative humidity does not rise above 75%.

The archives and active and passive conditioning systems shown in this paper all failed to provide moisture control (Figs. 13–15), one of the key factors related to paper degradation.

Two of the archives show the bulk of indoor humidity conditions above 75%, when, according to Michalski [21], mould growth will greatly speed up.

According to the more restrictive PMV approach, for archive keepers appropriately dressed for the air-conditioned indoor space,

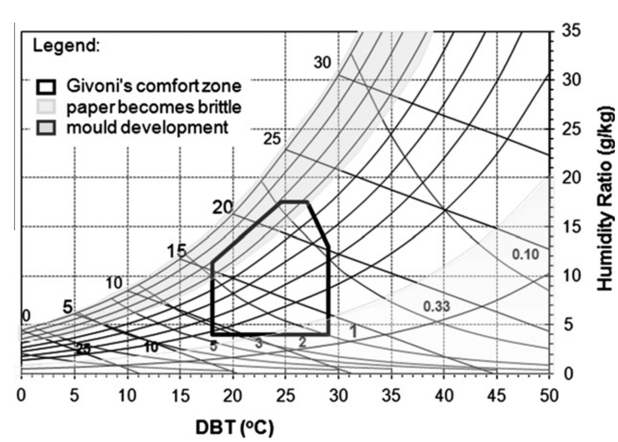

Fig. 12. Psychrometric chart with mould growth and paper brittleness regions, lines of constant lifetime (isoperms) and Givoni's comfort zone.

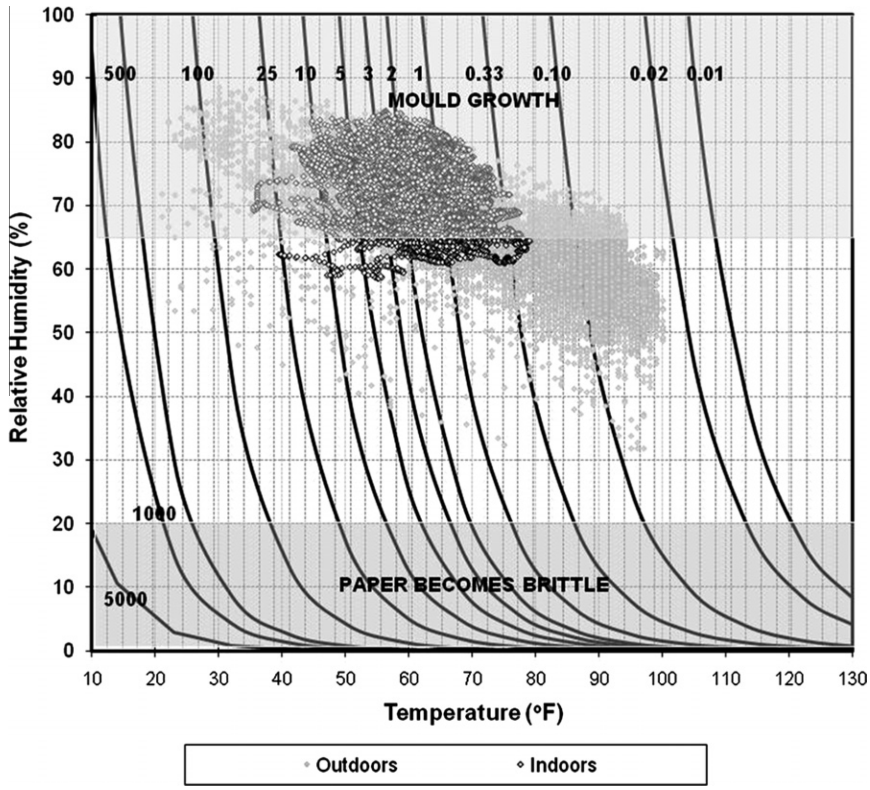

Fig. 13. Humidity conditions for monitoring data in Curitiba, plotted against mould growth and paper brittleness regions and lines of constant lifetime (isoperms).

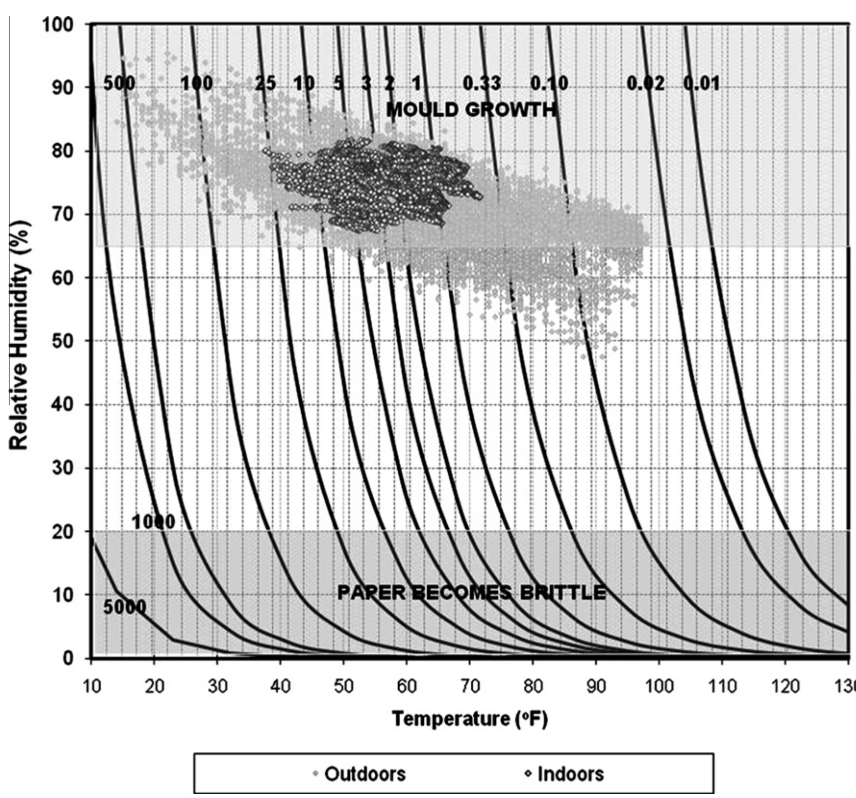

Fig. 14. Humidity conditions for monitoring data in Belo Horizonte, plotted against mould growth and paper brittleness regions and lines of constant lifetime (isoperms).

with clothing insulation of 1 clo, metabolic rate of 1.2 met and low air speed (<0.1 m/s), ISO 7730 would allow variations in room temperature (Class B, for offices) ranging 20–24 °C, which are close to the above mentioned limits suggested by Givoni. But the issue of controlling indoor moist, crucial for paper collections, would still remain.

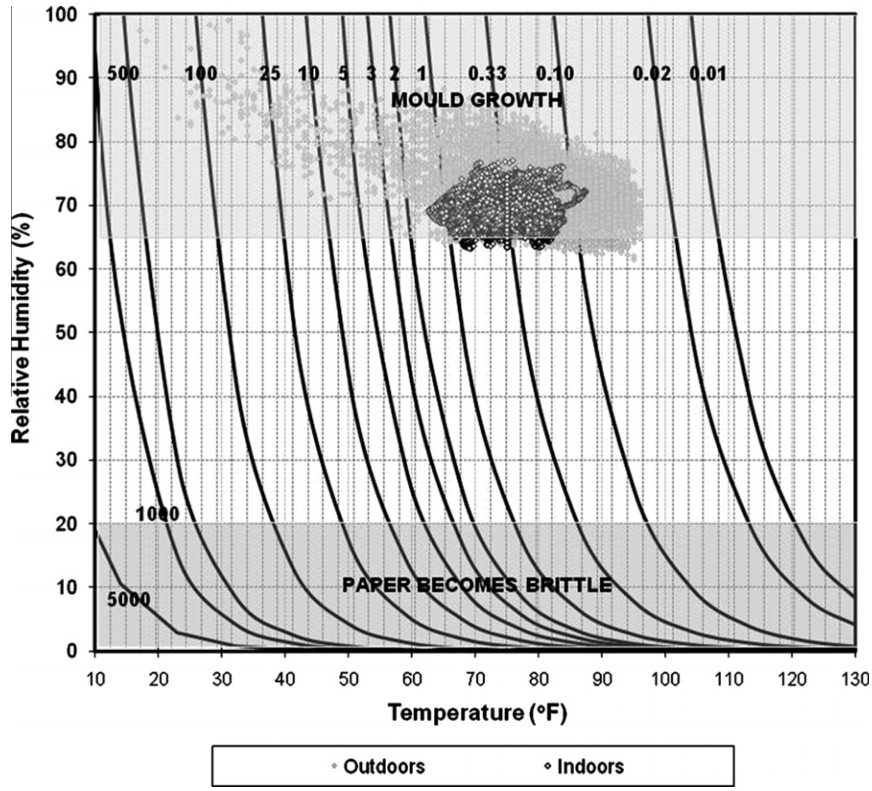

Fig. 15. Humidity conditions for monitoring data in Rio de Janeiro, plotted against mould growth and paper brittleness regions and lines of constant lifetime (isoperms).

From the eight bioclimatic zones, determined for the Brazil by Roriz et al. [25], it can be verified that high humidities characterize most of the Brazilian territory. Such conditions are mostly concentrated in the warm–humid region (over 50% of the surface area), where the combined effect of high air temperature and humidity would require permanent air-conditioning in archives. In some regions, including the Brazilian capital, Brasilia, a dry period takes place during the year, usually accompanied by lower temperatures, below 25 °C. Such conditions, while restricted to a small part of the Brazilian territory would allow free-running archives during a small part of the year. The southern region has in general mild winter periods, although such periods present high humidities, usually above 60%. The corresponding bioclimatic zones of the southern region, which represent nearly 7% of the Brazilian territory, indicate the possibility of a controlled use of heaters for room dehumidification, in the colder periods of the year, when ambient temperatures can range from under 10 °C up to around 20 °C.

6. Summary

Although results from the comfort analysis using the BBCC showed very similar results, thermal comfort calculations using the PMV index, based on Fanger's mathematical thermal model provided a more detailed analysis. It is suggested that free-running buildings, when well designed according to local climatic conditions, may provide amenable conditions for human thermal comfort as well as promote a favorable environment for storing paper and document collections.

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