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Article

The European Standard EN 15757 Concerning Specifications for Relative Humidity: Suggested Improvements for Its Revision

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Abstract: The European Standard EN 15757: 2010 'Conservation of Cultural Property—Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials' is a guide specifying the allowed limits of variability of the indoor climate, in particular relative humidity (RH) to preserve cultural heritage objects and collections composed of climate-vulnerable materials. This paper is finalized to provide useful elements to improve the Standard at its next revision, based on focused research. The methodologies and the mathematical tools used are performed on 18 case studies representing different buildings, climates, and use, including heated and unheated buildings, museums, churches, concert halls, archives, and storage rooms. The first aim is to compare the method based on the centred moving average suggested by Annex A of EN15757 with an alternative method based on percentile interpolation to calculate the reference RH values, and in particular the safe band of RH variability, as well as the upper and lower risky bands. It has been found that the two methods provided the same results, but the latter is easier to manage. The second aim is to verify if the duration of the record necessary for the determination of the safe band is really 13 months of measurements as required by the Standard to account for the specific request of the centred moving average with a 30-day time window. This paper demonstrates that the same goal may be reached with a 12-month record, but extracting from the record itself the two periods required by the time window, i.e., the last 15 days of the year will be copied before the start of the record, and the same with the first 15 days after the end. The third aim is to test if the particular choice of the width of the time window is influential on the width of the safe band, and to assess the relationship between the width of the safe band and the width of the time window. The results show that the safe band logarithmically depends on the length of the time window, so it is crucial to respect the 30-day window established by the Standard.

Keywords: European standard; indoor climate; relative humidity; environmental diagnostics; conservation of cultural heritage

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1. Introduction

The European Standard EN 15757: 2010 (This Standard was produced in 2010 and confirmed in 2015 and 2020. In confirmed standards, the use is to cite the year of the first adoption, not the last confirmation).'Conservation of Cultural Property—Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials' [1] is a guide specifying the temperature (T) and relative humidity (RH) to preserve cultural heritage by limiting physical damage induced by strain-stress cycles in objects composed of, or containing organic hygroscopic materials, e.g., wood, painting on canvas, books, graphic documents, textiles, bone, ivory, or leather. The aim is to preserve the physical integrity of cultural objects, avoiding either the deterioration of the materials of which they are composed, or critical conditions when different materials are bound together, e.g., in a book the shrinkage of the sheets of paper is different from that of its lambskin cover and twine binding; if the RH drops too much, the tensions between these different elements will tear off the book.

The rationale of the Standard EN 15757 is that over time the considered materials have 'acclimatised' to the microclimate conditions where they have been kept for significant periods of time. These conditions are named 'historical microclimate'. This means that these materials have been adapted to the average values, the seasonal changes, and the everyday fluctuations of the ambient T and RH. The adaptation process is long and causes negative consequences for the materials because seasonal cycles and short-term fluctuations of T and RH cause repeated internal stress, temporary or permanent deformations (e.g., shrinkage or swelling), and create internal micro or macro fractures. The role of these fractures is to act as expansion joints to dissipate internal stress, thus enabling a wider range of acceptable T and RH fluctuations. However, this acclimatisation is achieved at the expense of the integrity of the material which is now weaker and more vulnerable. The repetition of new stress, especially for enhanced RH fluctuations, may induce some internal micro cracks to grow, extend in size, become visible, and disfigure the object.

Section 5 contains the Standard's explanation for why it is especially focused on RH. The reason is that, in organic hygroscopic materials, the mechanical damage (e.g., permanent deformation, formation of cracks) is more affected by changes in RH than in T. The Standard specifies, however, that in the particular case RH and T have the same priority, i.e., similar impacts, the specifications and the methodologies given for RH hold for T as well. This article adopts the same criterion, i.e., it formally deals with RH, but the same conclusions can be applied to T.

As illustrated in other papers [2,3], this European Standard establishes two basic principles: (i) the need to maintain stable environmental conditions, and (ii) the priority of historical climate. If this Standard is compared with ASHRAE [4,5], one finds that the former priority is considered in both, while only the European Standard considers the historical climate as a priority.

In reality, ASHRAE [4,5] considers selected bands of T and RH, irrespective of the past history of the objects. In addition, ASHRAE introduces the concept of taking advantage of unplanned extreme events, that may be interpreted like a crash test, i.e., suppose an extreme, unplanned RH fluctuation happened by chance, could the object survive this tremendous impact without serious consequences? This unplanned test has been called 'proofed' fluctuation [6] and is the largest climate fluctuation that an object has accidentally experienced passing apparently untouched. The underlying idea is that if the object has survived the first time, it can survive all the others as well. However, it has been observed that this is not true and that in the long run the micro cracks grow internally until they reach the surface and appear as macroscopic cracks [2,7–13].

When the European Standard was drafted (one of the authors is among the drafters), the experts of the working group discussed how to define and calculate the safe and the risky fluctuations. Using the findings of measurements performed by the experts with laboratory tests and several case studies in museums, historical buildings, and churches, as a basis, it was agreed that a safe condition may be reached by excluding the most extreme fluctuations that have the highest potential of risk. It was agreed to exclude the most severe fluctuations up to 14% of the total, i.e., 7% of the lowest and 7% of the highest ones. The RH values falling between two reference percentiles, i.e., the 7-ile and the 93-ile are considered to lie in a safe band (SB) and acceptable; those external to SB lie in a risky area, are dangerous, and should be excluded. This situation determines two risky bands (RB): the lower RB form 0-ile to 7-ile characterised by the most extreme dry conditions, and the upper RB form 93-ile to 100-ile characterised by the most extreme humid conditions.

However, if the RH fluctuations depart less than 10% from the seasonal RH level, all fluctuations are considered acceptable.

This method complies with the World Meteorological Organization (WMO) and the Intergovernmental Panel on Climate Change (IPCC), i.e., "an extreme event is generally defined as the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends ('tails') of the range of observed values of the variable" [14]. "An extreme weather event is an event that is rare within its statistical reference distribution at a particular place. Definitions of 'rare' vary, but an extreme weather event would normally be as rare as, or rarer than, the 10th or 90th percentiles" [15].

In general, for the plot showing SB, the upper and lower RB calculated over a calendar year define the microclimate of a room, with its seasonal variability and daily fluctuations. The method to calculate the target values, i.e., average, upper, and lower limit of SB and RB, as well as their quantitative assessment (i.e., the 7-ile and 93-ile) was not included in the normative part, but shown as an example in an informative Annex A. The example in Annex A was based on a record concerning a church in Poland, occasionally heated with warm air.

A number of researchers have investigated the historical climate of selected case studies and their studies constitute useful examples of application of this standard [13,16–26]. However, the methodology and the calculations required to assess the target values of this standard may be subject to some criticisms and simplifications, as discussed later, and may be improved.

It must be specified that the innovative European Standard EN 15757 was unanimously approved in 2010 and confirmed in 2015 and 2020. The next planned revision will be in 2025. However, this Standard has found some difficulty in practical applications. The Technical Committee 346, 'Conservation of Cultural Heritage', of the European Committee for Standardization (CEN) keeps yearly meetings for decision making, planning, and implementation. On the meeting of December 2021, it was decided that the next revision will be useful for 'an editorial restyling of the Standard in order to improve the editing and comprehensibility, but leaving the content unchanged'. The next revision is an opportunity for a clearer presentation of methods and calculations. The task is assigned to the Working Group 7 (WG7), responsible for indoor climate issues.

This paper has the following aims: (i) to compare the method suggested in Annex A of EN 15757 with an alternative method to calculate the reference values, and in particular SB, and the upper and lower RB; (ii) to verify if the duration of the record necessary for the determination of SB is really 13 months as required by the Standard, or if the same goal can be reached with a 12-month record; (iii) to test if the width of the time window is influential on the width of SB, and to assess the physical relationship between time window and SB width; and (iv) to provide useful elements to WG7 to improve the Standard at its next revision.

2. Data and Methods

2.1. Datasets

This paper utilizes 18 case studies representing different buildings, climates, and use, including museums, churches, concert halls, archives, and storage rooms. Some of them are heated and some unheated, as specified in Table 1. The aim is not to compare different systems, but to test mathematical methods on a wide dataset. It must be specified, however, that the used records must be complete, without gaps [19]. As winter is the most critical period for the impact of heating, and the period of severe cold and intensive heating is relatively short, even a short gap in the record may severely affect the results.

The indoor climate of the case studies used in this paper is shown in Figure 1. Even if RH constitutes the key variable, the association with T is very useful to interpret RH and its dynamics for diagnostic purposes. For instance, the plot of T helps to recognize whether a room is heated (i.e., mild temperature (e.g., 12–18 °C) and low RH in winter) or unheated (i.e., low temperature (e.g., 0–6 °C) and unchanged RH in winter), as well its use (e.g., a continuous T line suggests no heating or continuous heating; peaks of T indicate occasional heating). Peaks of T associated with RH drops are typical of sudden central heating (e.g., warm-air heating); RH variability not strictly related to T is mainly due to weather. This helps to distinguish the natural RH variability due to climate, which is accepted by the Standard, from the RH variability due to use, that should be controlled.

Table 1. Characterization of the case studies.

No	Name	Location	Use	Climate Control	Period
1	Uffizi Gallery °	Florence (IT)	Museum	HVAC during opening hours; continuous RH control	1998
2	Ala Ponzone °	Cremona (IT)	Museum	HVAC, humidity control	2011
3	Museo Vescovile °	Udine (IT)	Museum	passive climate control; filtered light and shutter control	2015–2016
4	Ca' Granda °	Milano (IT)	Archive & book storage with restricted access	passive climate control	2011–2012
5	Liviano °	Padua (IT)	Monumental concert hall	continuous basic heating + occasional extra heating	2002–2003
6	S. Maria Gloriosa dei Frari °	Venice (IT)	Church; tourist attraction	modest local heating	2009–2010
7	S. Maria Maddalena °	Rocca Pietore (IT)	Church	occasional winter heating	2002–2003
8	S. Maria Maggiore °	Rome (IT)	Church; tourist attraction	no HVAC	1996–1997
9	St Andrew the Apostle °	Olkusz (PO)	Church	occasional winter heating	2007–2008
10	Madonna di Campagna *	Valtellina (IT)	Church with concerts	no HVAC	2003–2004
11	S. Maria Collemaggio *	L'Aquila (IT)	Church with concerts	no HVAC	2003–2004
12	Walloon Church (Waalse Kerk) *	Amsterdam (NL)	Church with concerts	continuous winter heating	2003–2004
13	St Willibrord (Groene Kerk) *	Oegstgeest (NL)	Church with concerts	continuous winter heating	2003–2004
14	St Jacob *	Hamburg (GE)	Church with concerts	occasional winter heating	2003–2004
15	St Michael *	Leuven (BE)	Church with concerts	continuous winter heating	2004–2005
16	Notre Dame du Sablon *	Brussels (BE)	Church with concerts	uneven winter heating	2004–2005
17	Old Choir Monastic Church °	Padua (IT)	Church with restricted access	no HVAC; almost unperturbed indoor climate	2011–2012
18	Church basement °	Venice (IT)	Basement with restricted access	no HVAC; unperturbed indoor climate	2020

The case studies with ° have been monitored by the Institute of Atmospheric Sciences and Climate. Those with * have been shared by Carl Johan Bergsten, Gothenburg University, during the common project SENSORGAN. All records are unpublished.

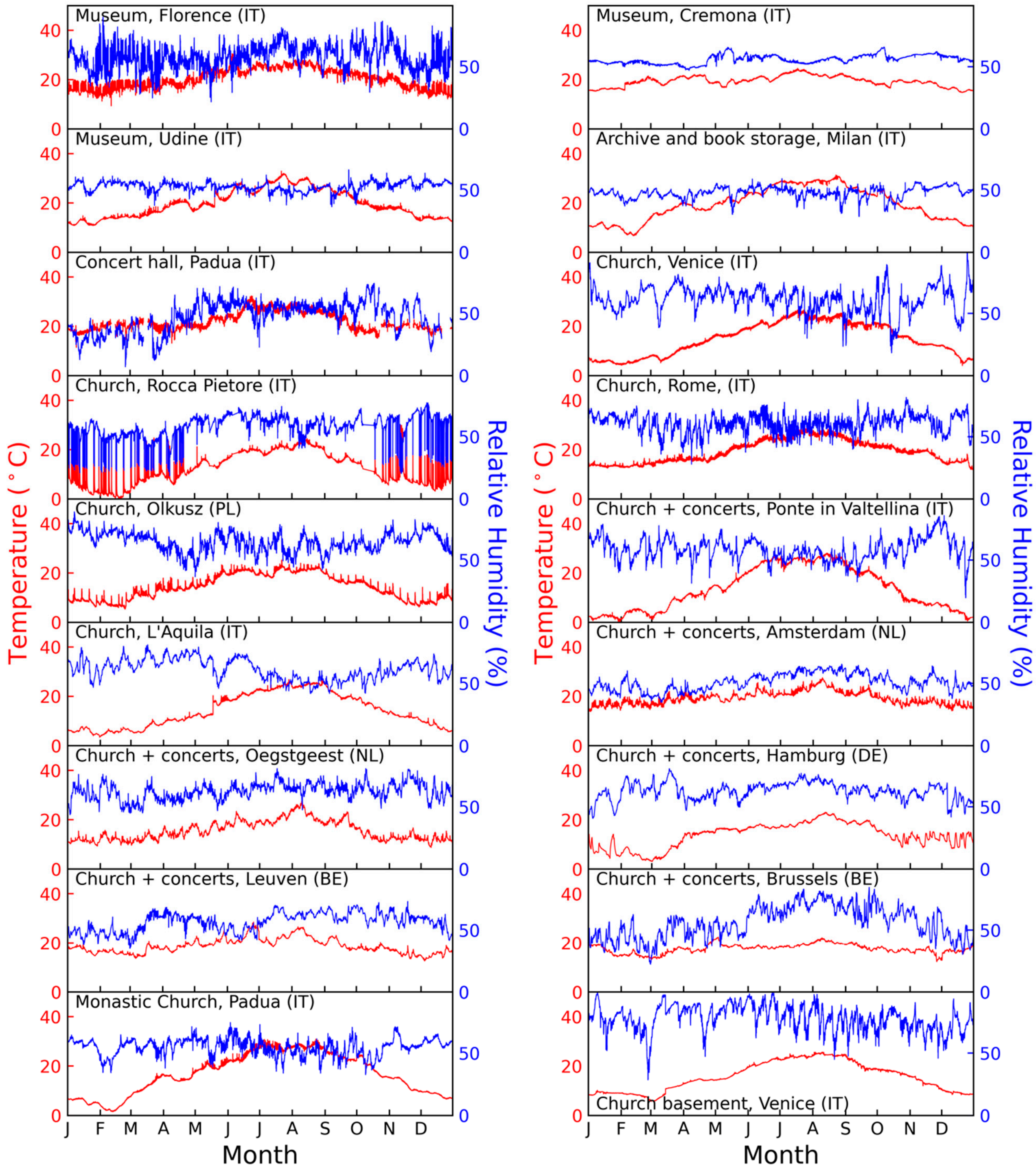


Figure 1. Indoor climate, i.e., temperature and relative humidity of the selected case studies.

2.2. Methods

2.2.1. Datasets Necessary for the Determination of the Safe Band: 12 or 13 Months?

The Standard requires a RH record to document the yearly cycle of RH and the short-term fluctuations. At least a one-year record is requested, or integer multiples of it. The record should include a whole yearly cycle, no matter the starting day.

However, the example reported in Annex A of EN 15757 is based on the centred moving average (CMA) with a 30-day time window, which requires 15 days before and after each reading [27]. In a 365-day record, the truncation at both ends of the record constitutes a problem because in the first and last 14 days of the record the RH readings are widow of those symmetrically distributed for 15 days around them, and it is impossible to calculate CMA. Suppose that we are dealing with a calendar year from 1 January to 31 December 2020 (Figure 2a). This is equivalent to a strip with two ends. To provide the necessary data, the Standard suggests extending the length of the strip, starting the record 15 days earlier (i.e., red rectangle from 16 to 31 December of the previous year 2019) and ending it 15 days later (i.e., red rectangle from 1 to 15 January of the subsequent year 2021).

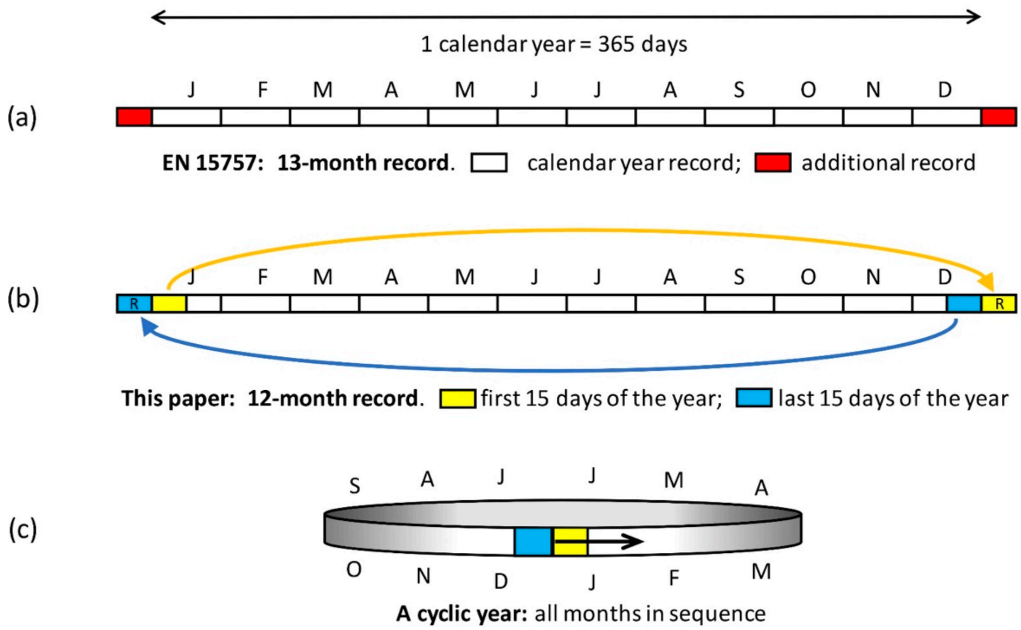


Figure 2. (**a**) The method proposed by EN 15757 requires a 13-month record: i.e., 12 months of the calendar year (white strip) plus two periods of 15 days at both extremes (red rectangles). (**b**) The method proposed in this paper, i.e., 12-month record and repetition of the first 15 days (yellow rectangle) and last 15 days (cyan rectangle) at both ends of the year for calculation purposes. R for 'repeated'. (**c**) A cyclic year, where all months are in circular sequence with December connected to January.

The conclusion is that a record of 13 months is necessary to calculate CMA over 12 months. Observations continued for this additional month constitute a cost and a serious inconvenience. In addition, the added values recorded in the previous and the subsequent years are always slightly different, and this causes an inconsistency: the SB values calculated for the end of the year are not coincident with those at the beginning. In case the first 15 days, or the last 15 days, of the year depart a bit from the normal climate conditions, by combining them with the moving average, one obtains a mean value, which is better representative than each of the 15-day additional periods taken separately. It must be kept in mind that the year selected for the record is assumed to be, and must be, representative of the normal climate. Consequently, if the winter in the record has been characterized by unusual weather, the anomalous year cannot be taken as a typical reference. If the climate at the beginning of the recorded year does not match with the situation at the end of it, i.e., if the circle does not close, this becomes a serious concern.

We have considered that the additional month is requested by the particular method of calculation but does not add physical information to reach the target values required by the Standard. Therefore, it is advisable to avoid this extra month and perform the same calculations over the calendar year, e.g., from 1 January to 31 December 2020, but with a 12-month record (Figure 2b). The 15-day extension at both ends has been formally performed by repeating the corresponding data at both ends. Before the start of the record on 1 January 2020, we added the ending period of the record from 16 to 31 December 2020 (cyan rectangle). Similarly, after the end of the record on 31 December 2020, we repeated the period 1 to 15 January 2020 (yellow rectangle). This partial repetition at both ends for calculation purposes is acceptable because the record is considered representative of a normal year, so that the days of December of the previous year 2019, as well as those of January of the subsequent year 2021, are consistent with the corresponding days of the 2020 record. This method substantially bends the linear strip of the calendar year and joins the end of December with the beginning of January. In a two-dimensional representation (Figure 2c) this becomes a cyclic year, where all months are in circular sequence. The artifice of joining December with January allows the continuous calculation of CMA over all the months of a calendar year, and needs a 12-month record instead of a 13-month one. In addition, this method combines the two extremes of the year, thus ensuring the consistency between the SB values calculated for the end and the beginning of the year. The same considerations hold for any other selected date to start the climate record.

2.2.2. Method of the Informative Annex A: Fluctuations from the Centred Moving Average

The key variables used in the informative Annex A of EN 15757 are summarized in Table 2:

Table 2. Key variables used in the informative Annex A of EN 15757.

Variable	Definition	Example
n	sequential number of the reading sampled in the calendar day j	n = 1 is the first reading of the day j, starting from midnight; n = 2 is the second reading and so on
j	sequential number of the calendar day ($1 \leq j \leq 365$)	j = 45 represents the 45th day of the year, i.e., 14 February
RH(n, j)	individual readings of the record RH(n, j)	the *n*th value of RH recorded in the day j of the calendar year
$<RH_{mo}(n, j)>$	average of RH calculated with the centred moving average, using a monthly window	$<RH_{mo}(n, 45)>$ for j= 45 (i.e., 14 February). It represents the average RH around the reading n, from j − 15 = 30 (i.e., 30 January) to j + 15 = 60 (i.e., 1 March)
ΔRH(n, j)	fluctuations defined as the difference $RH(n, j) - <RH_{mo}(n, j)>$	difference between every individual reading RH(n, j) and the moving average $<RH_{mo}(n, j)>$ centred on it
<RHyr>	yearly average of RH	average from 1 January to 31 December

The informative Annex A is conceived to assist users in these calculations step by step. To this aim, Annex makes an example to fix the main concepts, i.e., key variables, and how to perform calculations. The used method, i.e., the centred moving average, is illustrated in this section and in the flowchart (Figure 3, first column).

The first step is to calculate CMA, a tool used to smooth out short-term fluctuations and highlight longer-term trends. The CMA value $<RH_{mo}(n, j)>$ is constituted by the average of all the readings falling within the 30-day window and is attributed to the central value position (n, j). If the record is based on N_D readings per day, the time window includes 30 N_D +1 readings. If readings are sampled every 5 min, N_D = 288; 10 min, N_D = 144; 15 min, N_D = 96, and so on. After having calculated the average over the selected time window, the software continues repeating the same calculations of the unweighted arithmetic average, by advancing one reading (i.e., lower end from (n, j − 15) to (n + 1, j − 15); central value from (n, j) to (n + 1, j), and upper end from (n, j + 15) to (n + 1, j + 15)), and skipping the last value (i.e., (n, j − 15)).

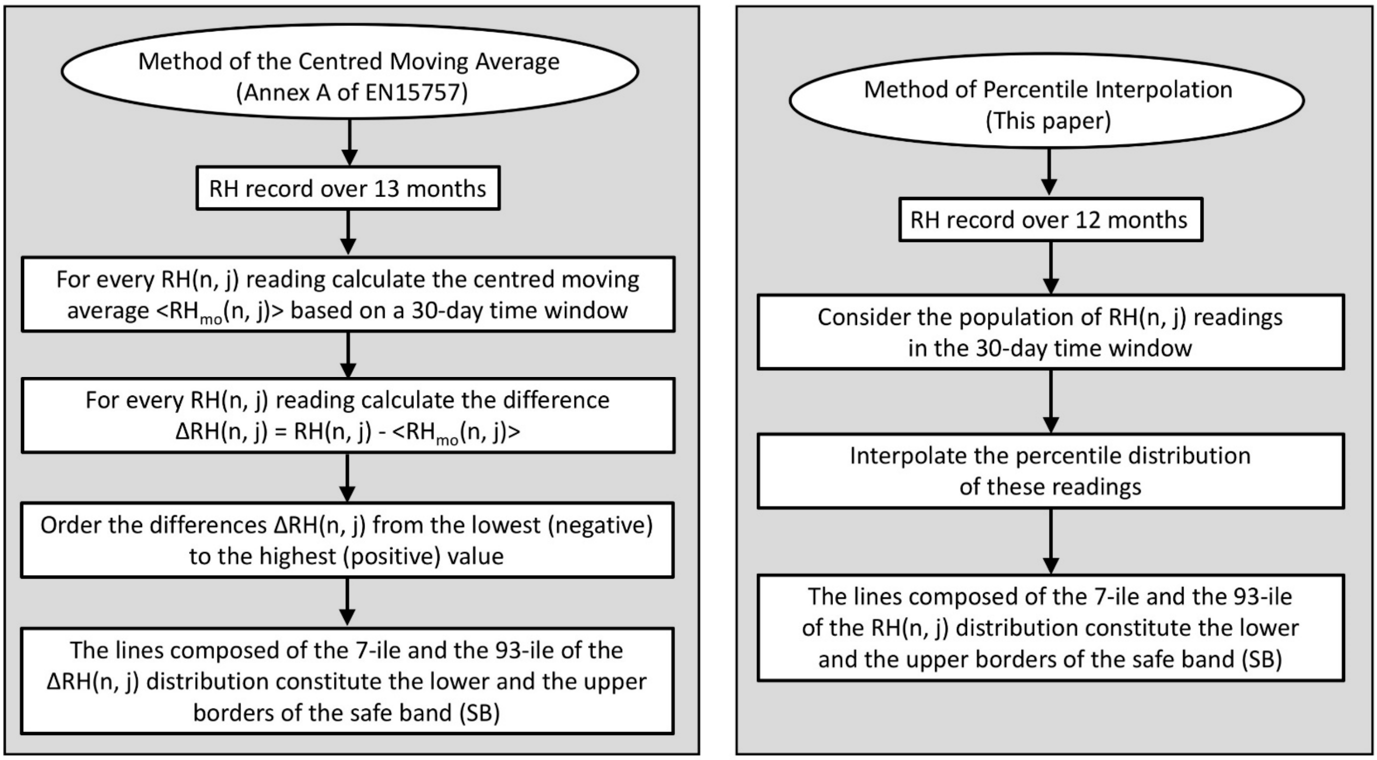


Figure 3. Flowcharts showing the method of the centred moving average used in the Annex A of EN15757, and the method based on the interpolation of percentiles to obtain the safe band (SB).

For every individual reading, RH(n, j), the CMA value $<RH_{mo}(n, j)>$ is calculated, with a 30-day time window. Then the differences, $\Delta RH(n, j)$, between every reading and the corresponding mean are calculated, i.e., the most extreme negative value to the most extreme positive one. Fluctuations falling within the interval between the 7-ile and the 93-ile constitute SB, while the external ones RA. The 7-ile represents the lower boundary between SB and RA, while the 93-ile the upper boundary.

$$\Delta RH(n, j) = RH(n, j) - <RH_{mo}(n, j)> \quad (1)$$

These differences constitute the so-called fluctuations. Finally, for each distribution, these fluctuations are ordered from the most extreme negative value to the most extreme positive one.

2.2.3. Alternative Method: Interpolation of the Percentile Distribution

An alternative method of calculating the same values is proposed in this paper and the comparison with the Standard is shown in the flowchart (Figure 3, second column). As the safe band is defined in terms of percentiles, it can be directly obtained from two selected percentiles, i.e., the 7-ile and the 93-ile of the RH(n, j) readings over the calendar year, avoiding the unnecessary calculations of the CMA value $<RH_{mo}(n, j)>$ and all the differences of $\Delta RH(n; j)$ from it. Briefly, it is sufficient to plot all the RH(n, j) readings over the calendar year and draw two interpolation lines, i.e., the 7-ile and 93-ile.

In fact, by summing the differences in Equation (1) to the CMA value, one obtains the original RH(n, j) readings:

$$\Delta RH(n; j) + <RH_{mo}(n, j)> = [RH(n, j) - <RH_{mo}(n, j)>] + <RH_{mo}(n, j)> = RH(n, j) \quad (2)$$

i.e., the use of the single values RH(n, j) adopted by the percentile analysis is equivalent to summing the fluctuations to CMA as suggested by the Annex A.

It is evident that Equation (2) holds for any reference used instead of $<RH_{mo}(n, j)>$, e.g., using the 50-ile instead of CMA.

Using percentiles, the temporal bin to be considered is the monthly time window, e.g., 30 days as in the Annex A. The percentile distribution can be directly calculated and interpolated with specific mathematic tools and the selected time window may be established as an optional input.

Theoretically, it should be noted that mean, mode, and median are coincident in a symmetrical distribution, while they are not in an asymmetrical one, as typically occurs for RH. Therefore, for RH, it is theoretically preferable to deal in terms of median, i.e., 50-ile, instead of mean, i.e., the centred mobile average, and then calculate fluctuations as the difference between the current reading and the 50-ile. The Working Group of the CEN Standard drafters discussed this item but concluded that this is a too subtle theoretical issue for the majority of users, and that it was preferable to use the concept of mean that has the advantage of being largely popular.

In this work, CMA and the method based on the interpolation of percentiles have been applied to the same set of case studies, putting into evidence the 0-ile, 7-ile, 50-ile, 93-ile, and 100-ile that represent the range, the median, and the borders of SB and the two RB. To test if the two methodologies give exactly the same results, the calculation of percentiles has been done using the same 30-day time window around RH(n, j).

2.2.4. Evaluation of the Most Convenient Time Window

The Standard establishes that the most extreme RH fluctuations shall be excluded, starting from the highest and lowest ones, until 7% of them has been excluded from the lower humidity side (i.e., the lower RB) and 7% from the higher humidity side (i.e., the upper RB). If RH readings are represented in a two-dimensional graph, having the calendar year in the abscissa and RH in the ordinate, one obtains a cloud of dots lying on a band that may change average value and width with the season. The central part of the band is more densely populated, and the density decreases approaching the upper and the lower boards. Removing the most extreme 7% of the dots on both sides has the effect of thinning the band. With a percentile computing facility, this is a very simple task.

However, if the issue is solved following the method described in Annex A, it is necessary to calculate all the distances, $\Delta RH(n; j)$, from a reference value, that has been suggested (i.e., suggested because the Appendix is only informative) to be the CMA with monthly window, i.e., $<RH_{mo}(n, j)>$. The monthly window (i.e. 30 days) has been selected to confer stability to the reference value of the calendar day j. In fact, in the normal climate statistics, WMO [28] recommended referring to a period composed of 30 years which implies that the calendar day j is represented by the average of 30 years, e.g., j = 150 is represented by the average of all the days dated 30 May in the 1991–2020 period. As it is extremely rare to dispose of indoor records over a 30-year period, the Standard has considered obtaining a 30-day average by taking advantage of 15 days before and 15 days after the selected reading or the selected calendar day. This choice is finalized to reduce instability, i.e., the random difference between a selected calendar day j and the next one j + 1. The 30-year period is not related to physical issues, e.g., the relaxation time of wooden objects depends on the wooden species, wood thickness, surface treatment, and coatings.

Another crucial issue is related to the time window. In theory, if the RH distribution is homogeneous over the calendar year, always keeping the same distribution (e.g., purely random, Gaussian, Gamma), the SB width is independent of the selected time window, i.e., a horizontal band. However, if the distribution is subject to seasonal cycles, e.g., lower RH values in winter caused by heating, the band will be curved with lower values in the cold season. When the band is curved, by increasing the time window, one meets larger RH ranges and widens SB.

In this work, different options are considered for the time window to investigate if the safe band changes with the time window and how. Finally, we want to verify how critical the choice of one month for the time window is.

3. Results and Discussions

3.1. Comparison between the Two Methods: Centred Moving Average and Percentile Interpolation

The two methods, i.e., the centred moving average (CMA) suggested in Annex A, and the interpolation of the percentile distribution (IPD) have been applied to the selected case studies to investigate if they provide different results and to test which of them is easier to apply. For reasons of space, only four cases are shown in detail.

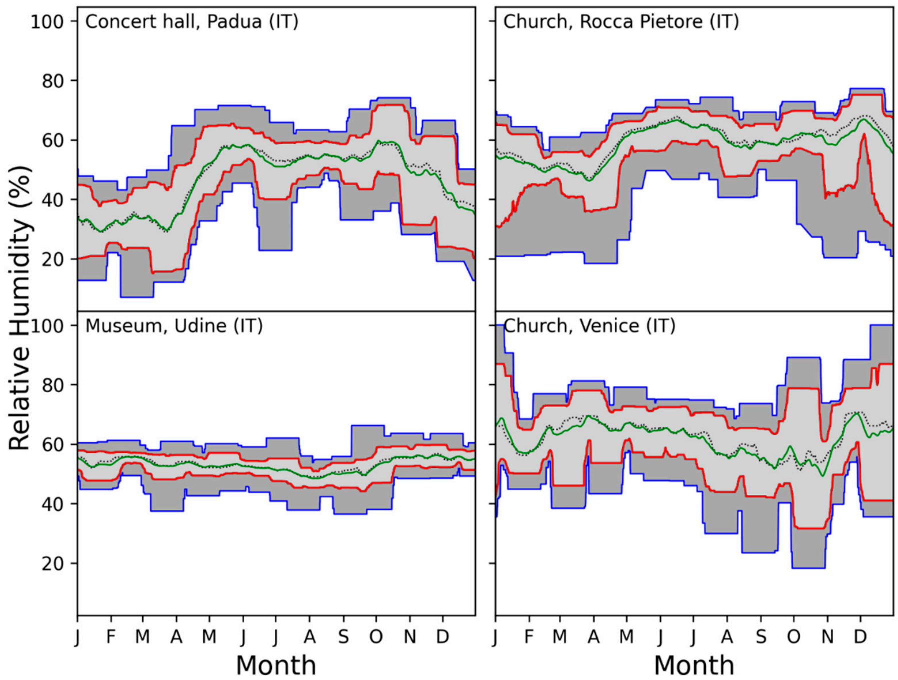
The CMA method has been calculated as indicated in Annex A that requires only three lines: the mean, 7-ile, and 93-ile. We have added the range, i.e., 0-ile and 100-ile. The lines are reported in Figure 4a, i.e., the red lines represent the contour lines of SB (i.e., 7-ile and 93-ile), while the blue lines the extremes of RB (i.e., 0-ile and 100-ile).

The IPD method has been calculated and reported on the same Figure 4a, but represented in terms of bands, i.e., light grey for SB, and dark grey for RB. Overlapping the two plots (i.e., the plot with bands and the plot with lines), they coincide, giving the appearance of only one plot, with contour lines highlighting the bands. This is obvious because the contours and the bands are given by the same percentiles, i.e., the two methods provide the same results because they calculate in different ways the same items.

In the same figure, we have added the mean (Annex A, green line) and the median (i.e., 50-ile, dotted line). The former is calculated as CMA; the latter is calculated as IPD, i.e., the median of a population included in a bin of 30 days around the central value, and then moving the window (i.e., the bin) to the next value and so on. Although mean and median are different statistical quantities, their values do not reach significant differences: in the plots, they appear very close between them, with some small departures. Instead of using the mean (Annex A), we propose adopting the median (i.e., 50-ile) because it is more consistent with the percentile method, is easier to calculate, and is supplied by the same mathematical tool. The choice of the reference for a central value, either mean or median, is the only small difference.

It is evident that the two methods, i.e., CMA and IPD, do not reach significant differences: i.e., the 0-ile, 7-ile, 93-ile, and 100-ile are exactly the same; the only small difference is the central line, i.e., CMA mean or IPD 50-ile. Therefore, each of the two methods can be equally taken as a target reference.

In the plots, the two external RB, and to a lesser extent SB, have the appearance of rectangles, with 30-day width. This is a consequence of the choice of using a simple mobile average with rectangular window, i.e., the arithmetic average of data all with equal weight $1/N_{TW}$, where N_{TW} is the number of data included in the time window [27,29]. When the rectangular window of a mobile average includes the peak of an extreme event, the arithmetic average abruptly increases forming a rectangle, and the rectangle continues until the window with its movement moves forward and leaves out the extreme event. The same happens with the percentile analysis when an extreme event enters a mobile bin. To avoid the issue of extreme events that may generate rectangles, a weighted moving average with a different shape should be preferred, with low weight at the borders and high weight at the centre, either linearly distributed (e.g., triangular), or bell shaped (e.g., Gaussian, cosine, parabolic, Poisson, Hann, Abel, Cauchy, Tukey, Tuckey-Hanning) [29,30]. Another strategy is to apply filters or interpolation tools to smooth edges. However, the aim of this paper is to show and explain the methods given by the Standard. The user is free to consider an edgy or a smooth plot, and adopt any smoothing tool, simply because this topic is not considered in the normative part.



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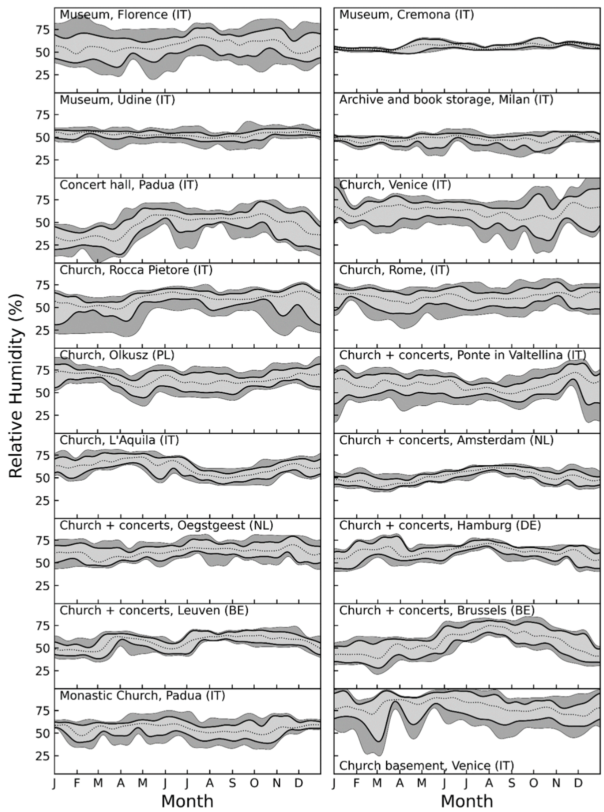

(**b**)

Figure 4. (**a**) Comparison between the CMA method suggested in the Annex A (represented with contour lines, i.e.,: blue: 0-ile and 100-ile, red: 7-ile, 93-ile; green: mean), and the IPD method (represented with bands, i.e., light grey: safe band; dark grey: risky band; dotted line: median, i.e., 50-ile). Lines and bands are calculated as moving average, or moving bins, with a 30-day time window. (**b**) Safe band (light grey) and risky band (dark grey) of all the case studies to which smoothing has been applied.

It may be useful to comment on the examples in Figure 4a, by comparing them with their indoor climate in Figure 1. In the case study of the unheated Museum, Udine, with passive climate control, the SB width is basically constant over time and quite horizontally distributed over the calendar year. The case study of the Concert Hall, Padua with continuous basic heating with an occasional extra heating, shows that SB is lower in winter and higher in summer, except in July when the windows are randomly opened for ventilation to resist the hot local climate. In such a case, the abrupt change in thickness of SB is a diagnostic index of incorrect use of doors or windows for summer ventilation. Another typical example is the Church of Rocca Pietore, where the occasional warm-air heating for the Sunday celebrations cause dramatic peaks of temperature and drops of RH, widening very much SB and RB. The peaks of warm-air heating can be recognized by the increase of both bands, but especially RB. The Basilica S. Maria Gloriosa dei Frari, Venice, has a modest local occasional heating for celebrations with a very low impact on the indoor climate, but is a tourist attraction for the important artworks kept inside. The combination of the humid winter climate in Venice and the intense use widens the safe band in winter.

The whole dataset is represented in Figure 4b where a soft, numerical smoothing filter has been applied to smooth the rough edges of the plot that are affected by some random noise for the limited population of readings. We must specify that the filter is not necessary, but has been applied for educational purposes, i.e., to point out that the user should not be concerned to strictly follow the small day-by-day changes, but should have a broad vision of the general trend on a wider timescale. To avoid random noise, it is possible to use various systems. For instance, one may apply this procedure not to the whole dataset, but to a subsample of it, e.g., two or three values per month to obtain smooth plots that show long-term variations, reducing noise. Plots in Figure 4a are without smoothing. Plots in Figure 4b have been obtained by applying the techniques described in Annex A, but with two values per month. Using opportune mathematical tools, in this case a spline interpolation, the resolution of the data has been increased to one value per day. The soft smoothing level of the filter is evident by comparing the four examples in Figure 4a (unfiltered) with the same in Figure 4b (filtered). However, the Standard does not consider these aspects, and the user may either avoid filters or adopt the preferred one.

3.2. Comparison between Different Time Windows

Selected time windows have been considered to investigate how the safe band is affected by this choice. The time windows used are 1 day, 1 week, two weeks, 1 month, 2 months, and 1 year. This choice has been made to test the different impact that the time window may have on sites with higher or lower seasonal cycles. The investigation has shown that the average safe band width <SBW> (i.e., the average of the SB over the calendar year) is highly dependent on the particular choice of the time window; the wider the time window, the wider <SBW>.

In a linear diagram, i.e., with <SBW> in ordinate (Y), and the number of days of which the time window is composed in abscissa (X), and both X and Y have a linear scale, the plots of Y versus X are logarithmic (Figure 5a). Therefore, if a semi-logarithmic diagram is considered, i.e., the axis X with a logarithmic scale, and Y with a linear scale, the plots become straight-lines, as shown in Figure 5b for four case studies in expanded size. The whole set is represented in Figure 5c.

For all the case studies, the relationship between <SBW> and the width X (in days) of the time window is given by the general logarithmic equation

$$\langle SBW \rangle = a \ln X + b \tag{3}$$

where ln is the natural logarithm. The coefficient a is representative of the weight of the logarithmic function that represents the slope of the best-fit line in the semi-logarithmic plots in Figure 5a,b. The constant term b [%] is not the intercept with the Y axis (the scale is logarithmic and there is not X = 0) but is the starting value, i.e., the SB obtained with

1-day time window. The coefficients a [%], b [%], are reported in Table 3. In the selected case studies, $1.35 \leq a \leq 5.37\%$; the coefficient b is largely variable, i.e., $0.48 \leq b \leq 13.76\%$.

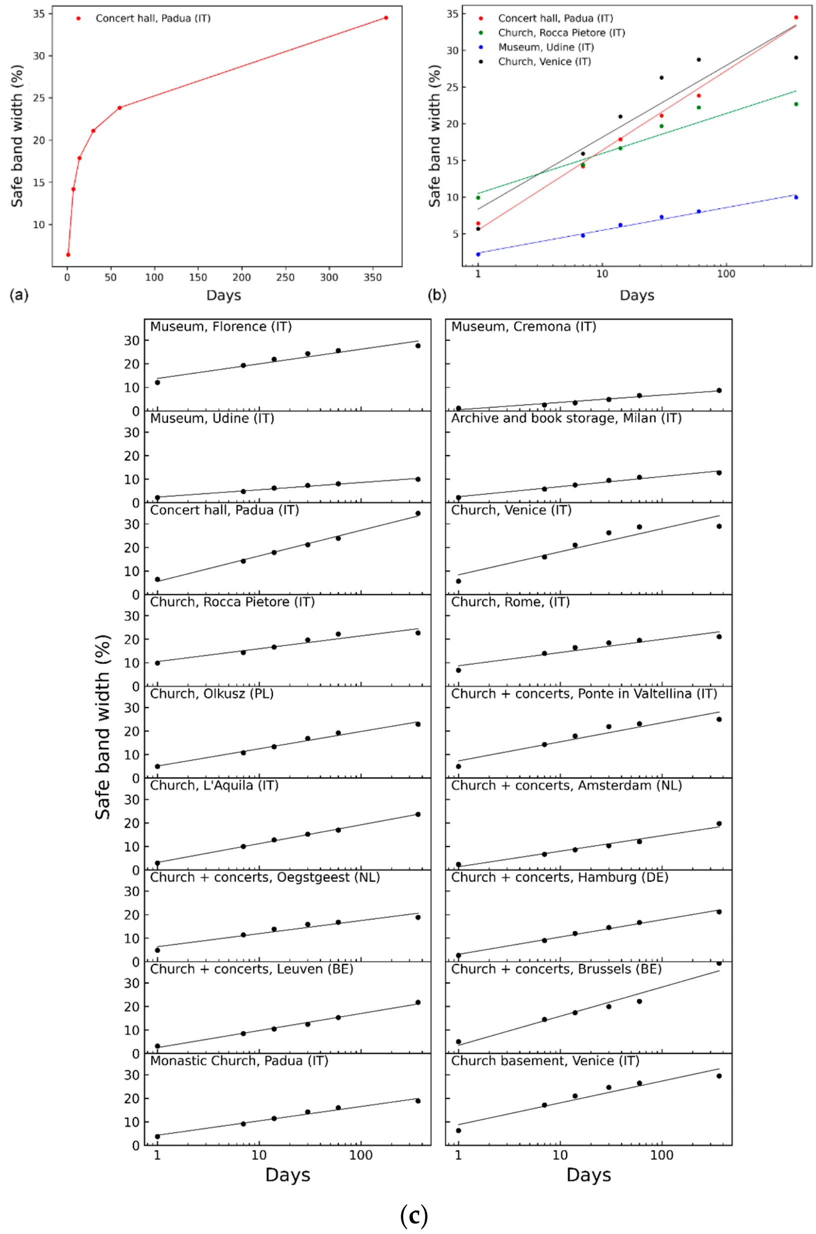

Figure 5. The safe band width is logarithmically related to the time window. (**a**) The example of a case study in a linear coordinate paper. The plot is logarithmic. (**b**) In semi-logarithmic paper (i.e., days in logarithmic scale) the plots become straight-lines. The four case studies used as detailed examples. (**c**) The whole set of case studies.

The last column in Table 3 is the 30-day intercept that corresponds to the value selected by the Standard as a reference. It represents the average value of the RH (%) variability that characterizes SB over the whole calendar year. The lowest values correspond to a thin SB, which indicates that the indoor climate is very stable and provides the best conditions for conservation. On the contrary, a large intercept means a wide SB, high indoor climate variability, and poor conditions for conservation. The observed values of the 30-day intercept lie between 5.1 and 22.9%. Only three cases stay below 10%; more than 50% of them lie between 15 and 23%; and 5 of them exceed 20%.

Table 3. Coefficients *a*, *b* of the logarithmic Equation (3) representing the dependence of the average safe band on the selected time window duration. The last column is the 30-day intercept.

No	Case Study	*a*	*b*	30-d Intercept
1	Museum, Florence (IT)	2.70	13.76	22.9
2	Museum, Cremona (IT)	1.36	0.48	5.1
3	Museum, Udine (IT)	1.35	2.38	7.0
4	Archive and book storage, Milan (IT)	1.86	2.53	8.9
5	Concert hall, Padua (IT)	4.72	5.52	21.6
6	Church, Venice (IT)	4.26	8.34	22.8
7	Church, Rocca Pietore (IT)	2.37	10.49	18.6
8	Church, Rome, (IT)	2.44	8.72	17.0
9	Church, Olkusz (PL)	3.18	5.12	15.9
10	Church + concerts, Ponte in Valtellina (IT)	3.52	7.31	19.3
11	Church, L'Aquila (IT)	3.47	3.16	15.0
12	Church + concerts, Amsterdam (NL)	2.87	1.33	11.1
13	Church + concerts, Oegstgeest (NL)	2.41	6.36	14.6
14	Church + concerts, Hamburg (DE)	3.19	3.12	14.0
15	Church + concerts, Leuven (BE)	3.14	2.49	13.2
16	Church + concerts, Brussels (BE)	5.37	3.47	21.7
17	Monastic Church, Padua (IT)	2.65	4.27	13.3
18	Church basement, Venice (IT)	4.02	8.76	22.4

A comment on the four examples in Figure 5a. The Museum, Udine, with homogeneous SB quite horizontally distributed over the calendar year has very low coefficients $a = 1.35\%$ and $b = 2.38\%$. The Church of Rocca Pietore, is characterized by an intermediate value of $a = 2.37\%$ and a very high value of $b = 10.49\%$. The Concert Hall, Padua, and the Basilica S. Maria Gloriosa dei Frari, Venice, have quite similar values, i.e., high $a = 4.72\%$ and 4.26% and intermediate $b = 5.52\%$ and 8.34%, respectively.

It is not surprising to find that the best-fit of Equation (3) is a logarithm. The Lognormal is a right-skewed continuous probability distribution introduced by Galton [31], frequently used to represent physical variables that never take negative values, or to represent risk as a function of the time [32–34]. This is consistent with the extreme value theory (EVT), where extreme events are those contained in the tail distribution of a given variable [35]. The longer the record, or the wider the time window, the higher the probability of including the most extreme events located in the upper part of the probability distribution.

4. Language and Communication

In this paper, the term 'safe band' has been used relying on the standard. However, it may be useful to underline that the term 'safe' might be misleadingly interpreted. For instance, if some activity is performed that widens the span between the 7-ile and the 93-ile, this increases the width of SB, but does not correspond to an increase of safety. Conversely, every widening of SB corresponds to a worsening of the conditions for conservation. This becomes clearer when the risky bands are considered: every widening of RB implies a worsening for conservation.

Therefore, instead of 'safe' it may be appropriate to speak in terms of 'accustomed' band, but only when the natural, unperturbed indoor climate is considered, i.e., non-biased for use, heating, or air conditioning. In the general case, the use of neutral names, e.g., 'usual variability band' or 'band between the 7-ile and the 93-ile' may be preferable.

This is a further aspect that should be considered by WG7 in the forthcoming revision of this Standard.

5. Conclusions

The first important conclusion is that the methodology proposed by the Standard EN 15757 was tested on 18 case studies and was compared with another alternative methodology in view of the next revision of the Standard that has been decided by the European Committee for Standardization. These findings will help to simplify and improve the quality of the standard after having considered the two main difficulties met by most users, i.e., the practical application of centred moving average and the need to monitor over 13 months to get information for a single calendar year.

A relevant conclusion is that the centred moving average suggested in the informative Annex A of the Standard may be substituted with the method of the interpolation of the percentile distribution that gives the same results, but with an easier mathematical approach. It has recognized that the centred moving average requires a lot of unnecessary calculations that may create serious difficulties for most users. On the other hand, the method of interpolation of the percentile distribution is much easier, and specific statistical tools are directly available for the calculation of selected percentiles. In the Standard revision, it will be advisable to present and explain both methods, and leave the user free to choose.

It has been recognized that the adoption of a rectangular window, either for simple (unweighted) arithmetic moving average, or for a moving bin in the case of percentiles, isolated peaks, or drops, do generate rectangles with the same width of the time window. This drawback may be reduced using a weighted moving average or a smoothing filter. Alternatively, the user should be prepared to correct the interpretation of plots.

A relevant simplification is that it is not necessary to monitor for 13 months to characterize a calendar year using centred moving average calculations. A 12-month record is sufficient if one uses the artifice of extending the data set by reporting the first 15 days of the year at the end of the record, and the last 15 days of the year before the beginning of the record. This is equivalent to dispose of a circular, cyclic year, not a single strip broken at both ends. This choice reduces costs and time for preliminary investigations.

A further conclusion is the relevance of the duration of the interval of time selected for the time window. It has been clarified that the safe band increases with the time window, following a logarithmic law. However, the coefficients that determine the equations change case by case, depending on the indoor climate, winter heating, use, and ventilation. Therefore, the impact is different, being smaller in the case of homogeneous RH distributions over the calendar year, and stronger in the case of winter heating, especially when this is made occasionally with warm-air systems that generate sharp peaks of temperature and drops of relative humidity.

A final note concerns language and communication. The term 'safe band' might be misleadingly interpreted and it would be preferable to substitute it with a neutral name. Some suggestions have been made, but the most convenient term will be decided by the Working Group 7 at the next Standard revision.

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