Indoor Microclimate Quality (IMQ) certification in heritage and museum buildings : the case study of Vleeshuis museum in Antwerp

Reference:
Litti Giovanni, Audenaert Amaryllis, Fabbri Kristian.- Indoor Microclimate Quality (IMQ) certification in heritage and museum buildings : the case study of Vleeshuis museum in Antw erp
Building and environment - ISSN 0360-1323 - 124(2017), p. 478-491
Full text (Publisher's DOI): https://doi.org/10.1016/J.BUILDENV.2017.08.013
To cite this reference: https://hdl.handle.net/10067/1453180151162165141

Indoor Microclimate Quality (IMQ) certification in heritage and museum buildings: the case study of Vleeshuis museum in Antwerp

Comment [G1]: The Title is changed the term diagnosis is no longer in the title as this aspect (the analysis of the microclimatic diagnosis results) is no longer in the contribution "see genera comments to reviewers"

The text is completely rewritten, therefore this note is the sole in the text.

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Abstract

In order to detect possible downsides of building microclimate management or for identifying performance improvement options, it is fundamental to assess and certify building Indoor Microclimate Quality (IMQ).
Considering that in heritage and museum buildings, the indoor microclimate should simultaneously ensure comfort of people and safety for the cultural heritage, its management takes on a multidimensional nature.
Although in the literature IMQ certification methodologies for people already exist, these do not encompass the cultural heritage. We believe this integration, would be a valid management instrument for heritage buildings, historic houses and museums, especially if they are not equipped with full microclimate control systems.
However, because environmental data acquisition activities have direct influence on the certification results, it is essential to evaluate them. These methodological aspects are here discussed on the basis of results from a microclimate monitoring in the main exhibition hall of Vleeshuis museum in Antwerp. Further, in accordance to the introduced methodological considerations, an IMQ certification model for building users and movable heritage is proposed.

Keywords: heritage and museum buildings, Indoor Microclimate Quality certification, multicriteria modelling applied to cultural heritage

Nomenclature and terminology

φ^{th}	Environmental parameter
$\mu_{(\varphi)}$	Mean value of environmental parameters sampled in different point of the space
$a_{(\varphi)}$	Requested/ desirable environmental parameter measurement accuracy
Δ_{Temp}	Absolute Temperature difference between two points
Δ_{RH}	Absolute Relative Humidity difference between two points
$\Delta_{(Temp,\ day)}$	Daily Cycle Temperature (°C)
$\Delta_{(RH,\ day)}$	Daily Cycle Relative Humidity (%)
$\Delta_{(RH,\ plast)}$	Cycle Relative Humidity causing plastic deformation (%)
T	Air Temperature (°C)
T_g	Temperature of glass transition
RH	Relative Humidity (%)
OP	Operative Temperature (°C)
MRT	Mean Radiant Temperature (°C)
RSD	Root Squared Deviation
RMSD	Root Mean Squared Deviation
CMA	Cantered Moving Average
(spatial)	with reference to the mean value of measurement points
(i)	with reference to a measurement point
(t)	With reference to a time interval
$N_1, N_2...$	Sampled data population. If considering more than one string, N_1 refers to string 1; N_2 refers to string to 2 etc.

The Terms: ***IMQ certification, movable and immovable heritage, object, tangible cultural heritage; cultural heritage; value*** and ***significance*** are reported in Note 1 in the supplementary material

1. Introduction

The IMQ of a building may be affected either by external climate or by internal loads. The building envelope is the first filter to the external climate and buffers the outer weather fluctuations keeping more steady the indoor building climate. Building systems, if present, ensure additional indoor microclimate control beyond the one allowed by the envelope itself. However, a constant microclimate control is not easily viable in historic buildings.

Cantin et. al. in [1] observed that indoor microclimate in historic buildings is strongly influenced by outdoor environmental conditions. This was observed to be not solely caused by the poor envelope hygrothermal performance but also by the unavoidable indoor-outdoor eco system interaction historic buildings have with the outdoor microclimate. This interaction is observable whether the building is equipped or not with mechanical installations [2-4]

Considering that a poor IMQ might influence building users comfort and cultural heritage conservation, it is fundamental to assess and certify it continuously.

In contrast with an indoor microclimate diagnosis, considered as an one-time action with explorative assessment purposes, the certification as intended in this article, is a continuous ordinary practice. A mere quality control. In other words, it is the systematic verification of given microclimate parameters fulfilment to intervals of quality, performance, safety, or steadiness. The parameters benchmarks may be suggested by current standards or in field research [5–7]

Nevertheless, since IMQ certification allows understanding: building equipment effectiveness, artefacts state of conservation, people thermal satisfaction etc., it might be a powerful instrument for supporting decisions upon environmental retrofitting actions, building installations improvement and preventive conservation strategies [8–10]

It is clear that if the mentioned certification verifies simultaneously the multiple IMQ aspects in relation to different certification targets (people, movable heritage, building materials, etc.), it gains additional significance. However, given its practical and theoretical complexity, methodological issues might arise both 1) during onsite-data acquisition processes and/or 2) during the IMQ certification model development (e.g. inappropriate model hypothesis and limitations). In this article we focus on the first point.

In the Literature, methodologies for heritage buildings and museums environmental diagnosis are widely diffused [11–18]; however, microclimate certification models incorporating people comfort and cultural heritage safety are not yet available despite their value for a more holistic building management. Moreover, although IMQ certification for people comfort already exists [5,6], the methodological issues to be considered during onsite data acquisition prior to the certification model development have not yet been addressed. This unavoidably results in different monitoring activities and therefore in certification results which are not comparable [19].

2. Research objectives and constraints

1. The study analyses methodological issues emerging during infield microclimate monitoring targeted to IMQ certification. More specifically, it focusses on time-spatial representativeness and resolution of acquired data to be inputted in the certification model.
2. For verifying the time-spatial resolution of the acquired data the study introduces the analysis of microclimate heterogeneity as preparatory activity to IMQ certification. The mentioned analysis is valuable especially with regard to IMQ certification for movable heritage, however a sensitivity analysis was performed for evaluating people thermal comfort variations (on PMV scale) as a consequence of spatial hygrothermal variations.
3. The study introduces a multicriteria model for the simultaneous certification of IMQ for building users and movable heritage. In the present contribution the model is limited to hygrothermal quality verification and climate induced mechanical damage for objects. Criteria, such as acoustic and lighting comfort for people, or biological and chemical deterioration risk for movable heritage, are not included.

   The IMQ categories for people comfort are derived from the ISO 7730 and EN 15251 standards for heating and free running period respectively. Among others, the IMQ categories for movable heritage are derived from the EN 15757 standard. Since the objects exposed to the free air in the monitored exhibition hall are mainly lacquered pianos, harpsichord and paintings on timber support, the mechanical deterioration model is focussed on timber panels.

4. Additional comfort criteria and deterioration risk assessment models can be added to the developed multi-objectives model. This will be an object of further research.

3. Indoor Microclimate Quality certification for building users and cultural heritage.

The Indoor Microclimate Quality (IMQ) certification for *movable and immovable heritage* as well as for building users consists in the evaluation of multiple aspects of safety and comfort.

Often, especially with regard to thermal comfort studies, the optimal comfort for people is identified as neutral sensation. This sensation can be defined as the psychological condition in which the person is satisfied about the surrounding environment and no variation is wished to compensate any discomfort [20]. Similarly, the region of microclimate safety for objects is the area in which the hygrothermal fluctuations are comprised within a range between zero and a safety threshold [21]. Within this neutral (safe) area no deterioration occurs. On basis of this parallelism it is possible to develop IMQ certification models including both building users and movable heritage.

With regard to people, a short and non-exhaustive list of comfort aspects is: thermal comfort, lighting comfort, acoustic comfort and air quality comfort, while with regard to artefacts the aspects of safety are related to hygrothermal quality, light and level of pollutants in the air. Not fulfilling the mentioned comfort or safety aspects might cause discomfort for the people and physical, chemical or biological deterioration for the artefacts.

Theoretically, the global comfort for people is reached only if all the multiple levels of comfort are simultaneously accomplished. Nevertheless, it may be still possible to evidence environmental acceptability even if one or more environmental criteria is out of the comfort area. This occurs because, depending on the activity in which people are involved, the physical attributes characterizing the environmental comfort sensation acquire different importance [22–24]. Conversely for ensuring safety to the cultural heritage, all the environmental aspects need to be simultaneously satisfied. Hence verified. However often, relative humidity, especially in the case of hygroscopic materials is responsible for faster material deterioration processes (due to its direct influence on materials equilibrium moisture content variation). Therefore its control and adjustment might have priority over air temperature [25,26] and it is indeed considered for the target-microclimate definition according to the EN 15757. Also thermal gradients can cause mechanical stress in materials; therefore, air temperature short term fluctuations should be controlled and limited.

4. Methodological issues during onsite data acquisition preparatory to IMQ certification

The principal aim of a microclimate certification is to facilitate its management. In other words identifying risks of damage for housed objects or discomfort for people. This is valid still more (but not only) for those buildings not equipped with automatic microclimatic control.

Considering that a certification procedure starts from the preparatory data acquisition, the onsite building monitoring activities take on a fundamental role. This is valid both if the IMQ certification is based on onsite building environmental monitoring (instrumental or subjective) or if it is based on outputs from a dynamic building model (simulation-based IMQ certification). In the latter case the monitored data allow for model calibration [27–29].

As environmental parameters are time-spatial dependent, and the monitored space might be more or less stable than another one or than itself in a different moment, it is necessary to define the extent of the microclimate spatial variability throughout the time. Hence, time-spatial representativeness and resolution of the monitored data should be analysed; see Fig. 4.1.

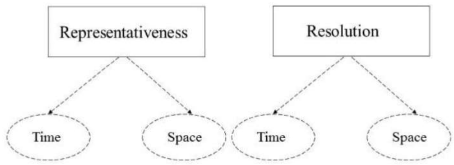

Figure 4.1 Representativeness and Resolution diagram

- Temporal representativeness: monitoring period duration. This interval elucidates the temporal representativeness of the certification results but it does not necessarily coincide with it, indeed, a monitoring campaign can be longer than the period to which the certification refers.

- Temporal resolution: level of details (in time) of the acquired data, i.e., the parameters sampling interval. This might have an influence on the certification results in case of outliers.
- Spatial representativeness: representativeness of the measured building part in relation to the whole building.
- Spatial resolution: level of details (in space) of the acquired data.

4.1 Representativeness and Resolution of acquired microclimate data targeted to IMQ certification for cultural heritage and building users

For the IMQ assessment of cultural heritage, the EN 15757 is largely considered especially in the EU Countries [30]. The standard introduces a novel methodology for calculating the optimal microclimate interval for allowing hygroscopic objects preservation. This interval, named target microclimate, is calculated according to infield hygrothermal monitoring. Knowledge on the object historic climate and on its dynamic interactions with the microclimate proximity should be acquired during the monitoring. If the IMQ certification for cultural heritage wants to be developed by following the EN 15757, two issues should be evaluated.

Firstly, the calculated target microclimate range should be used with care for defining the target microclimate interval as it is dependant on the monitoring time representativeness. Target microclimate range variation if considering one or multi years data series is discussed by the authors in [31].

Secondly, the monitoring of each object microclimate proximity (though theoretically understandable), might require a countless amount of sensors that does not necessarily bring to an increased spatial resolution of the acquired data, hence of the certification results. This large effort in terms of sensors number might constitute an issue for professionals and museum curators [32,33] Indeed, “what if several objects, with similar sensitivity and state of conservation, are exhibited for a long time (say the known historic climate) in the same space and location? Is it not reasonable to imagine that as the global space microclimate is unchanged so it is for each object microclimate proximity?”

In the authors opinion, if the objects are scattered in the space, and the microclimate through the space is proven to be sufficiently homogeneous, one measurement point in an undisturbed position of the space or the average of the readings from different loggers, can deliver a sufficiently accurate esteem of each object microclimate proximity. The resulting target microclimate, may apply to all the objects exposed in the free air. As a consequence, a reduction of measurement points can be allowed while still obtaining accurate IMQ certification results.

Obviously this concept holds valid only if, rather small variations occur between the free air and the objects interface (in the studied case <0.5°C and <1.50% T and RH). This should be a priori verified during a microclimate diagnosis. These variations might be reasonably large for objects located onto the building envelope and small for objects exposed in the free air. In the present case, no movable heritage is exposed onto the building envelope.

The above mentioned methodological considerations are, in fact, already implemented within research or microclimate management praxis. The application of one sensor per exhibition space in the free air rather than in contact or semi contact with each exhibited object is considered a good practice, hence implicitly considered representative of each object microclimate proximity in [32–37].

With regard to people, especially if involved in non-stationary activities, the considerations discussed above are less meaningful. Indeed, because people move in the space, it is arguable that their thermal comfort sensation alters during their movement. However, that their transient comfort sensation is somehow compensative and that their thermal acceptance does not vary if small hygrothermal time-spatial variations occur may be expected.

With regard to time-dependent variations, the ISO 7730 states that temperature cycles within 1°K as well as temperature drifts of 2°K/hour are unlikely to affect people thermal comfort. Therefore, the space microclimate may be considered steady and the PMV-PPD model applies [5]. This was also observed in a study by L. Schellen [38]. In our study, the monitored space complies with the mentioned conditions.

With regard to space-dependent variations, the ISO 7730, though developed for fully controlled environments, admits minor spatial (operative) temperature variations. Indeed, the temperature considered within PMV interval categories is not expressed by a deterministic value but rather by a range; Table A1 in [5].

In this study, the microclimate spatial variability was assessed firstly according to existing standard methodologies, secondly by evaluating the actual spatial parameters difference (between sensors). On the basis of this analysis it was possible to drawn conclusion about the microclimate heterogeneity for both movable heritage and building users. With regard to the latter an additional sensitivity analysis was necessary.

It is worth mentioning that there is a difference between microclimate heterogeneity analysis targeted at IMQ diagnosis or IMQ certification. In the first case, even tiny variations need to be carefully investigated as they may stand for specific microclimate issues caused by e.g. building envelope or installations failures. In the second case, variations within homogeneous IMQ quality intervals are negligible (unless controllable by the building equipment). In other words, because IMQ certification aims at linking microclimate control with building management, the small microclimate spatial variations are unlikely handleable by common HVAC systems. Hence, they may be disregarded. This condition does not apply if the system allows for high-resolution control of the confined space.

5. Vleeshuis museum: history and building characteristics

The monitored building, *het Vleeshuis*, is the museum of musical instruments in Antwerp. It was built between 1501 and 1504 by the Belgian architect Herman de Waghemakere (the elder) as new slaughterhouse of the city. Although the building use has changed across the Centuries, it is still possible to observe the original building architectonic integrity both on the inside and outside. See Figure 5.1.

Figure 5.1 internal view of the monitored exhibition hall (Litti 2013)

The cellar and the main exhibition hall on the ground floor currently house the permanent collection of musical instruments, while the upper levels are utilized as artefacts storage and offices. The basement and ground floor are characterized by brick vaults. The volumetric proportions of the spaces at the basement and ground floor are different; the maximum height of the basement is 3.45m and on the ground floor 8.50m. The total net volume is respectively ≈1300m^3 and ≈5300 m^3 on the basement and ground floor. In this contribution only the exhibition hall at the ground floor is considered; however an analysis of the microclimate quality including the exhibition space at the basement level was discussed by the authors in [39][40].

6. Methodology

6.1 Building microclimate monitoring

The exhibition hall on the ground floor of the building was continuously monitored throughout the year 2014-15. The monitoring protocol, especially with regard to the sensors location, was developed on basis of findings from a preparatory short term monitoring performed in 2013 [39]. The environmental parameters continuously monitored in the exhibition space are given in Table 6.1.1.

Inside-position code	Physical Parameter	Logger	Accuracy (of absolute reading)
0.1.2-0.1.4-0.1.5	Dry bulb temperature (°C)	Hobo U12	(±0.35)
0.1.2-0.1.4-0.1.5	Dew temperature (°C)	Hobo U12	(± 2.5%)
0.1.2-0.1.4-0.1.5	Relative Humidity (%)	Hobo U12	(± 2.5%)
0.1.2-0.1.4-0.1.5	Light Intensity (lux)	Hobo U12	(± 2.5%)
0.1.2	CO2 (ppm)	Vaisala GM70	(± 2%)
0.1.2	Radiant temperature asymmetry (°C, W/m²)	MM 0036 Innova	(± 1) *
0.1.2	Operative Temperature (°C)	MM 0060 Innova	(± 0.3)
0.1.2	Air Velocity (m/s)	MM 0038 Innova	(0.05α+0.05) **

* Difference Air Temperature- Plane Radiant Temperature <20°K
** with air velocity <1m/s and 0.25α with air velocity up to 10m/s

Table 6.1.1; Parameters monitored in the exhibition hall

The parameters for the assessment of building-users thermal comfort were measured during three short time intervals throughout the 2014 in point 012; while parameters measured for IMQ assessment for movable heritage, were measured continuously through the whole year in all the measurement points, see Table 6.1.2. However, due to loggers failure, data from July the 20th to September the 8th are not taken into account in the analysis.

	Temporal representativeness		**Temporal resolution**	
	Start (date)	End (date)	Sampling (minutes)	Averaging (minutes)
Building users				
heated period 1	04/03/2014	12/04/2014	120	120
warm period	11/08/2014	30/09/2014	15	60
heated period 2	01/10/2014	26/11/2014	120	120
Movable Heritage				
	19/02/2014	31/01/2015	15	60

Table 6.1.2; Characteristics of the monitoring campaign: temporal representativeness and resolution

Parameters in Table 6.1.1, were sampled each 15 minutes with the exception of: operative temperature, radiant temperature asymmetry and air velocity, sampled each 120 minutes. Because this low temporal resolution (given by logger memory capacity) might yield to biased results in presence of outliers, a data analysis prior to the IMQ certification was performed.
In order to acquire data in vicinity of the certification targets, the sensors were installed 1.30 m high from the floor. To avoid biased heat and moisture transfer due to contact between sensors and building (or other) surfaces, each logger was installed on an independent support distant from any environmental disturbance. At the top of each support, a 1.5 mm thick highly conductive metal wire extension (0.15 m long) was installed for hanging the instruments and measuring the free air. Sensors MM 036, MM038 and MM060 were positioned on a dedicated support also distant from surfaces, see Figure 6.1.1 a- b.

Figure 6.1.1 a (left) and b (right); Hobo U 12 data logger during the installation (left); Innova MM 0036, MM 038, MM 060 and Vaisala GM 70 sensors during the installation

The position code for each logger is given in Table 6.1.1 and in Figure 6.1.2. The distance between sensor 014 (entrance) and 012 (centre of the exhibition space) is ±10m, the distance between sensors 012 and 015 (back of the exhibition space) is ±13m and the distance between sensors 012 and 015 is ±22m.

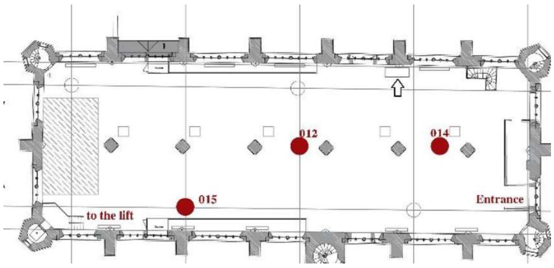

Figure 6.1.2; Localization of sensors (circles) and indication of the air-heating unit (arrow)

6.2 Analysis of microclimate heterogeneity

Methodologies for the evaluation of environmental heterogeneity of a given monitored space for the purpose of people thermal comfort assessment or microclimate diagnosis are introduced respectively by the EN 7726 and UNI 10829 standards [41,42]. The latter, does not propose a tailored analysis of space heterogeneity, however it introduces a stepwise methodology for deciding upon sensors location on basis of some considerations of spatial microclimate variability; in fact it can be considered a spatial heterogeneity analysis.
Furthermore, a widely accepted methodology for the representation of environmental parameters spatial variability, to support microclimate studies, is introduced by D. Camuffo [43] and integrated within the EN 16242 [44].
The EN 7726 method, recalled within the EN 15251[6], defines a monitored space bioclimatically homogeneous if the relation in (1) in a given moment is verified.

$$\varphi_{(i)} - \mu_{\varphi_{(i)}} < a_{(\varphi)} X \quad (1)$$

Where $\varphi_{(i)}$ is the punctual reading registered at the point (i) for the (φ^{th}) environmental parameter, ($\mu_{(\varphi)}$) is the mean value of the (φ^{th}) parameter measured in all the measurement points; ($a_{(\varphi)}$) is the required or desirable sensors accuracy with regard to the (φ^{th}) environmental parameter and (X) is a constant; see table 4 in [41];
The standard ISO 7730, does not provide a methodology for the spatial microclimate analysis of the monitored space, but it rather suggests interval of maximum Operative Temperature variation; see Table A1 in [5].
The UNI 10829 method, suggests to assess whether temperature and relative humidity readings from preparatory snap-shots measurements satisfy the relations in (2) and (3).

$$\Delta_{Temp} \leq 2°C \quad (2)$$
$$\Delta_{RH} \leq 5\% \quad (3)$$

Where (Δ_{Temp}) and (Δ_{RH}) are temperature and relative humidity absolute differences between knots on a 5m space meshing. If the relations are satisfied, the space can be considered reasonably homogeneous and long term microclimate monitoring can be performed on the same mesh. Even if the mentioned methodologies allow for a general evaluation of the spatial microclimate variability, they do not allow for a precise appreciation of the actual spatial hygrothermal heterogeneity as the following limits may be observed:

- The actual hygrothermal deviation between points is not taken into account as only maximum thresholds are considered;
- The extent of the actual parameters variation in relation to the actual instruments distance is neglected;
- The heterogeneity assessment is dependent on instruments accuracy (EN 7726);
- The heterogeneity assessment is not considered in function of time.

The UNI 10829 gives a threshold for maximum temperature and relative humidity variability with reference to a max distance, however the consideration of a maximum threshold does not allow to identify actual microclimate heterogeneities.
In the authors opinion, the consideration of actual microclimate variation related to the sensors distance is fundamental. Higher environmental readings deviations can be tolerated for larger measurement point distances. Moreover, the evaluation of the microclimate heterogeneity should be independent from the sensors accuracy, otherwise a given environment may be judged homogeneous by less accurate instruments and vice versa.

Further, it should be considered, the time frequency of the environmental parameters spatial variations. How should a space be judged if it is not homogeneous for only 10% or 5% of time? This issue is even more stringent when performing short monitoring intervals as hygrothermal dynamics are more or less stable during critical moments of the year.
For the reasons above explained, the spatial heterogeneity was tested by means of pairwise comparison of the differences between the current hygrothermal readings from the three measurement points. The absolute difference was calculated by the Root Squared Deviation (RSD) (minimum and maximum) and by the Root Mean Squared Deviation (RMSD) of temperature and relative humidity readings; see eq. 4 and 5.

$$\mathrm{RSD} = \sqrt{(\varphi_{(i,t)} - \varphi_{(i,t)})^2} \qquad i = \overline{1,n} \quad t = \overline{1,m} \tag{4}$$

$$\mathrm{RMSD} = \sqrt{\frac{\sum_{t=1}^{n} (\varphi_{(i,t)} - \varphi_{(i,t)})^2}{n}} \qquad i = \overline{1,n} \quad t = \overline{1,m} \tag{5}$$

$$\mathrm{RSD}' = \frac{\sqrt{(\varphi_{(i,t)} - \varphi_{(i,t)})^2}}{d} \qquad i = \overline{1,n} \quad t = \overline{1,m} \tag{6}$$

$$\mathrm{RMSD}' = \frac{\sqrt{\frac{\sum_{t=1}^{n} (\varphi_{(i,t)} - \varphi_{(i,t)})^2}{n}}}{d} \qquad i = \overline{1,n} \quad t = \overline{1,m} \tag{7}$$

Where ($\varphi_{(i,t)}$) is the (φ^{th}) environmental parameter measured at the time *t (1, m)* in the point *i (1, n)*. Both RSD and RMSD can be standardized on the actual sensors distance (*d*), see eq. 6 and 7.
In our case study, the sensors distance is higher than the one suggested by the UNI 10829 and no vertical gradient is taken into account because the collection and visitors are located at a maximum height of 3m. However, during the 2013 monitoring the space was monitored by five sensors with a distance of ≈5m between each and it was observed to be homogeneous; Note 2 in the supplementary information.
The heterogeneity analysis allowed not only the evaluation of IMQ spatial variability for movable heritage but also for building users. However, because it was only possible to install an indoor microclimate station in one measurement point (012), the spatial microclimate heterogeneity, and its influence on the thermal comfort was quantified by means of sensitivity analysis.
Operative Temperature (OT) and Mean Radiant Temperature (MRT) from point 012 (see Table 6.1.1 and Fig. 5.1.3) were altered considering the maximum measured spatial temperature deviation at the 95th percentile. Considering the altered parameters (including relative humidity), the PMV was re-calculated and the IMQ re-certified. The following simplifications were admitted:

- Air temperature spatial deviation instead of OT or MRT ones was considered because the latter two were measured only in one measurement point (012). However, from a comparison of T, OT and MRT in point 012 the difference between MRT and T was negligible (≤1°C), meaning that the radiative component in the monitored space is rather small, see Fig. 6.2.1. This simplification is admitted in EN 15251, Annex A.
- Air velocity was considered constant in the space. The air velocity was measured < 0.1m/s and <0.15m/s respectively for the 77.8% and 99.6% of sampled data.

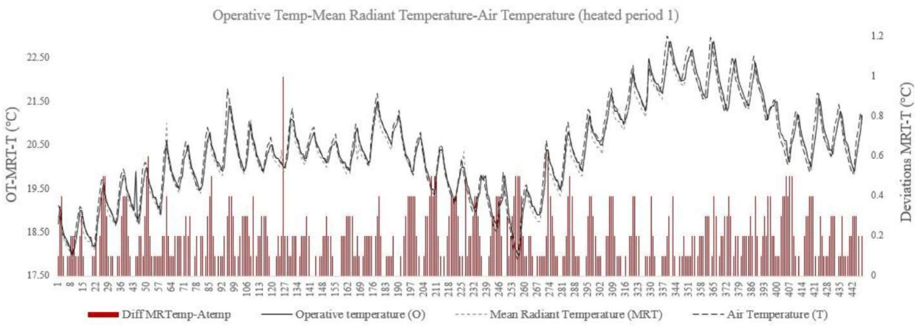

Figure 6.2.1; First vertical axes: Air temperature, Operative Temperature, Mean Radiant Temperature during heating period 1 (point 012); second vertical axes Difference Mean Radiant Temperature- Air Temperature (°C)

6.4 Microclimate certification

The developed certification model is based on the concept of microclimate neutrality mentioned in section 3. The model considers the neutrality condition as zero and the deviation from it as symmetrical stepwise numerical (and linguistic) alterations, such as: good conditions (±1), moderate conditions (±2) unacceptable conditions (±3). The here presented model is symmetric and category- dependent.

The advantage of a symmetrical IMQ long-term certification model as well as the disadvantages of a categories-dependency are discussed by S. Carlucci in [45]. Although a category-based IMQ certification model generates discontinuities at the edge of each category interval (because not developed on a continuous function), it allows a rapid microclimate control, crucial in the management process of heritage buildings and museums.

For allowing a long term evaluation of the hygrothermal comfort, the model refers to Percentage Inside the Ranges (PIR). This allows to verify the cumulated time frequency of each criterion ($\varphi_{(k)}$) in the category intervals for each assessment criterion for both people ($IMQ_{(P)}$) and movable heritage ($IMQ_{(H)}$); see Eq. (8).

$$IMQ_{(H,P)} = \sum_{k_i=1}^{n} \varphi_{(k_i)} \qquad \text{Where} \begin{cases} \varphi_{(k)} \leq \text{Cat}_{(\partial)} \text{ upper limit} \\ \varphi_{(k)} \geq \text{Cat}_{(\partial)} \text{lower limit} \end{cases} \tag{8}$$

In the first step, two dimensionless time frequency matrices, for people ($T_{(P)}$) and movable heritage ($T_{(H)}$), are built considering respectively the frequency of time during which the *($\varphi^{th}{}_{(P)}$)* or *($\varphi^{th}{}_{(H)}$)* criterion (in rows) falls in the *(∂^{th})* category interval in column (9).

$$T_{(\alpha)} = \begin{bmatrix} t_{1,1} \dots t_{1,\partial} \dots t_{1,n} \\ \vdots \\ t_{\varphi,1} \dots t_{\varphi,\partial} \dots t_{\varphi,n} \\ \vdots \\ t_{m,1} \dots t_{m,\partial} \dots t_{\varphi,\partial} \end{bmatrix} \qquad \varphi = \overline{1,m} \quad \partial = \overline{1,n} \tag{9}$$

Where (α) refers respectively to people (P) or movable heritage (H); (m) refers to number of (φ) criteria; (n) refers to number of (∂) category intervals. In this study *($m_{(P)} = 1$), ($m_{(H)} = 2$),* while *($n = 7$).*

The magnitude of the microclimate deviations from the neutral comfort, is expressed by a stepwise numerical perturbation of 0. With this purpose, the vector (β) is introduced. The incidence vector (β) is a (7x1) matrix, with elements ranging from {-3,…,+3}. In this study symmetrical importance is given to upper and lower deviations, however a weighted or asymmetrical incidence might be considered according to the specific building and collection requirements.

With regard to the movable heritage and for taking into account the daily fluctuations and the risk of mechanical deterioration of the objects in the collection, the incidence vectors includes incremental factors; see Table 6.4.1.1 and Table 6.4.1.2.

In the second step, the incidence matrices for heritage *($P_{(H)}$)* and people *($P_{(P)}$)*, are calculated as the product of the time frequency matrices *($T_{(H)}$)* or *($T_{(P)}$)* and the perturbation (β) vector; considering its elements in absolute value. The result is a (mx1) matrix describing, for each considered criterion, the severity of deviation from the microclimate neutrality. Therefore, the severity of the deviations is evaluated by the product of the deviation time frequency (time frequency matrix) and the deviation magnitude (perturbation vector with incremental factors); see Eq. (10-11).

$$\left(P_{(H)}\right) = \left(T_{(H)}\right) \cdot (\beta) \qquad (10)$$
$$\left(P_{(P)}\right) = \left(T_{(P)}\right) \cdot (\beta) \qquad (11)$$

Because the different indoor climate aspects may play a different role in the global comfort perception and even more for hygroscopic materials, it is considered a weighting step. In the following study, the importance for the considered hygrothermal indicators with regard to the cultural heritage objects was defined according to literature results. The weights, respectively 0.33 for temperature and 0.67 for relative humidity, are considered for the long term fluctuation.
In the third step, the weighted incidence matrices for people $(\overline{P_{(P)}})$ and heritage $(\overline{P_{(H)}})$ are calculated as the product of the transposed incidence matrices, $(P_{(P)})^T$or $(P_{(P)})^T$ and the theoretical weighting vector $\{\overline{\omega}_P\}$ or $\{\overline{\omega}_H\}$; see Eq. (12-13).

$$(\overline{P_P}) = (P_P)^{T} \cdot (\overline{\omega}_P) \qquad (m = 1) \qquad (12)$$

$$(\overline{P_H}) = (P_H)^{T} \cdot (\overline{\omega}_H) \qquad (m = 2) \qquad (13)$$

The results of the matrices can be intended as single scores for each microclimate criteria representing the current performance with regard to people or heritage criteria, considering at the same time the severity of the occurred deviations and the importance of the single examined environmental criterion.
Finally, if necessary, a simultaneous index of performance (Simultaneous Performance Index-SPI) can be calculated in order to provide a complete picture of the current microclimate quality with regard to movable heritage and building users, see Eq. (14).

$$SPI = \frac{\sum_{m=1}^{n} \overline{P_{(H,P)}}}{\sum m} \qquad (m = 3) \qquad (14)$$

Where *m* - number of criteria considered with regard to both heritage and people. At this point, an adjunctive weighting process, for distinguishing the importance between heritage and people needs according to the space requirements, may be introduced although not considered in this contribution. As above mentioned, the optimal microclimate quality coincides with the microclimate neutrality (0). The obtained SPI, other than 0, represents the deviation from the optimal microclimate comfort.

6.4.1 Microclimate quality categories for movable heritage

For the definition of IMQ for the cultural heritage, multiple microclimate categories of comfort were considered. Progressive intervals of deviation from the microclimate neutrality were determined on basis of the building target microclimate inferred from the building historic climate [26,46,47].
The neutral microclimate (target range) for hygroscopic movable heritage, is calculated by admitting short-term fluctuations not higher than the ones already experienced by the building materials in the past. Only the 14% of risky short-term fluctuations: the 7th and 93rd percentile, are eliminated, see Annex A in EN 15757.
Less demanding, but still safe hygrothermal ranges, are proposed in the literature considering the 10% positive and negative variation around the hygrothermal seasonal cycles or the exclusion of the 10% extreme short term fluctuations instead of 14% [37]. The mentioned two microclimate relaxation limits are here considered as additional categories: "still acceptable" (±2) and "good" (±1); see Table 6.4.1.1.

Deviation (β)	MCH Microclimate Comfort Heritage	Short term fluctuations; Incremental factors to (β)	
±3	$\varphi_{(k)} > \overline{\varphi}_{30}(k)+\overline{\varphi}_{30}(k)10\%$; $\varphi_{(k)} < \overline{\varphi}_{30}(k)-\overline{\varphi}_{30}(k)10\%$	-	
±2	$\overline{\varphi}_{30}(k)-\overline{\varphi}_{30}(k)10\% \leq \varphi_{(k)} \leq \overline{\varphi}_{30}(k)+\overline{\varphi}_{30}(k)10\%$	Temp-RH short fluctuations	
		0	Condition A
		0.5	Condition B
		2 Collapse in 3	Condition C
±1	$\overline{\varphi}_{30}(k)-\Delta_{\varphi L} \leq \varphi_{(k)} \leq \overline{\varphi}_{30}(k)+\Delta_{\varphi U}$ $\Delta_{\varphi L} = 5^{th}$ perc; $\Delta_{\varphi U} = 95^{th}$ perc.	Temp-RH short fluctuations	
		0	Condition A
		0.5	Condition B
		1 Collapse in 3	Condition C
0	$\overline{\varphi}_{30}(k)-\Delta_{\varphi L} \leq \varphi_{(k)} \leq \overline{\varphi}_{30}(k)+\Delta_{\varphi U}$ $\Delta_{\varphi L} = 7^{th}$ perc; $\Delta_{\varphi U} = 93^{rd}$ perc.	Temp-RH short fluctuations	
		0	Condition A
		0.5	Condition B
		0 Collapse in 3	Condition C

Table 6.4.1.1; Categories ranges for collection (H)

Condition A (RH)	Condition A (Temp)

$\begin{cases}\Delta_{(\mathrm{RH,day})} < \Delta_{(\mathrm{RH,90})} \\ \Delta_{(RH,i)} < \Delta_{(RH,plast)}\end{cases}; \geq 90\% \, (N_1), \geq 95\% \, (N_2)$	$\begin{cases}\Delta_{(\mathrm{Temp,day})} < \Delta_{(\mathrm{Temp,90})} \\ T_{(i)} > T_{(g)}\end{cases}; \geq 90\% \, (N_1), \geq 95\% \, (N_2)$
Condition B (RH)	Condition B (Temp)
$\begin{cases}\Delta_{(\mathrm{RH,day})} > \Delta_{(\mathrm{RH,90})} \\ \Delta_{(RH,i)} < \Delta_{(RH,plast)}\end{cases}; \geq 80\% \, (N_1), \geq 95\% \, (N_2)$	$\begin{cases}\Delta_{(\mathrm{Temp,day})} < \Delta_{(\mathrm{Temp,90})} \\ T_{(i)} > T_{(g)}\end{cases}; \geq 80\% \, (N_1), \geq 95\% \, (N_2)$
Condition C (RH)	Condition C (Temp)
$\{\Delta_{(RH,i)} > \Delta_{(RH,plast)}; > 5\% \, (N)$	$\{T_{(i)} > T_{(g)}; > 5\% \, (N)$

Table 6.4.1.2; Conditions a, b and c for short fluctuations (H)

It is well known that short-term fluctuations might generate even higher risk than seasonal ones as likely to affect the surface layers of a given cultural object and generate high risk of mechanical deterioration on the stratum and sub-stratum of the object. For these reasons the assessment of the short-term (daily) cycles was included in the certification model.

The calculation of daily hygrothermal cycles is not unequivocal and, by varying the calculation method, the results are different. In the authors opinion, the Centred Moving Average (49 periods) is the most appropriate methodology. Note 3 in the supplementary information.

In Fig. 6.4.1, temperature and relative humidity daily cycles, calculated on the CMA (49 periods) with regard to the spatial average are ordered and plotted in a scatter plot. The resulting logarithmic curve shows (risky) outlying values on the top- right corner. If considering temperature and relative humidity daily cycles up to the 95th percentile, these are 2.5°C and 7% maximum. For allowing a conservative scenario, in the model we considered the 90th percentile of the mentioned fluctuations.

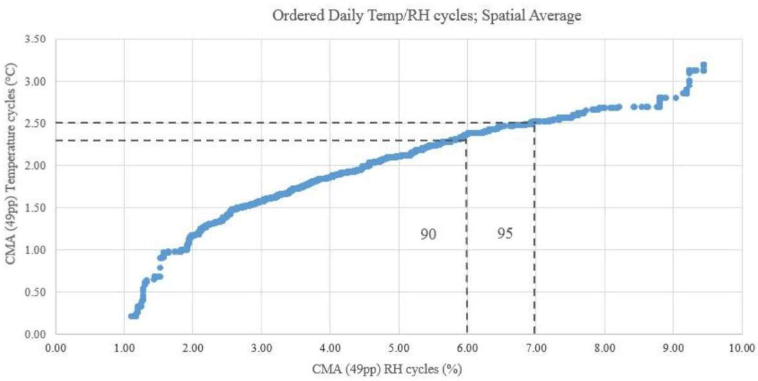

Figure 6.4.1; Ordered CMA (49 periods) temperature and relative humidity fluctuations; the readings refer to the spatial average; in grey 90th and 95th percentiles

It is worth remembering that preventing daily fluctuations other than the most frequently experienced ones by the materials (e.g., 90th percentile), does not mean avoiding the risk of materials deterioration, but rather means reducing the probability that it occurs. This approach, especially valid in case of hygroscopic materials, is meaningful if also combined with a specific materials-based risk assessment.

Since in the monitored exhibition space, the majority of the objects exposed in the free air is made up of timber panels (e.g. pianoforte or painted panels) we included in the IMQ certification model the climate-induced mechanical deterioration model by M.F. Mecklenburg et. al [48,49]. Coded with good level of approximation by P. Lankester and P. Brimblecombe in [50]; Note 4 in the supplementary information.

For certifying the IMQ including short-term fluctuations, two additional levels of assessment were integrated in the model, described by conditions A-C in Table 6.4.1.2; Note 5 in the supplementary information.

The first assessment level aims at evaluating if short-term (daily) fluctuations deviate from the ones recurrently experienced by the materials in the historic microclimate. The second one aims at verifying whether the relative humidity cycling generates plastic deformation to timber panels ($\Delta_{\mathrm{RH,\ plast}}$). In the second assessment level it is also verified whether the air dry bulb temperature is higher than 12°C (glass transition temperature). Temperature below the glass transition $T_{(g)}$ might increase the risk of painted film cracking: oil, alkyd or acrylic layer become brittle with air temperature lower than ±12°C [13].

6.4.2 Microclimate quality categories for building users

For the definition of the category intervals with regard to building users thermal comfort, the intervals provided by the ISO 7730 and EN 15251 standards respectively for the cold and warm period were used; see Table 6.4.2.1

Deviation (β)	MCP (Microclimate Comfort People) winter	MCP Microclimate Comfort People) free running
±3	PMV < -0.7; PMV> + 0,7	$\theta_{imax} > 0.33\theta_{rm} + 18.8 + 4$; $\theta_{imin} < 0.33\theta_{rm} + 18.8 - 4$
±2	-0,7 ≤ PMV ≤ + 0,7	$0.33\theta_{rm} + 18.8 - 4 \leq \theta_i \leq 0.33\theta_{rm} + 18.8 + 4$
±1	-0,5 ≤ PMV ≤ + 0,5	$0.33\theta_{rm} + 18.8 - 3 \leq \theta_i \leq 0.33\theta_{rm} + 18.8 + 3$
0	-0,2 ≤ PMV ≤ + 0,2	$0.33\theta_{rm} + 18.8 - 2 \leq \theta_i \leq 0.33\theta_{rm} + 18.8 + 2$

Table 6.4.2.1; Categories ranges for people (P)

7. Results

7.1 Analysis of microclimate heterogeneity

A summary statistics of the Root Squared Deviation (RSD) and Root Mean Squared Deviation (RMSD) of temperature and relative humidity between measurement points is given in Table 7.1.1.
The analysis of the actual maximum RSD between points for temperature and relative humidity permitted an understanding of the actual indoor microclimate heterogeneity in the space. Even if the space can be considered homogeneous according to the EN 7726 and UNI 10829 standards, a hygrothermal variability between measured points is still observable, see Table 7.1.2.

	RMSD (%)	RSD Min. (%)	RSD Max. (%)	RMSD' (%/m)	RSD' max (%/m)
RH 012-014	1.934	0.000	6.709	0.193	0.671
RH 012-015	0.858	0.000	3.914	0.066	0.300
RH 014- 015	1.864	0.000	7.158	0.084	0.325
	RMSD (°C)	RSD Min. (°C)	RSD Max. (°C)	RMSD' (°C/m)	RSD' max (°C/m)
Temp 012- 014	0.349	0.000	1.136	0.035	0.113
Temp 012- 015	0.210	0.000	1.260	0.016	0.096
Temp 014- 015	0.253	0.000	1.020	0.011	0.046

Table 7.1.1; Pairwise temperature (Temp) and relative humidity (RH) difference between measurement points.

Mean temperature difference between points was between 0.21°C (± 0.35°C) and 0.35°C (± 0.35°C) with maximum difference 1.26°C (±0.35°C). However, the measured maximum difference was an exceptional event as for the 95th percentile the absolute temperature difference between points was <0.71°C (±0.35°C); see Table 7.1.2
From a diagnostic point of view, though temperature difference between points is numerically low, it is still possible to observe a partialization of the temperature distribution in the space. Indeed, the air temperature difference between the entrance and the centre of the space (points 014-012) is almost constantly 0.17°C higher than the one registered between the centre and the back (012-015).

Percentiles	5.00	10.00	25.00	50.00	75.00	90.00	95.00
RH RSD 012-014	0.42	0.69	1.17	1.76	2.59	3.37	3.99
RH RSD 012-015	0.06	0.11	0.29	0.70	1.28	1.85	2.24
RH RSD 014-015	0.18	0.38	0.94	1.67	2.60	3.71	4.22
Temp RSD 012- 014	0.04	0.07	0.17	0.35	0.49	0.62	0.71
Temp RSD 012- 015	0.01	0.02	0.06	0.14	0.36	0.48	0.54
Temp RSD 014- 015	0.02	0.04	0.10	0.22	0.39	0.51	0.58

Table 7.1.2; Percentiles of pairwise temperature and relative humidity differences

This is also observable with respect to the relative humidity. In the 95th percentile, the RH difference between entrance and centre of the space was 3.99% (±1.50%) while it was 2.24% (±1.52%) between the centre and the back. This may suggest that the indoor microclimate from the centre to the back is more homogeneous than the one from the entrance to the centre. The hygrothermal variations between the back and the centre of the space are negligible from the 75th percentile. In other words, the residual variation between the entrance and the centre of the space (014-012) with regard to temperature and relative humidity is not higher than 0.05°C/m and 0.26%/m respectively for 75% of the sampled data.
For assessing the thermal comfort variability of building users according to the discussed spatial hygrothermal variations, the maximum temperature deviation registered for the 95% of sampled data (±0.71°C) was respectively added and subtracted to OT and MRT from point 012. The same was done for the RH (±3.99%).

The 2-hour based PMV for heating period and boundaries of indoor (operative) temperature for free running period were recalculated considering the positively and negatively altered parameters. The IMQ was recertified. The obtained (altered) PMV (or operative temperature ranges) represent the maximum spatial thermal comfort deviations according to the registered microclimate variability.
If developing an IMQ certification for movable artefacts (especially if the EN 15757 is taken into account), the analysis of the differences between hygrothermal fluctuations in each measurement point, is even more relevant than the analysis of the absolute difference of temperature and relative humidity readings. These fluctuations play a more significant role on objects conservation than temperature and relative humidity absolute values themselves. For this purpose, the short and long term fluctuations, calculated for each measurement points and for the spatial average (in accordance to the EN 15757) were compared.
As mentioned in section 3, if a collection is kept in a given open space, it is reasonable to suppose that the objects interact with the indoor microclimate. If a given environment is spatially homogeneous, seasonal and short-term fluctuations should be identical in each point. In reality a perfect homogeneity is impossible, however if the deviations are negligible, the certification of the room microclimate can be considered representative for all the objects microclimate proximity.
For evaluating the deviation between objects microclimate proximity and free air, the hygrothermal conditions in proximity of randomly located objects in the exhibition space were measured and compared to their closest measurement point. During these snapshot measurements, air velocity, air temperature, relative humidity and contact temperature were measured. The latter was measured by means of IR imaging. In presence of glass, the IR thermography was done by previously taping a portion of the target surface with paper tape (see Fig. 7.1.1.a-c).
Specific attention was given to the objects located on the direction of the air-heating unit outlets (Fig. 6.1.2 and 7.1.1.a). Indeed, during the museum opening hours the unit is in work and in the cold period, the warm air blowing from the unit causes air velocity and temperature increase. This circumstance is less sharp during the warm period as the unit does not provide cooling.
Currently, a large amount of objects near the unit is exposed either in unsealed showcases or behind protective (not in touch) glass panels. In proximity of the showcases most close to the unit outlet (Fig. 7.1.1.a-c), hygrothermal conditions similar to the closest point 014 were observed. Air temperature and contact temperature were 0.48°C and 0.46°C higher than point 014, air velocity was 0.03m/s and relative humidity was 1.49% lower compared to point 014. Nowhere were sharp differences between free air and objects proximity registered.

Figure 7.1.a; Localization of the air-heating unit in the exhibition room (during measurement at the inlet)
Figure 7.1.b Microclimate measurement in proximity of the first unsealed showcase in the direction of the heating unit airflow
Figure 7.1.c Air temperature 19.2°C, air velocity 0.03m/s; contact temperature 19°C (IRT on paper spot); relative humidity 59%

Long and short-term fluctuations for temperature and relative humidity were calculated for each measurement point. Successively pairwise variations between points were quantified. The long-term fluctuations are calculated as parameters- CMA (30days) while short ones are the differences between current parameter reading and CMA value; see Annex A in [30]. The results confirmed what was described above in relation to absolute hygrothermal readings.
The CMA of temperature for the 95th percentile was max 0.57°C (±0.35°C) different between the entrance and centre of the space (014-012); the same difference was negligible between the centre and the back (012-015). Similarly, for the 95th percentile, the CMA of relative humidity was up to 2.96% (±1.50%) different between the entrance and the centre of the space (014-012), while it was negligible from the centre to the back (012-015); see Table 7.1.3. The Pearson coefficient for the three CMA pairwise correlation was always > 0.997 (sig. 0.01) explaining the overall homogeneity of the indoor microclimate dynamics.

Percentiles	**5**	**10**	**25**	**50**	**75**	**90**	**95**
RSD CMA Temp 012-014	0.10	0.11	0.25	0.35	0.41	0.52	0.57

RSD CMA Temp 012-015	0.09	0.10	0.12	0.16	0.23	0.24	0.25
RSD CMA Temp 014-015	0.01	0.03	0.10	0.18	0.30	0.37	0.45
RSD CMA RH 012- 014	1.12	1.18	1.41	1.72	2.45	2.75	2.96
RSD CMA RH 012- 015	0.11	0.14	0.24	0.42	0.79	1.01	1.11
RSD CMA RH 014- 015	0.88	1.01	1.25	1.76	2.23	3.15	3.41

Table 7.1.3; pairwise difference between seasonal fluctuations (CMA)

Consistently with what was observed above, the microclimate is more stable to short fluctuations at the back of the exhibition space compared to the entrance.
In Table 7.1.4, the corresponding 7th and 93rd percentile values of short-term fluctuations for each measurement point are given as also for the spatial average. On the right side of the table are reported absolute deviations between single points percentiles and spatial average percentiles.
Because of the temporary interruption of the monitoring between July and September, the percentiles are calculated for two time intervals, 06/03-03/07/2014 and 21/09-31/12/2014. However, according to the results from the monitoring campaign in 2013, it is expected that the absence of readings in August does not vary the calculated percentiles.

Temperature	Temp 015	Temp 014	Temp 012	Temp (spatial)	Dev. 012 (RSD)	Dev. 014 (RSD)	Dev. 015 (RSD)
7th Percentile (°C)	-1.50	-1.46	-1.37	-1.43	0.07	0.03	0.07
93th Percentile (°C)	1.61	1.58	1.51	1.55	0.04	0.03	0.06
Relative Humidity	RH 015	RH 014	RH 012	RH (spatial)	Point 012 (RSD)	Point 014 (RSD)	Point 015 (RSD)
7th Percentile (%)	-3.15	-3.47	-2.88	-3.06	0.18	0.42	0.09
93th Percentile (%)	2.90	2.96	2.64	2.81	0.17	0.15	0.09

Table 7.1.4; short term fluctuations 7th and 93rd Percentiles for three measured points and spatial average; absolute deviation between spatial average and single measurement points percentiles (right side)

From Table 7.1.4, it can be seen that the central part of the space (point 012) is the most stable to short term hygrothermal fluctuations, the back part (015) has highest and lowest temperature short term fluctuations, while the front (014) has the highest relative humidity short term fluctuations. This is consequent to the door operating and vicinity to the air heating unit (without humidity control).
As mentioned in section 3, it should be noted that a difference exists between microclimate heterogeneity with regard to IMQ diagnosis and certification. With regard to the first, if considering the discussed results from Tables 7.1.1 and 7.1.2, it is evident that a slight hygrothermal partialization of the monitored space exists, especially between the front and the back. However, in order to understand if the space is also heterogeneous from an IMQ certification view point (for movable heritage), it was evaluated whether the spatial mean of temperature and relative humidity (from the three points) is representative of each point microclimate.
The Centred Moving Average of the spatial average ($CMA_{(spatial)}$), was calculated for temperature and relative humidity as well as the RSD between CMA of each point and the $CMA_{(spatial)}$. This difference represents the variation between seasonal fluctuations calculated in each individual point and the one calculated from the spatial average.
In Table 7.1.5, can be observed that the seasonal fluctuations of the spatial mean temperature and relative humidity ($CMA_{(spatial)}$) accurately represent the one of each measurement point ($CMA_{(i)}$). The highest deviation between CMA spatial average and CMA single point is observable in point 014. In this point, the maximum CMA deviation for temperature is 0.36°C and for relative humidity is 2.07%. This deviation represents however only 5% of the data population.

Percentiles	**5**	**10**	**25**	**50**	**75**	**90**	**95**	**max**
RSD CMA_{012}- $CMA_{(spatial)}$ (°C)	0.10	0.11	0.14	0.17	0.19	0.22	0.23	0.24
RSD CMA_{014}- $CMA_{(spatial)}$ (°C)	0.00	0.01	0.09	0.17	0.24	0.30	0.34	0.36
RSD CMA_{015}- $CMA_{(spatial)}$ (°C)	0.01	0.02	0.03	0.07	0.10	0.11	0.12	0.13
RSD CMA_{012}- $CMA_{(spatial)}$ (%)	0.18	0.27	0.44	0.59	0.74	1.13	1.25	1.30
RSD CMA_{014}- $CMA_{(spatial)}$ (%)	0.68	0.73	0.92	1.15	1.62	1.80	1.97	2.07
RSD CMA_{015}- $CMA_{(spatial)}$ (%)	0.19	0.25	0.31	0.44	0.73	1.40	1.44	1.51

Table 7.1.5; Pairwise difference of the seasonal fluctuations (CMA); temperature (above) and relative humidity (below)

According to the EN 15757 the target microclimate can be calculated as algebraic addition of the short term fluctuations to the long-term fluctuations (seasonal fluctuations).

It is worth noting that, the target-microclimate according to EN 15757 refers only to RH (for the reasons explained in section 3). However, for giving a complete overview of the extent of the microclimate deviations between specific and spatial average we refer to both temperature and relative humidity.
Considering the cumulative effect of the long and short-term deviations between point 014 and spatial average, it can be concluded that the maximum deviation in terms of microclimate targets definition, is 0.42°C for temperature and 2.63% for relative humidity.
In other words, if the microclimate in point 014: the one deviating the most from the spatial average, is certified considering the target microclimate range calculated on the spatial average, the maximum occurring error for temperature is lower than 0.5°C and for relative humidity is lower than 3%; Note 6 in the supplementary information.
Given the small microclimate target deviation (<0.5°C Temp and 3% RH) and the low frequency of occurrence (<5%), as well as considering the current objects position (not out from the monitored domain), it can be concluded that in the reported case study, the spatial average accurately represents the microclimate proximity of each measurement point.
The target microclimate calculated according to the spatial average differs negligibly from the target microclimate calculated on basis of each point readings. For the purpose of IMQ certification of movable heritage, the readings from the spatial average can be inputted in the model.

7.2 Microclimate certification

The cold period considered in the certification is made up of two intervals: March-April 2014 and October-November 2014. For the two intervals, 2 hours-based PMV was calculated [5]. Statistics for both the PMV data samples are given in Table 7.2.1. For the warm period: August- September 2014, the indoor operative temperature intervals per three categories of comfort were calculated on the basis of the free running mean temperature outside [6].

	PMV March-April 2014		PMV October-November 2014	
	Statistic	Std. Error	Statistic	Std. Error
Mean	0.067	0.01	-0.249	0.014
Std. Deviation	0.22		0.353	
Minimum	-0.58		-1.02	
Maximum	0.6		0.49	
Skewness	0.07	0.115	-0.023	0.098
Kurtosis	-0.247	0.23	-1.032	0.196

Table 7.2.1; Statistics PMV period 1 (March-April 2014), period 2 (October-November 2014)

The first heating period has positive mean around zero, meaning a thermal sensation around the thermal neutrality, while the second one has negative mean around -0.25, meaning a thermal sensation skewed towards cold.
The PMV samples for both the periods were tested for normality. Test results evidenced that the distribution from the first period (March-April) is normal (Shapiro-Wilk normality test Sig. 0.064), while the one from the second period (October-November) slightly departs from the normality. This occurred due to indoor temperature readings found below the ones outdoor. Nevertheless, the outlying values were consistent with the indoor environmental variations in the specific period, therefore retained in the certification.

	Thermal Quality Heritage (H)	Hygrometric Quality Heritage (H)	Thermal Comfort People (P)	Simultaneous Performance Index (SPI)
	0.11	0.23	0.48	0.27
incidence	13.69%	27.48%	58.83%	100.00%

Table 7.2.2; SPI with three indicators (m=3)

On basis of the certification methodology presented in section 6.4 and considering the conclusions from section 7.1, the Simultaneous Performance Index (SPI) was calculated for thermal quality and hygrometric quality of movable heritage and hygrothermal comfort of building users. The obtained value (0.27) falls in the first category of deviation from optimal microclimate; this stands for good and safe indoor microclimate.
From the results in Table 7.2.2 it can be seen that the hygrometric and thermal microclimate quality for movable heritage only slightly deviates from the optimal microclimate. It should be mentioned that the microclimate short term fluctuations were always found in compliance with condition A in Table 6.4.1.2, therefore there was no evidence of mechanical deterioration risk (plastic deformation) for timber panels or embrittlement risk for the painted layer. The main observed deviation, though numerically small, is related to hygrothermal comfort for building users.

Table 7.2.3 reports the same results as in Table 7.2.2 but considering four indicators instead of three. Results regarding people thermal comfort are separated for the cold and warm period: the larger deviations from neutrality occurred during the heated period (P 0.72) while no departures from the neutrality were registered during the warm period (P 0.01).

	Thermal Quality Heritage (H)	Hygrometric Quality Heritage (H)	Thermal Comfort People Cold Period (P)	Thermal Comfort People Warm Period (P)	Simultaneous Performance Index (SPI)
	0.11	0.23	0.72	0.01	0.27
incidence	10.55%	21.18%	67.75%	0.52%	100.00%

Table 7.2.3; SPI with four indicators

Table 7.2.4 shows the frequencies of deviation from the thermal neutrality with regard to people hygrothermal comfort; the three monitored periods are considered separately with their specific $P_{(p)}$ value. The results from the sensitivity analysis related to the hygrothermal comfort spatial variability are included both in term of percentage of deviations from zero and (P_p) values.
As mentioned above, building users hygrothermal comfort during the warm period (August-September) is optimal. The total deviation from the first thermal comfort quality is negligible (P 0.01). This is unchanged also when considering the operative temperature alteration within the space. No spatial thermal comfort variation occurs because the registered maximum spatial temperature deviation (±0.71°C) is lower than the minimum one considered by the EN 15251 as likely to generate thermal sensation variation (±2°C); see Table 6.4.2.1. In this period the building was not equipped with mechanical cooling (free running).
Good thermal comfort quality was also observed during the first heating period. The PMV samples registered during this time-interval were scattered below and above the range of thermal neutrality meaning that slight cool and warm sensations occurred concomitantly. This condition resulted in an IMQ close to the neutrality (P 0.41). But a tendency towards slightly warm thermal sensation is observable. This tendency increases if considering the PMV samples resulting from the positive alteration of temperature and relative humidity (Alteration +).
In this case it can be observed that the IMQ deviates more significantly from the neutrality (P 0.72). Nevertheless, given the cumulative percentage of PMV in categories 0 and 1 ($-0.5 \leq PMV \leq 0.5$) the IMQ is good and no category variations is observable.
If the PMV is subjected to the negative alteration, the final result is rather similar to the original one (P 0.45). This occurs because of the redistribution of the votes between categories -1 and 1. Unlike to generate category variations.

	Categories of deviation from 0 (optimal IMQ)							$\overline{P_p}$
	-3	-2	-1	0	1	2	3	
Cold period; heating period 1	**0.0%**	**0.0%**	**11.0%**	**62.0%**	**24.0%**	**2.0%**	**0.0%**	**0.41**
Alteration (+)	0.00%	0.00%	2.24%	43.62%	40.49%	11.86%	1.79%	0.72
Alteration (-)	0.22%	2.91%	28.19%	57.94%	10.74%	0.00%	0.00%	0.45
Warm period; free running	**0.00%**	**0.00%**	**0.37%**	**99.44%**	**0.19%**	**0.00%**	**0.00%**	**0.01**
Alteration (+)	0.00%	0.00%	0.37%	99.44%	0.19%	0.00%	0.00%	0.01
Alteration (-)	0.00%	0.00%	0.37%	99.44%	0.19%	0.00%	0.00%	0.01
Cold period; heating period 2	**13.0%**	**15.0%**	**24.0%**	**37.0%**	**11.0%**	**0.0%**	**0.0%**	**1.04**
Alteration (+)	2.10%	13.89%	23.91%	34.25%	21.32%	4.52%	0.00%	0.88
Alteration (-)	26.01%	16.32%	25.69%	29.40%	2.58%	0.00%	0.00%	1.39

Table 7.2.4; Frequency of deviations from thermal comfort optimality for three monitoring intervals and associated P (people) values; Alteration (+/-) refers to the categories of deviations calculated considering PMV altered by the addition (+) or subtraction (-) of temperature and relative humidity maximum deviations

Conversely, during the second heating period (October –November), the deviations were mainly negative (minimum PMV -1.02, Table 7.2.1), standing for a remarkable cooling of the space (P 1.04). In this period, The air temperature was registered for 56 hours below the one outside. This condition caused a shift of the registered PMV towards negative categories -2 and -3 ($PMV \leq -0.7$). The readings in category *-1*, doubled compared to the ones in the first heating period. PMV categories *-2* and *-3* accounted for a total 28% of samples population compared to 0% of the readings population in the first heating period.
As it may be expected, if the PMV is subjected to positive alteration, a reduction of the deviation from the thermal quality occurs because of the significant diminishing of PMV samples within category -3 (P 0.88). Conversely, in case of PMV negative alteration, the increased population sample in the negative categories resulted in a shift of the total thermal comfort quality to the centre of the moderate category (P 1.39). It is worth mentioning that during the second heating period, the increase of relative humidity consequent to the temperature drop was not found risky for the objects. Moreover the indoor air temperature never dropped beyond the glass transition temperature.

8. Conclusions

With the purpose of detecting possible downsides of the current building microclimate management as well as for identifying microclimate management improvement solutions, it is fundamental to continuously certify the Indoor Microclimate Quality (IMQ). If this certification is based on a multi-objective assessment procedure, it facilitates to simultaneously assess the conflicting aspects of microclimate quality in heritage buildings and museums.

In this contribution we discussed the methodological aspects to be considered during data acquisition process finalized at IMQ certification. Issues regarding temporal and spatial representativeness and resolution of monitoring results were analysed.

Although results and conclusions refer to the reported case study, the research methodology may be replicated in other buildings.

The analysis pointed out that, although the monitored space was observed heterogeneous from a microclimate diagnostic point of view, it was rather homogeneous from a management one. Indeed, the hygrothermal parameters calculated from the spatial average were observed to not significantly deviate from each measurement point included in the domain. Therefore, accurate IMQ certification for movable heritage was allowed considering the target microclimate calculated from the spatial average instead of from each measurement point. The results shed some light on the possibility of optimizing number and location of measurement instruments during infield data acquisition when targeted to IMQ certification.

Results from sensitivity analysis clarified that small spatial temperature variations may result in spatial partialization of the people thermal comfort depending on the applied thermal model. This is not a minor aspect to consider during IMQ certification. Further research is solicited for identifying methodologies tailored at assessing the influence of environmental spatial heterogeneity on the actual thermal comfort sensation variation of people in motion.

In the reported case study; the alteration of ±0.71°C temperature during the warm period (considering the EN 15251 adaptive model) did not bring to comfort category variation in the space. However this occurred during the (second) heating period (considering the ISO 7730 non adaptive thermal model). In the latter case, a variation of thermal comfort quality was registered despite the environment was considerable uniform according to the standard.

In this study, we proposed a multicriteria-based model for the certification of Indoor Microclimate Quality (IMQ) for building users and cultural heritage. The model permitted an holistic understanding of the microclimate quality during different moments of the monitored year for different certification targets. Throughout the monitored period, the exhibition hall was characterized by good microclimate quality and absence of danger for the collection, caused by risky fluctuations or mechanical damage for the timber panels.

However, since a slight cooling of the space during the cold period was observed, consideration might be given to the adjustment of the temperature set-points. This is viable after a revaluation of the short hygrothermal fluctuations. On the contrary, given the perfect hygrothermal quality registered during the warm period, the installation of a cooling system in the studied exhibition hall is strongly discouraged.

9. Acknowledgments

The authors wish to thank the Vleeshuis museum director Timothy De Paepe and the former director Karel Moens for their kind support during the research. The research was financed by IWT - Instituut voor Innovatie door Wetenschap en Technologie, Belgium

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Indoor Microclimate Quality (IMQ) certification in heritage and museum buildings: the case study of Vleeshuis museum in Antwerp

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Abstract

In order to detect possible downsides of building microclimate management or for identifying performance improvement options, it is fundamental to assess and certify building Indoor Microclimate Quality (IMQ).
Considering that in heritage and museum buildings, the indoor microclimate should simultaneously ensure comfort of people and safety for the cultural heritage, its management takes on a multidimensional nature.
Although in the literature IMQ certification methodologies for people already exist, these do not encompass the cultural heritage. We believe this integration, would be a valid management instrument for heritage buildings, historic houses and museums, especially if they are not equipped with full microclimate control systems.
However, because environmental data acquisition activities have direct influence on the certification results, it is essential to evaluate them. These methodological aspects are here discussed on the basis of results from a microclimate monitoring in the main exhibition hall of Vleeshuis museum in Antwerp. Further, in accordance to the introduced methodological considerations, an IMQ certification model for building users and movable heritage is proposed.

Keywords: heritage and museum buildings, Indoor Microclimate Quality certification, multicriteria modelling applied to cultural heritage

Nomenclature and terminology

φ^{th}	Environmental parameter
$\mu_{(\varphi)}$	Mean value of environmental parameters sampled in different point of the space
$a_{(\varphi)}$	Requested/ desirable environmental parameter measurement accuracy
Δ_{Temp}	Absolute Temperature difference between two points
Δ_{RH}	Absolute Relative Humidity difference between two points
$\Delta_{(Temp,\ day)}$	Daily Cycle Temperature (°C)
$\Delta_{(RH,\ day)}$	Daily Cycle Relative Humidity (%)
$\Delta_{(RH,\ plast)}$	Cycle Relative Humidity causing plastic deformation (%)
T	Air Temperature (°C)
T_g	Temperature of glass transition
RH	Relative Humidity (%)
OP	Operative Temperature (°C)
MRT	Mean Radiant Temperature (°C)
RSD	Root Squared Deviation
$RMSD$	Root Mean Squared Deviation
CMA	Cantered Moving Average
(spatial)	with reference to the mean value of measurement points
(i)	with reference to a measurement point
(t)	With reference to a time interval
N_1, N_2...	Sampled data population. If considering more than one string, N_1 refers to string 1; N_2 refers to string to 2 etc.

The Terms: ***IMQ certification, movable and immovable heritage, object, tangible cultural heritage; cultural heritage; value*** and ***significance*** are reported in Note 1 in the supplementary material

1. Introduction

The IMQ of a building may be affected either by external climate or by internal loads. The building envelope is the first filter to the external climate and buffers the outer weather fluctuations keeping more steady the indoor building climate. Building systems, if present, ensure additional indoor microclimate control beyond the one allowed by the envelope itself. However, a constant microclimate control is not easily viable in historic buildings.

Cantin et. al. in [1] observed that indoor microclimate in historic buildings is strongly influenced by outdoor environmental conditions. This was observed to be not solely caused by the poor envelope hygrothermal performance but also by the unavoidable indoor-outdoor eco system interaction historic buildings have with the outdoor microclimate. This interaction is observable whether the building is equipped or not with mechanical installations [2-4]

Considering that a poor IMQ might influence building users comfort and cultural heritage conservation, it is fundamental to assess and certify it continuously.

In contrast with an indoor microclimate diagnosis, considered as an one-time action with explorative assessment purposes, the certification as intended in this article, is a continuous ordinary practice. A mere quality control. In other words, it is the systematic verification of given microclimate parameters fulfilment to intervals of quality, performance, safety, or steadiness. The parameters benchmarks may be suggested by current standards or in field research [5–7]

Nevertheless, since IMQ certification allows understanding: building equipment effectiveness, artefacts state of conservation, people thermal satisfaction etc., it might be a powerful instrument for supporting decisions upon environmental retrofitting actions, building installations improvement and preventive conservation strategies [8–10]

It is clear that if the mentioned certification verifies simultaneously the multiple IMQ aspects in relation to different certification targets (people, movable heritage, building materials, etc.), it gains additional significance. However, given its practical and theoretical complexity, methodological issues might arise both 1) during onsite-data acquisition processes and/or 2) during the IMQ certification model development (e.g. inappropriate model hypothesis and limitations). In this article we focus on the first point.

In the Literature, methodologies for heritage buildings and museums environmental diagnosis are widely diffused [11–18]; however, microclimate certification models incorporating people comfort and cultural heritage safety are not yet available despite their value for a more holistic building management. Moreover, although IMQ certification for people comfort already exists [5,6], the methodological issues to be considered during onsite data acquisition prior to the certification model development have not yet been addressed. This unavoidably results in different monitoring activities and therefore in certification results which are not comparable [19].

2. Research objectives and constraints

1. The study analyses methodological issues emerging during infield microclimate monitoring targeted to IMQ certification. More specifically, it focusses on time-spatial representativeness and resolution of acquired data to be inputted in the certification model.
2. For verifying the time-spatial resolution of the acquired data the study introduces the analysis of microclimate heterogeneity as preparatory activity to IMQ certification. The mentioned analysis is valuable especially with regard to IMQ certification for movable heritage, however a sensitivity analysis was performed for evaluating people thermal comfort variations (on PMV scale) as a consequence of spatial hygrothermal variations.
3. The study introduces a multicriteria model for the simultaneous certification of IMQ for building users and movable heritage. In the present contribution the model is limited to hygrothermal quality verification and climate induced mechanical damage for objects. Criteria, such as acoustic and lighting comfort for people, or biological and chemical deterioration risk for movable heritage, are not included.

   The IMQ categories for people comfort are derived from the ISO 7730 and EN 15251 standards for heating and free running period respectively. Among others, the IMQ categories for movable heritage are derived from the EN 15757 standard. Since the objects exposed to the free air in the monitored exhibition hall are mainly lacquered pianos, harpsichord and paintings on timber support, the mechanical deterioration model is focussed on timber panels.

4. Additional comfort criteria and deterioration risk assessment models can be added to the developed multi-objectives model. This will be an object of further research.

3. Indoor Microclimate Quality certification for building users and cultural heritage.

The Indoor Microclimate Quality (IMQ) certification for *movable and immovable heritage* as well as for building users consists in the evaluation of multiple aspects of safety and comfort.

Often, especially with regard to thermal comfort studies, the optimal comfort for people is identified as neutral sensation. This sensation can be defined as the psychological condition in which the person is satisfied about the surrounding environment and no variation is wished to compensate any discomfort [20]. Similarly, the region of microclimate safety for objects is the area in which the hygrothermal fluctuations are comprised within a range between zero and a safety threshold [21]. Within this neutral (safe) area no deterioration occurs. On basis of this parallelism it is possible to develop IMQ certification models including both building users and movable heritage.

With regard to people, a short and non-exhaustive list of comfort aspects is: thermal comfort, lighting comfort, acoustic comfort and air quality comfort, while with regard to artefacts the aspects of safety are related to hygrothermal quality, light and level of pollutants in the air. Not fulfilling the mentioned comfort or safety aspects might cause discomfort for the people and physical, chemical or biological deterioration for the artefacts.

Theoretically, the global comfort for people is reached only if all the multiple levels of comfort are simultaneously accomplished. Nevertheless, it may be still possible to evidence environmental acceptability even if one or more environmental criteria is out of the comfort area. This occurs because, depending on the activity in which people are involved, the physical attributes characterizing the environmental comfort sensation acquire different importance [22–24]. Conversely for ensuring safety to the cultural heritage, all the environmental aspects need to be simultaneously satisfied. Hence verified. However often, relative humidity, especially in the case of hygroscopic materials is responsible for faster material deterioration processes (due to its direct influence on materials equilibrium moisture content variation). Therefore its control and adjustment might have priority over air temperature [25,26] and it is indeed considered for the target-microclimate definition according to the EN 15757. Also thermal gradients can cause mechanical stress in materials; therefore, air temperature short term fluctuations should be controlled and limited.

4. Methodological issues during onsite data acquisition preparatory to IMQ certification

The principal aim of a microclimate certification is to facilitate its management. In other words identifying risks of damage for housed objects or discomfort for people. This is valid still more (but not only) for those buildings not equipped with automatic microclimatic control.

Considering that a certification procedure starts from the preparatory data acquisition, the onsite building monitoring activities take on a fundamental role. This is valid both if the IMQ certification is based on onsite building environmental monitoring (instrumental or subjective) or if it is based on outputs from a dynamic building model (simulation-based IMQ certification). In the latter case the monitored data allow for model calibration [27–29].

As environmental parameters are time-spatial dependent, and the monitored space might be more or less stable than another one or than itself in a different moment, it is necessary to define the extent of the microclimate spatial variability throughout the time. Hence, time-spatial representativeness and resolution of the monitored data should be analysed; see Fig. 4.1.

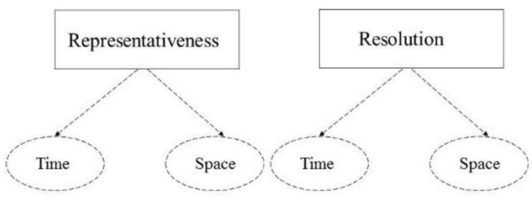

Figure 4.1 Representativeness and Resolution diagram

- Temporal representativeness: monitoring period duration. This interval elucidates the temporal representativeness of the certification results but it does not necessarily coincide with it, indeed, a monitoring campaign can be longer than the period to which the certification refers.

- Temporal resolution: level of details (in time) of the acquired data, i.e., the parameters sampling interval. This might have an influence on the certification results in case of outliers.
- Spatial representativeness: representativeness of the measured building part in relation to the whole building.
- Spatial resolution: level of details (in space) of the acquired data.

4.1 Representativeness and Resolution of acquired microclimate data targeted to IMQ certification for cultural heritage and building users

For the IMQ assessment of cultural heritage, the EN 15757 is largely considered especially in the EU Countries [30]. The standard introduces a novel methodology for calculating the optimal microclimate interval for allowing hygroscopic objects preservation. This interval, named target microclimate, is calculated according to infield hygrothermal monitoring. Knowledge on the object historic climate and on its dynamic interactions with the microclimate proximity should be acquired during the monitoring. If the IMQ certification for cultural heritage wants to be developed by following the EN 15757, two issues should be evaluated.

Firstly, the calculated target microclimate range should be used with care for defining the target microclimate interval as it is dependant on the monitoring time representativeness. Target microclimate range variation if considering one or multi years data series is discussed by the authors in [31].

Secondly, the monitoring of each object microclimate proximity (though theoretically understandable), might require a countless amount of sensors that does not necessarily bring to an increased spatial resolution of the acquired data, hence of the certification results. This large effort in terms of sensors number might constitute an issue for professionals and museum curators [32,33] Indeed, "what if several objects, with similar sensitivity and state of conservation, are exhibited for a long time (say the known historic climate) in the same space and location? Is it not reasonable to imagine that as the global space microclimate is unchanged so it is for each object microclimate proximity?"

In the authors opinion, if the objects are scattered in the space, and the microclimate through the space is proven to be sufficiently homogeneous, one measurement point in an undisturbed position of the space or the average of the readings from different loggers, can deliver a sufficiently accurate esteem of each object microclimate proximity. The resulting target microclimate, may apply to all the objects exposed in the free air. As a consequence, a reduction of measurement points can be allowed while still obtaining accurate IMQ certification results.

Obviously this concept holds valid only if, rather small variations occur between the free air and the objects interface (in the studied case <0.5°C and <1.50% T and RH). This should be a priori verified during a microclimate diagnosis. These variations might be reasonably large for objects located onto the building envelope and small for objects exposed in the free air. In the present case, no movable heritage is exposed onto the building envelope.

The above mentioned methodological considerations are, in fact, already implemented within research or microclimate management praxis. The application of one sensor per exhibition space in the free air rather than in contact or semi contact with each exhibited object is considered a good practice, hence implicitly considered representative of each object microclimate proximity in [32–37].

With regard to people, especially if involved in non-stationary activities, the considerations discussed above are less meaningful. Indeed, because people move in the space, it is arguable that their thermal comfort sensation alters during their movement. However, that their transient comfort sensation is somehow compensative and that their thermal acceptance does not vary if small hygrothermal time-spatial variations occur may be expected.

With regard to time-dependent variations, the ISO 7730 states that temperature cycles within 1°K as well as temperature drifts of 2°K/hour are unlikely to affect people thermal comfort. Therefore, the space microclimate may be considered steady and the PMV-PPD model applies [5]. This was also observed in a study by L. Schellen [38]. In our study, the monitored space complies with the mentioned conditions.

With regard to space-dependent variations, the ISO 7730, though developed for fully controlled environments, admits minor spatial (operative) temperature variations. Indeed, the temperature considered within PMV interval categories is not expressed by a deterministic value but rather by a range; Table A1 in [5].

In this study, the microclimate spatial variability was assessed firstly according to existing standard methodologies, secondly by evaluating the actual spatial parameters difference (between sensors). On the basis of this analysis it was possible to drawn conclusion about the microclimate heterogeneity for both movable heritage and building users. With regard to the latter an additional sensitivity analysis was necessary.

It is worth mentioning that there is a difference between microclimate heterogeneity analysis targeted at IMQ diagnosis or IMQ certification. In the first case, even tiny variations need to be carefully investigated as they may stand for specific microclimate issues caused by e.g. building envelope or installations failures. In the second case, variations within homogeneous IMQ quality intervals are negligible (unless controllable by the building equipment). In other words, because IMQ certification aims at linking microclimate control with building management, the small microclimate spatial variations are unlikely handleable by common HVAC systems. Hence, they may be disregarded. This condition does not apply if the system allows for high-resolution control of the confined space.

5. Vleeshuis museum: history and building characteristics

The monitored building, *het Vleeshuis*, is the museum of musical instruments in Antwerp. It was built between 1501 and 1504 by the Belgian architect Herman de Waghemakere (the elder) as new slaughterhouse of the city. Although the building use has changed across the Centuries, it is still possible to observe the original building architectonic integrity both on the inside and outside. See Figure 5.1.

Figure 5.1 internal view of the monitored exhibition hall (Litti 2013)

The cellar and the main exhibition hall on the ground floor currently house the permanent collection of musical instruments, while the upper levels are utilized as artefacts storage and offices. The basement and ground floor are characterized by brick vaults. The volumetric proportions of the spaces at the basement and ground floor are different; the maximum height of the basement is 3.45m and on the ground floor 8.50m. The total net volume is respectively ≈1300m^3 and ≈5300 m^3 on the basement and ground floor. In this contribution only the exhibition hall at the ground floor is considered; however an analysis of the microclimate quality including the exhibition space at the basement level was discussed by the authors in [39][40].

6. Methodology

6.1 Building microclimate monitoring

The exhibition hall on the ground floor of the building was continuously monitored throughout the year 2014-15. The monitoring protocol, especially with regard to the sensors location, was developed on basis of findings from a preparatory short term monitoring performed in 2013 [39]. The environmental parameters continuously monitored in the exhibition space are given in Table 6.1.1.

Inside-position code	Physical Parameter	Logger	Accuracy (of absolute reading)
0.1.2-0.1.4-0.1.5	Dry bulb temperature (°C)	Hobo U12	(±0.35)
0.1.2-0.1.4-0.1.5	Dew temperature (°C)	Hobo U12	(± 2.5%)
0.1.2-0.1.4-0.1.5	Relative Humidity (%)	Hobo U12	(± 2.5%)
0.1.2-0.1.4-0.1.5	Light Intensity (lux)	Hobo U12	(± 2.5%)
0.1.2	CO2 (ppm)	Vaisala GM70	(± 2%)
0.1.2	Radiant temperature asymmetry (°C, W/m²)	MM 0036 Innova	(± 1) *
0.1.2	Operative Temperature (°C)	MM 0060 Innova	(± 0.3)
0.1.2	Air Velocity (m/s)	MM 0038 Innova	(0.05α+0.05) **

* Difference Air Temperature- Plane Radiant Temperature <20°K
** with air velocity <1m/s and 0.25α with air velocity up to 10m/s

Table 6.1.1; Parameters monitored in the exhibition hall

The parameters for the assessment of building-users thermal comfort were measured during three short time intervals throughout the 2014 in point 012; while parameters measured for IMQ assessment for movable heritage, were measured continuously through the whole year in all the measurement points, see Table 6.1.2. However, due to loggers failure, data from July the 20th to September the 8th are not taken into account in the analysis.

	Temporal representativeness		Temporal resolution	
	Start (date)	End (date)	Sampling (minutes)	Averaging (minutes)
Building users				
heated period 1	04/03/2014	12/04/2014	120	120
warm period	11/08/2014	30/09/2014	15	60
heated period 2	01/10/2014	26/11/2014	120	120
Movable Heritage				
	19/02/2014	31/01/2015	15	60

Table 6.1.2; Characteristics of the monitoring campaign: temporal representativeness and resolution

Parameters in Table 6.1.1, were sampled each 15 minutes with the exception of: operative temperature, radiant temperature asymmetry and air velocity, sampled each 120 minutes. Because this low temporal resolution (given by logger memory capacity) might yield to biased results in presence of outliers, a data analysis prior to the IMQ certification was performed.

In order to acquire data in vicinity of the certification targets, the sensors were installed 1.30 m high from the floor. To avoid biased heat and moisture transfer due to contact between sensors and building (or other) surfaces, each logger was installed on an independent support distant from any environmental disturbance. At the top of each support, a 1.5 mm thick highly conductive metal wire extension (0.15 m long) was installed for hanging the instruments and measuring the free air. Sensors MM 036, MM038 and MM060 were positioned on a dedicated support also distant from surfaces, see Figure 6.1.1 a- b.

Figure 6.1.1 a (left) and b (right); Hobo U 12 data logger during the installation (left); Innova MM 0036, MM 038, MM 060 and Vaisala GM 70 sensors during the installation

The position code for each logger is given in Table 6.1.1 and in Figure 6.1.2. The distance between sensor 014 (entrance) and 012 (centre of the exhibition space) is ±10m, the distance between sensors 012 and 015 (back of the exhibition space) is ±13m and the distance between sensors 012 and 015 is ±22m.

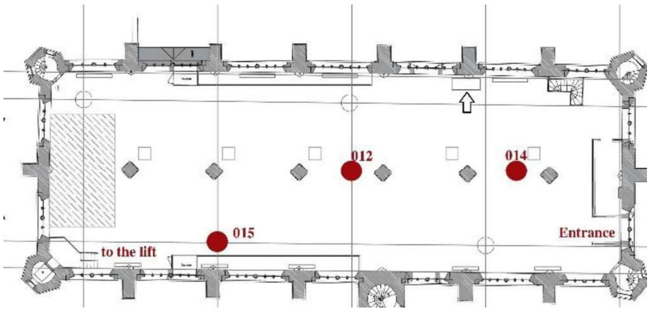

Figure 6.1.2; Localization of sensors (circles) and indication of the air-heating unit (arrow)

6.2 Analysis of microclimate heterogeneity

Methodologies for the evaluation of environmental heterogeneity of a given monitored space for the purpose of people thermal comfort assessment or microclimate diagnosis are introduced respectively by the EN 7726 and UNI 10829 standards [41,42]. The latter, does not propose a tailored analysis of space heterogeneity, however it introduces a stepwise methodology for deciding upon sensors location on basis of some considerations of spatial microclimate variability; in fact it can be considered a spatial heterogeneity analysis.
Furthermore, a widely accepted methodology for the representation of environmental parameters spatial variability, to support microclimate studies, is introduced by D. Camuffo [43] and integrated within the EN 16242 [44].
The EN 7726 method, recalled within the EN 15251[6], defines a monitored space bioclimatically homogeneous if the relation in (1) in a given moment is verified.

$$\varphi_{(i)} - \mu_{\varphi_{(i)}} < a_{(\varphi)} X \qquad (1)$$

Where $\varphi_{(i)}$ is the punctual reading registered at the point (i) for the (φ^{th}) environmental parameter, ($\mu_{(\varphi)}$) is the mean value of the (φ^{th}) parameter measured in all the measurement points; ($a_{(\varphi)}$) is the required or desirable sensors accuracy with regard to the (φ^{th}) environmental parameter and (X) is a constant; see table 4 in [41];
The standard ISO 7730, does not provide a methodology for the spatial microclimate analysis of the monitored space, but it rather suggests interval of maximum Operative Temperature variation; see Table A1 in [5].
The UNI 10829 method, suggests to assess whether temperature and relative humidity readings from preparatory snap-shots measurements satisfy the relations in (2) and (3).

$$\Delta_{Temp} \leq 2°C \qquad (2)$$
$$\Delta_{RH} \leq 5\% \qquad (3)$$

Where (Δ_{Temp}) and (Δ_{RH}) are temperature and relative humidity absolute differences between knots on a 5m space meshing. If the relations are satisfied, the space can be considered reasonably homogeneous and long term microclimate monitoring can be performed on the same mesh. Even if the mentioned methodologies allow for a general evaluation of the spatial microclimate variability, they do not allow for a precise appreciation of the actual spatial hygrothermal heterogeneity as the following limits may be observed:

- The actual hygrothermal deviation between points is not taken into account as only maximum thresholds are considered;
- The extent of the actual parameters variation in relation to the actual instruments distance is neglected;
- The heterogeneity assessment is dependent on instruments accuracy (EN 7726);
- The heterogeneity assessment is not considered in function of time.

The UNI 10829 gives a threshold for maximum temperature and relative humidity variability with reference to a max distance, however the consideration of a maximum threshold does not allow to identify actual microclimate heterogeneities.
In the authors opinion, the consideration of actual microclimate variation related to the sensors distance is fundamental. Higher environmental readings deviations can be tolerated for larger measurement point distances. Moreover, the evaluation of the microclimate heterogeneity should be independent from the sensors accuracy, otherwise a given environment may be judged homogeneous by less accurate instruments and vice versa.

Further, it should be considered, the time frequency of the environmental parameters spatial variations. How should a space be judged if it is not homogeneous for only 10% or 5% of time? This issue is even more stringent when performing short monitoring intervals as hygrothermal dynamics are more or less stable during critical moments of the year.

For the reasons above explained, the spatial heterogeneity was tested by means of pairwise comparison of the differences between the current hygrothermal readings from the three measurement points. The absolute difference was calculated by the Root Squared Deviation (RSD) (minimum and maximum) and by the Root Mean Squared Deviation (RMSD) of temperature and relative humidity readings; see eq. 4 and 5.

$$\mathrm{RSD} = \sqrt{(\varphi_{(i,t)} - \varphi_{(i,t)})^2} \qquad i = \overline{1,n} \quad t = \overline{1,m} \tag{4}$$

$$\mathrm{RMSD} = \sqrt{\frac{\sum_{t=1}^{n} (\varphi_{(i,t)} - \varphi_{(i,t)})^2}{n}} \qquad i = \overline{1,n} \quad t = \overline{1,m} \tag{5}$$

$$\mathrm{RSD'} = \frac{\sqrt{\left(\varphi_{(i,t)} - \varphi_{(i,t)}\right)^2}}{d} \qquad i = \overline{1,n} \quad t = \overline{1,m} \tag{6}$$

$$\mathrm{RMSD'} = \frac{\sqrt{\frac{\sum_{t=1}^{n} (\varphi_{(i,t)} - \varphi_{(i,t)})^2}{n}}}{d} \qquad i = \overline{1,n} \quad t = \overline{1,m} \tag{7}$$

Where ($\varphi_{(i,t)}$) is the (φ^{th}) environmental parameter measured at the time *t (1, m)* in the point *i (1, n).* Both RSD and RMSD can be standardized on the actual sensors distance (*d*), see eq. 6 and 7.

In our case study, the sensors distance is higher than the one suggested by the UNI 10829 and no vertical gradient is taken into account because the collection and visitors are located at a maximum height of 3m. However, during the 2013 monitoring the space was monitored by five sensors with a distance of ≈5m between each and it was observed to be homogeneous; Note 2 in the supplementary information.

The heterogeneity analysis allowed not only the evaluation of IMQ spatial variability for movable heritage but also for building users. However, because it was only possible to install an indoor microclimate station in one measurement point (012), the spatial microclimate heterogeneity, and its influence on the thermal comfort was quantified by means of sensitivity analysis.

Operative Temperature (OT) and Mean Radiant Temperature (MRT) from point 012 (see Table 6.1.1 and Fig. 5.1.3) were altered considering the maximum measured spatial temperature deviation at the 95th percentile. Considering the altered parameters (including relative humidity), the PMV was re-calculated and the IMQ re-certified. The following simplifications were admitted:

- Air temperature spatial deviation instead of OT or MRT ones was considered because the latter two were measured only in one measurement point (012). However, from a comparison of T, OT and MRT in point 012 the difference between MRT and T was negligible (≤1°C), meaning that the radiative component in the monitored space is rather small, see Fig. 6.2.1. This simplification is admitted in EN 15251, Annex A.
- Air velocity was considered constant in the space. The air velocity was measured < 0.1m/s and <0.15m/s respectively for the 77.8% and 99.6% of sampled data.

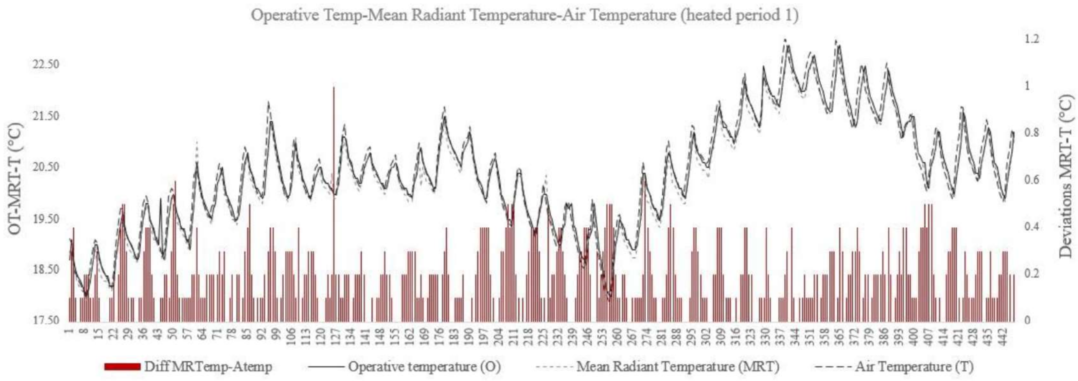

Figure 6.2.1; First vertical axes: Air temperature, Operative Temperature, Mean Radiant Temperature during heating period 1 (point 012); second vertical axes Difference Mean Radiant Temperature- Air Temperature (°C)

6.4 Microclimate certification

The developed certification model is based on the concept of microclimate neutrality mentioned in section 3. The model considers the neutrality condition as zero and the deviation from it as symmetrical stepwise numerical (and linguistic) alterations, such as: good conditions (±1), moderate conditions (±2) unacceptable conditions (±3). The here presented model is symmetric and category- dependent.

The advantage of a symmetrical IMQ long-term certification model as well as the disadvantages of a categories-dependency are discussed by S. Carlucci in [45]. Although a category-based IMQ certification model generates discontinuities at the edge of each category interval (because not developed on a continuous function), it allows a rapid microclimate control, crucial in the management process of heritage buildings and museums.

For allowing a long term evaluation of the hygrothermal comfort, the model refers to Percentage Inside the Ranges (PIR). This allows to verify the cumulated time frequency of each criterion ($\varphi_{(k)}$) in the category intervals for each assessment criterion for both people ($IMQ_{(P)}$) and movable heritage ($IMQ_{(H)}$); see Eq. (8).

$$IMQ_{(H,P)} = \sum_{k_i=1}^{n} \varphi_{(k_i)} \qquad \text{Where} \begin{cases} \varphi_{(k)} \leq \text{Cat}_{(\partial)} \text{ upper limit} \\ \varphi_{(k)} \geq \text{Cat}_{(\partial)} \text{lower limit} \end{cases} \tag{8}$$

In the first step, two dimensionless time frequency matrices, for people ($T_{(P)}$) and movable heritage ($T_{(H)}$), are built considering respectively the frequency of time during which the ($\varphi^{th}{}_{(P)}$) or ($\varphi^{th}{}_{(H)}$) criterion (in rows) falls in the (∂^{th}) category interval in column (9).

$$T_{(\alpha)} = \begin{bmatrix} t_{1,1} \dots t_{1,\partial} \dots t_{1,n} \\ \vdots \\ t_{\varphi,1} \dots t_{\varphi,\partial} \dots t_{\varphi,n} \\ \vdots \\ t_{m,1} \dots t_{m,\partial} \dots t_{\varphi,\partial} \end{bmatrix} \qquad \varphi = \overline{1,m} \quad \partial = \overline{1,n} \tag{9}$$

Where (α) refers respectively to people (P) or movable heritage (H); (m) refers to number of (φ) criteria; (n) refers to number of (∂) category intervals. In this study *($m_{(P)}=1$), ($m_{(H)}=2$),* while *($n=7$).*

The magnitude of the microclimate deviations from the neutral comfort, is expressed by a stepwise numerical perturbation of 0. With this purpose, the vector (β) is introduced. The incidence vector (β) is a (7x1) matrix, with elements ranging from {-3,…,+3}. In this study symmetrical importance is given to upper and lower deviations, however a weighted or asymmetrical incidence might be considered according to the specific building and collection requirements.

With regard to the movable heritage and for taking into account the daily fluctuations and the risk of mechanical deterioration of the objects in the collection, the incidence vectors includes incremental factors; see Table 6.4.1.1 and Table 6.4.1.2.

In the second step, the incidence matrices for heritage ($P_{(H)}$) and people ($P_{(P)}$), are calculated as the product of the time frequency matrices ($T_{(H)}$) or ($T_{(P)}$) and the perturbation (β) vector; considering its elements in absolute value. The result is a (mx1) matrix describing, for each considered criterion, the severity of deviation from the microclimate neutrality. Therefore, the severity of the deviations is evaluated by the product of the deviation time frequency (time frequency matrix) and the deviation magnitude (perturbation vector with incremental factors); see Eq. (10-11).

$$\left(P_{(H)}\right) = \left(T_{(H)}\right) \cdot (\beta) \quad (10)$$
$$\left(P_{(P)}\right) = \left(T_{(P)}\right) \cdot (\beta) \quad (11)$$

Because the different indoor climate aspects may play a different role in the global comfort perception and even more for hygroscopic materials, it is considered a weighting step. In the following study, the importance for the considered hygrothermal indicators with regard to the cultural heritage objects was defined according to literature results. The weights, respectively 0.33 for temperature and 0.67 for relative humidity, are considered for the long term fluctuation.
In the third step, the weighted incidence matrices for people ($\overline{P_{(P)}}$) and heritage ($\overline{P_{(H)}}$) are calculated as the product of the transposed incidence matrices, $(P_{(P)})^T$ or $(P_{(P)})^T$ and the theoretical weighting vector $\{\overline{\omega}_P\}$ or $\{\overline{\omega}_H\}$; see Eq. (12-13).

$$(\overline{P_P}) = (P_P)^T \cdot (\overline{\omega}_P) \qquad (m = 1) \quad (12)$$

$$(\overline{P_H}) = (P_H)^T \cdot (\overline{\omega}_H) \qquad (m = 2) \quad (13)$$

The results of the matrices can be intended as single scores for each microclimate criteria representing the current performance with regard to people or heritage criteria, considering at the same time the severity of the occurred deviations and the importance of the single examined environmental criterion.
Finally, if necessary, a simultaneous index of performance (Simultaneous Performance Index-SPI) can be calculated in order to provide a complete picture of the current microclimate quality with regard to movable heritage and building users, see Eq. (14).

$$SPI = \frac{\sum_{m=1}^{n} \overline{P_{(H,P)}}}{\sum m} \qquad (m = 3) \quad (14)$$

Where m - number of criteria considered with regard to both heritage and people. At this point, an adjunctive weighting process, for distinguishing the importance between heritage and people needs according to the space requirements, may be introduced although not considered in this contribution. As above mentioned, the optimal microclimate quality coincides with the microclimate neutrality (0). The obtained SPI, other than 0, represents the deviation from the optimal microclimate comfort.

6.4.1 Microclimate quality categories for movable heritage

For the definition of IMQ for the cultural heritage, multiple microclimate categories of comfort were considered. Progressive intervals of deviation from the microclimate neutrality were determined on basis of the building target microclimate inferred from the building historic climate [26,46,47].
The neutral microclimate (target range) for hygroscopic movable heritage, is calculated by admitting short-term fluctuations not higher than the ones already experienced by the building materials in the past. Only the 14% of risky short-term fluctuations: the 7th and 93rd percentile, are eliminated, see Annex A in EN 15757.
Less demanding, but still safe hygrothermal ranges, are proposed in the literature considering the 10% positive and negative variation around the hygrothermal seasonal cycles or the exclusion of the 10% extreme short term fluctuations instead of 14% [37]. The mentioned two microclimate relaxation limits are here considered as additional categories: "still acceptable" (±2) and "good" (±1); see Table 6.4.1.1.

Deviation (β)	MCH Microclimate Comfort Heritage	Short term fluctuations; Incremental factors to (β)	
±3	$\varphi_{(k)} > \overline{\varphi}_{30}(k)+\overline{\varphi}_{30}(k)10\%$; $\varphi_{(k)} < \overline{\varphi}_{30}(k)-\overline{\varphi}_{30}(k)10\%$	-	
±2	$\overline{\varphi}_{30}(k)-\overline{\varphi}_{30}(k)10\% \le \varphi_{(k)} \le \overline{\varphi}_{30}(k)+\overline{\varphi}_{30}(k)10\%$	Temp-RH short fluctuations	
		0	Condition A
		0.5	Condition B
		2 Collapse in 3	Condition C
±1	$\overline{\varphi}_{30}(k)-\Delta_{\varphi L} \le \varphi_{(k)} \le \overline{\varphi}_{30}(k)+\Delta_{\varphi U}$; $\Delta_{\varphi L} = 5^{th}$ perc; $\Delta_{\varphi U} = 95^{th}$ perc.	Temp-RH short fluctuations	
		0	Condition A
		0.5	Condition B
		1 Collapse in 3	Condition C
0	$\overline{\varphi}_{30}(k)-\Delta_{\varphi L} \le \varphi_{(k)} \le \overline{\varphi}_{30}(k)+\Delta_{\varphi U}$; $\Delta_{\varphi L} = 7^{th}$ perc; $\Delta_{\varphi U} = 93^{rd}$ perc.	Temp-RH short fluctuations	
		0	Condition A
		0.5	Condition B
		0 Collapse in 3	Condition C

Table 6.4.1.1; Categories ranges for collection (H)

Condition A (RH)	Condition A (Temp)

$\begin{cases}\Delta_{(\mathrm{RH,day})} < \Delta_{(\mathrm{RH,90})} \\ \Delta_{(RH,i)} < \Delta_{(RH,plast)}\end{cases}; \geq 90\%\ (N_1), \geq 95\%\ (N_2)$	$\begin{cases}\Delta_{(\mathrm{Temp,day})} < \Delta_{(\mathrm{Temp,90})} \\ T_{(i)} > T_{(g)}\end{cases}; \geq 90\%\ (N_1), \geq 95\%\ (N_2)$
Condition B (RH)	Condition B (Temp)
$\begin{cases}\Delta_{(\mathrm{RH,day})} > \Delta_{(\mathrm{RH,90})} \\ \Delta_{(RH,i)} < \Delta_{(RH,plast)}\end{cases}; \geq 80\%\ (N_1), \geq 95\%\ (N_2)$	$\begin{cases}\Delta_{(\mathrm{Temp,day})} < \Delta_{(\mathrm{Temp,90})} \\ T_{(i)} > T_{(g)}\end{cases}; \geq 80\%\ (N_1), \geq 95\%\ (N_2)$
Condition C (RH)	Condition C (Temp)
$\{\Delta_{(RH,i)} > \Delta_{(RH,plast)}; > 5\%$ (N)	$\{T_{(i)} > T_{(g)}; > 5\%$ (N)

Table 6.4.1.2; Conditions a, b and c for short fluctuations (H)

It is well known that short-term fluctuations might generate even higher risk than seasonal ones as likely to affect the surface layers of a given cultural object and generate high risk of mechanical deterioration on the stratum and sub-stratum of the object. For these reasons the assessment of the short-term (daily) cycles was included in the certification model.
The calculation of daily hygrothermal cycles is not unequivocal and, by varying the calculation method, the results are different. In the authors opinion, the Centred Moving Average (49 periods) is the most appropriate methodology. Note 3 in the supplementary information.
In Fig. 6.4.1, temperature and relative humidity daily cycles, calculated on the CMA (49 periods) with regard to the spatial average are ordered and plotted in a scatter plot. The resulting logarithmic curve shows (risky) outlying values on the top- right corner. If considering temperature and relative humidity daily cycles up to the 95th percentile, these are 2.5°C and 7% maximum. For allowing a conservative scenario, in the model we considered the 90th percentile of the mentioned fluctuations.

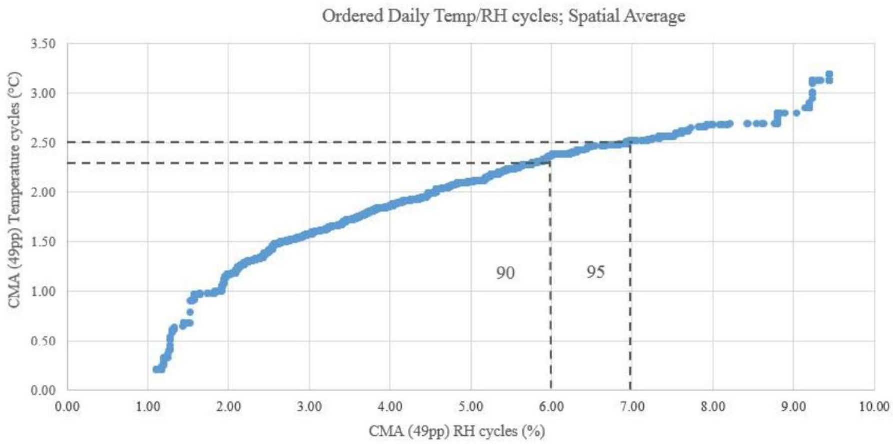

Figure 6.4.1; Ordered CMA (49 periods) temperature and relative humidity fluctuations; the readings refer to the spatial average; in grey 90th and 95th percentiles

It is worth remembering that preventing daily fluctuations other than the most frequently experienced ones by the materials (e.g., 90th percentile), does not mean avoiding the risk of materials deterioration, but rather means reducing the probability that it occurs. This approach, especially valid in case of hygroscopic materials, is meaningful if also combined with a specific materials-based risk assessment.
Since in the monitored exhibition space, the majority of the objects exposed in the free air is made up of timber panels (e.g. pianoforte or painted panels) we included in the IMQ certification model the climate-induced mechanical deterioration model by M.F. Mecklenburg et. al [48,49]. Coded with good level of approximation by P. Lankester and P. Brimblecombe in [50]; Note 4 in the supplementary information.
For certifying the IMQ including short-term fluctuations, two additional levels of assessment were integrated in the model, described by conditions A-C in Table 6.4.1.2; Note 5 in the supplementary information.
The first assessment level aims at evaluating if short-term (daily) fluctuations deviate from the ones recurrently experienced by the materials in the historic microclimate. The second one aims at verifying whether the relative humidity cycling generates plastic deformation to timber panels ($\Delta_{\mathrm{RH,\ plast}}$). In the second assessment level it is also verified whether the air dry bulb temperature is higher than 12°C (glass transition temperature). Temperature below the glass transition $T_{(g)}$ might increase the risk of painted film cracking: oil, alkyd or acrylic layer become brittle with air temperature lower than ±12°C [13].

6.4.2 Microclimate quality categories for building users

For the definition of the category intervals with regard to building users thermal comfort, the intervals provided by the ISO 7730 and EN 15251 standards respectively for the cold and warm period were used; see Table 6.4.2.1

Deviation (β)	MCP (Microclimate Comfort People) winter	MCP Microclimate Comfort People) free running
±3	PMV < -0.7; PMV> + 0,7	$\theta_{imax} > 0.33\theta_{rm} + 18.8 + 4;\ \theta_{imin} < 0.33\theta_{rm} + 18.8 - 4$
±2	-0,7 ≤ PMV ≤ + 0,7	$0.33\theta_{rm} + 18.8 - 4 \leq \theta_i \leq 0.33\theta_{rm} + 18.8 + 4$
±1	-0,5 ≤ PMV ≤ + 0,5	$0.33\theta_{rm} + 18.8 - 3 \leq \theta_i \leq 0.33\theta_{rm} + 18.8 + 3$
0	-0,2 ≤ PMV ≤ + 0,2	$0.33\theta_{rm} + 18.8 - 2 \leq \theta_i \leq 0.33\theta_{rm} + 18.8 + 2$

Table 6.4.2.1; Categories ranges for people (P)

7. Results

7.1 Analysis of microclimate heterogeneity

A summary statistics of the Root Squared Deviation (RSD) and Root Mean Squared Deviation (RMSD) of temperature and relative humidity between measurement points is given in Table 7.1.1.
The analysis of the actual maximum RSD between points for temperature and relative humidity permitted an understanding of the actual indoor microclimate heterogeneity in the space. Even if the space can be considered homogeneous according to the EN 7726 and UNI 10829 standards, a hygrothermal variability between measured points is still observable, see Table 7.1.2.

	RMSD (%)	RSD Min. (%)	RSD Max. (%)	RMSD' (%/m)	RSD' max (%/m)
RH 012-014	1.934	0.000	6.709	0.193	0.671
RH 012-015	0.858	0.000	3.914	0.066	0.300
RH 014- 015	1.864	0.000	7.158	0.084	0.325
	RMSD (°C)	RSD Min. (°C)	RSD Max. (°C)	RMSD' (°C/m)	RSD' max (°C/m)
Temp 012- 014	0.349	0.000	1.136	0.035	0.113
Temp 012- 015	0.210	0.000	1.260	0.016	0.096
Temp 014- 015	0.253	0.000	1.020	0.011	0.046

Table 7.1.1; Pairwise temperature (Temp) and relative humidity (RH) difference between measurement points.

Mean temperature difference between points was between 0.21°C (± 0.35°C) and 0.35°C (± 0.35°C) with maximum difference 1.26°C (±0.35°C). However, the measured maximum difference was an exceptional event as for the 95th percentile the absolute temperature difference between points was <0.71°C (±0.35°C); see Table 7.1.2
From a diagnostic point of view, though temperature difference between points is numerically low, it is still possible to observe a partialization of the temperature distribution in the space. Indeed, the air temperature difference between the entrance and the centre of the space (points 014-012) is almost constantly 0.17°C higher than the one registered between the centre and the back (012-015).

Percentiles	5.00	10.00	25.00	50.00	75.00	90.00	95.00
RH RSD 012-014	0.42	0.69	1.17	1.76	2.59	3.37	3.99
RH RSD 012-015	0.06	0.11	0.29	0.70	1.28	1.85	2.24
RH RSD 014-015	0.18	0.38	0.94	1.67	2.60	3.71	4.22
Temp RSD 012- 014	0.04	0.07	0.17	0.35	0.49	0.62	0.71
Temp RSD 012- 015	0.01	0.02	0.06	0.14	0.36	0.48	0.54
Temp RSD 014- 015	0.02	0.04	0.10	0.22	0.39	0.51	0.58

Table 7.1.2; Percentiles of pairwise temperature and relative humidity differences

This is also observable with respect to the relative humidity. In the 95th percentile, the RH difference between entrance and centre of the space was 3.99% (±1.50%) while it was 2.24% (±1.52%) between the centre and the back. This may suggest that the indoor microclimate from the centre to the back is more homogeneous than the one from the entrance to the centre. The hygrothermal variations between the back and the centre of the space are negligible from the 75th percentile. In other words, the residual variation between the entrance and the centre of the space (014-012) with regard to temperature and relative humidity is not higher than 0.05°C/m and 0.26%/m respectively for 75% of the sampled data.
For assessing the thermal comfort variability of building users according to the discussed spatial hygrothermal variations, the maximum temperature deviation registered for the 95% of sampled data (±0.71°C) was respectively added and subtracted to OT and MRT from point 012. The same was done for the RH (±3.99%).

The 2-hour based PMV for heating period and boundaries of indoor (operative) temperature for free running period were recalculated considering the positively and negatively altered parameters. The IMQ was recertified. The obtained (altered) PMV (or operative temperature ranges) represent the maximum spatial thermal comfort deviations according to the registered microclimate variability.

If developing an IMQ certification for movable artefacts (especially if the EN 15757 is taken into account), the analysis of the differences between hygrothermal fluctuations in each measurement point, is even more relevant than the analysis of the absolute difference of temperature and relative humidity readings. These fluctuations play a more significant role on objects conservation than temperature and relative humidity absolute values themselves. For this purpose, the short and long term fluctuations, calculated for each measurement points and for the spatial average (in accordance to the EN 15757) were compared.

As mentioned in section 3, if a collection is kept in a given open space, it is reasonable to suppose that the objects interact with the indoor microclimate. If a given environment is spatially homogeneous, seasonal and short-term fluctuations should be identical in each point. In reality a perfect homogeneity is impossible, however if the deviations are negligible, the certification of the room microclimate can be considered representative for all the objects microclimate proximity.

For evaluating the deviation between objects microclimate proximity and free air, the hygrothermal conditions in proximity of randomly located objects in the exhibition space were measured and compared to their closest measurement point. During these snapshot measurements, air velocity, air temperature, relative humidity and contact temperature were measured. The latter was measured by means of IR imaging. In presence of glass, the IR thermography was done by previously taping a portion of the target surface with paper tape (see Fig. 7.1.1.a-c).

Specific attention was given to the objects located on the direction of the air-heating unit outlets (Fig. 6.1.2 and 7.1.1.a). Indeed, during the museum opening hours the unit is in work and in the cold period, the warm air blowing from the unit causes air velocity and temperature increase. This circumstance is less sharp during the warm period as the unit does not provide cooling.

Currently, a large amount of objects near the unit is exposed either in unsealed showcases or behind protective (not in touch) glass panels. In proximity of the showcases most close to the unit outlet (Fig. 7.1.1.a-c), hygrothermal conditions similar to the closest point 014 were observed. Air temperature and contact temperature were 0.48°C and 0.46°C higher than point 014, air velocity was 0.03m/s and relative humidity was 1.49% lower compared to point 014. Nowhere were sharp differences between free air and objects proximity registered.

Figure 7.1.a; Localization of the air-heating unit in the exhibition room (during measurement at the inlet)
Figure 7.1.b Microclimate measurement in proximity of the first unsealed showcase in the direction of the heating unit airflow
Figure 7.1.c Air temperature 19.2°C, air velocity 0.03m/s; contact temperature 19°C (IRT on paper spot); relative humidity 59%

Long and short-term fluctuations for temperature and relative humidity were calculated for each measurement point. Successively pairwise variations between points were quantified. The long-term fluctuations are calculated as parameters- CMA (30days) while short ones are the differences between current parameter reading and CMA value; see Annex A in [30]. The results confirmed what was described above in relation to absolute hygrothermal readings.

The CMA of temperature for the 95th percentile was max 0.57°C (±0.35°C) different between the entrance and centre of the space (014-012); the same difference was negligible between the centre and the back (012-015). Similarly, for the 95th percentile, the CMA of relative humidity was up to 2.96% (±1.50%) different between the entrance and the centre of the space (014-012), while it was negligible from the centre to the back (012-015); see Table 7.1.3. The Pearson coefficient for the three CMA pairwise correlation was always > 0.997 (sig. 0.01) explaining the overall homogeneity of the indoor microclimate dynamics.

Percentiles	**5**	**10**	**25**	**50**	**75**	**90**	**95**
RSD CMA Temp 012-014	0.10	0.11	0.25	0.35	0.41	0.52	0.57

RSD CMA Temp 012-015	0.09	0.10	0.12	0.16	0.23	0.24	0.25
RSD CMA Temp 014-015	0.01	0.03	0.10	0.18	0.30	0.37	0.45
RSD CMA RH 012- 014	1.12	1.18	1.41	1.72	2.45	2.75	2.96
RSD CMA RH 012- 015	0.11	0.14	0.24	0.42	0.79	1.01	1.11
RSD CMA RH 014- 015	0.88	1.01	1.25	1.76	2.23	3.15	3.41

Table 7.1.3; pairwise difference between seasonal fluctuations (CMA)

Consistently with what was observed above, the microclimate is more stable to short fluctuations at the back of the exhibition space compared to the entrance.
In Table 7.1.4, the corresponding 7th and 93rd percentile values of short-term fluctuations for each measurement point are given as also for the spatial average. On the right side of the table are reported absolute deviations between single points percentiles and spatial average percentiles.
Because of the temporary interruption of the monitoring between July and September, the percentiles are calculated for two time intervals, 06/03-03/07/2014 and 21/09-31/12/2014. However, according to the results from the monitoring campaign in 2013, it is expected that the absence of readings in August does not vary the calculated percentiles.

Temperature	Temp 015	Temp 014	Temp 012	Temp (spatial)	Dev. 012 (RSD)	Dev. 014 (RSD)	Dev. 015 (RSD)
7th Percentile (°C)	-1.50	-1.46	-1.37	-1.43	0.07	0.03	0.07
93th Percentile (°C)	1.61	1.58	1.51	1.55	0.04	0.03	0.06
Relative Humidity	RH 015	RH 014	RH 012	RH (spatial)	Point 012 (RSD)	Point 014 (RSD)	Point 015 (RSD)
7th Percentile (%)	-3.15	-3.47	-2.88	-3.06	0.18	0.42	0.09
93th Percentile (%)	2.90	2.96	2.64	2.81	0.17	0.15	0.09

Table 7.1.4; short term fluctuations 7th and 93rd Percentiles for three measured points and spatial average; absolute deviation between spatial average and single measurement points percentiles (right side)

From Table 7.1.4, it can be seen that the central part of the space (point 012) is the most stable to short term hygrothermal fluctuations, the back part (015) has highest and lowest temperature short term fluctuations, while the front (014) has the highest relative humidity short term fluctuations. This is consequent to the door operating and vicinity to the air heating unit (without humidity control).
As mentioned in section 3, it should be noted that a difference exists between microclimate heterogeneity with regard to IMQ diagnosis and certification. With regard to the first, if considering the discussed results from Tables 7.1.1 and 7.1.2, it is evident that a slight hygrothermal partialization of the monitored space exists, especially between the front and the back. However, in order to understand if the space is also heterogeneous from an IMQ certification view point (for movable heritage), it was evaluated whether the spatial mean of temperature and relative humidity (from the three points) is representative of each point microclimate.
The Centred Moving Average of the spatial average ($CMA_{(spatial)}$), was calculated for temperature and relative humidity as well as the RSD between CMA of each point and the $CMA_{(spatial)}$. This difference represents the variation between seasonal fluctuations calculated in each individual point and the one calculated from the spatial average.
In Table 7.1.5, can be observed that the seasonal fluctuations of the spatial mean temperature and relative humidity ($CMA_{(spatial)}$) accurately represent the one of each measurement point ($CMA_{(i)}$). The highest deviation between CMA spatial average and CMA single point is observable in point 014. In this point, the maximum CMA deviation for temperature is 0.36°C and for relative humidity is 2.07%. This deviation represents however only 5% of the data population.

Percentiles	**5**	**10**	**25**	**50**	**75**	**90**	**95**	**max**
RSD CMA_{012}- $CMA_{(spatial)}$ (°C)	0.10	0.11	0.14	0.17	0.19	0.22	0.23	0.24
RSD CMA_{014}- $CMA_{(spatial)}$ (°C)	0.00	0.01	0.09	0.17	0.24	0.30	0.34	0.36
RSD CMA_{015}- $CMA_{(spatial)}$ (°C)	0.01	0.02	0.03	0.07	0.10	0.11	0.12	0.13
RSD CMA_{012}- $CMA_{(spatial)}$ (%)	0.18	0.27	0.44	0.59	0.74	1.13	1.25	1.30
RSD CMA_{014}- $CMA_{(spatial)}$ (%)	0.68	0.73	0.92	1.15	1.62	1.80	1.97	2.07
RSD CMA_{015}- $CMA_{(spatial)}$ (%)	0.19	0.25	0.31	0.44	0.73	1.40	1.44	1.51

Table 7.1.5; Pairwise difference of the seasonal fluctuations (CMA); temperature (above) and relative humidity (below)

According to the EN 15757 the target microclimate can be calculated as algebraic addition of the short term fluctuations to the long-term fluctuations (seasonal fluctuations).

It is worth noting that, the target-microclimate according to EN 15757 refers only to RH (for the reasons explained in section 3). However, for giving a complete overview of the extent of the microclimate deviations between specific and spatial average we refer to both temperature and relative humidity.
Considering the cumulative effect of the long and short-term deviations between point 014 and spatial average, it can be concluded that the maximum deviation in terms of microclimate targets definition, is 0.42°C for temperature and 2.63% for relative humidity.
In other words, if the microclimate in point 014: the one deviating the most from the spatial average, is certified considering the target microclimate range calculated on the spatial average, the maximum occurring error for temperature is lower than 0.5°C and for relative humidity is lower than 3%; Note 6 in the supplementary information.
Given the small microclimate target deviation (<0.5°C Temp and 3% RH) and the low frequency of occurrence (<5%), as well as considering the current objects position (not out from the monitored domain), it can be concluded that in the reported case study, the spatial average accurately represents the microclimate proximity of each measurement point.
The target microclimate calculated according to the spatial average differs negligibly from the target microclimate calculated on basis of each point readings. For the purpose of IMQ certification of movable heritage, the readings from the spatial average can be inputted in the model.

7.2 Microclimate certification

The cold period considered in the certification is made up of two intervals: March-April 2014 and October-November 2014. For the two intervals, 2 hours-based PMV was calculated [5]. Statistics for both the PMV data samples are given in Table 7.2.1. For the warm period: August- September 2014, the indoor operative temperature intervals per three categories of comfort were calculated on the basis of the free running mean temperature outside [6].

	PMV March-April 2014		PMV October-November 2014	
	Statistic	Std. Error	Statistic	Std. Error
Mean	0.067	0.01	-0.249	0.014
Std. Deviation	0.22		0.353	
Minimum	-0.58		-1.02	
Maximum	0.6		0.49	
Skewness	0.07	0.115	-0.023	0.098
Kurtosis	-0.247	0.23	-1.032	0.196

Table 7.2.1; Statistics PMV period 1 (March-April 2014), period 2 (October-November 2014)

The first heating period has positive mean around zero, meaning a thermal sensation around the thermal neutrality, while the second one has negative mean around -0.25, meaning a thermal sensation skewed towards cold.
The PMV samples for both the periods were tested for normality. Test results evidenced that the distribution from the first period (March-April) is normal (Shapiro-Wilk normality test Sig. 0.064), while the one from the second period (October-November) slightly departs from the normality. This occurred due to indoor temperature readings found below the ones outdoor. Nevertheless, the outlying values were consistent with the indoor environmental variations in the specific period, therefore retained in the certification.

	Thermal Quality Heritage (H)	Hygrometric Quality Heritage (H)	Thermal Comfort People (P)	Simultaneous Performance Index (SPI)
	0.11	0.23	0.48	0.27
incidence	13.69%	27.48%	58.83%	100.00%

Table 7.2.2; SPI with three indicators (m=3)

On basis of the certification methodology presented in section 6.4 and considering the conclusions from section 7.1, the Simultaneous Performance Index (SPI) was calculated for thermal quality and hygrometric quality of movable heritage and hygrothermal comfort of building users. The obtained value (0.27) falls in the first category of deviation from optimal microclimate; this stands for good and safe indoor microclimate.
From the results in Table 7.2.2 it can be seen that the hygrometric and thermal microclimate quality for movable heritage only slightly deviates from the optimal microclimate. It should be mentioned that the microclimate short term fluctuations were always found in compliance with condition A in Table 6.4.1.2, therefore there was no evidence of mechanical deterioration risk (plastic deformation) for timber panels or embrittlement risk for the painted layer. The main observed deviation, though numerically small, is related to hygrothermal comfort for building users.

Table 7.2.3 reports the same results as in Table 7.2.2 but considering four indicators instead of three. Results regarding people thermal comfort are separated for the cold and warm period: the larger deviations from neutrality occurred during the heated period (P 0.72) while no departures from the neutrality were registered during the warm period (P 0.01).

	Thermal Quality Heritage (H)	Hygrometric Quality Heritage (H)	Thermal Comfort People Cold Period (P)	Thermal Comfort People Warm Period (P)	Simultaneous Performance Index (SPI)
	0.11	0.23	0.72	0.01	0.27
incidence	10.55%	21.18%	67.75%	0.52%	100.00%

Table 7.2.3; SPI with four indicators

Table 7.2.4 shows the frequencies of deviation from the thermal neutrality with regard to people hygrothermal comfort; the three monitored periods are considered separately with their specific $P_{(p)}$ value. The results from the sensitivity analysis related to the hygrothermal comfort spatial variability are included both in term of percentage of deviations from zero and (P_p) values.
As mentioned above, building users hygrothermal comfort during the warm period (August-September) is optimal. The total deviation from the first thermal comfort quality is negligible (P 0.01). This is unchanged also when considering the operative temperature alteration within the space. No spatial thermal comfort variation occurs because the registered maximum spatial temperature deviation (±0.71°C) is lower than the minimum one considered by the EN 15251 as likely to generate thermal sensation variation (±2°C); see Table 6.4.2.1. In this period the building was not equipped with mechanical cooling (free running).
Good thermal comfort quality was also observed during the first heating period. The PMV samples registered during this time-interval were scattered below and above the range of thermal neutrality meaning that slight cool and warm sensations occurred concomitantly. This condition resulted in an IMQ close to the neutrality (P 0.41). But a tendency towards slightly warm thermal sensation is observable. This tendency increases if considering the PMV samples resulting from the positive alteration of temperature and relative humidity (Alteration +).
In this case it can be observed that the IMQ deviates more significantly from the neutrality (P 0.72). Nevertheless, given the cumulative percentage of PMV in categories 0 and 1 (-0.5≤PMV≤0.5) the IMQ is good and no category variations is observable.
If the PMV is subjected to the negative alteration, the final result is rather similar to the original one (P 0.45). This occurs because of the redistribution of the votes between categories -1 and 1. Unlike to generate category variations.

	Categories of deviation from 0 (optimal IMQ)							$\overline{P_p}$
	-3	-2	-1	0	1	2	3	
Cold period; heating period 1	**0.0%**	**0.0%**	**11.0%**	**62.0%**	**24.0%**	**2.0%**	**0.0%**	**0.41**
Alteration (+)	0.00%	0.00%	2.24%	43.62%	40.49%	11.86%	1.79%	0.72
Alteration (-)	0.22%	2.91%	28.19%	57.94%	10.74%	0.00%	0.00%	0.45
Warm period; free running	**0.00%**	**0.00%**	**0.37%**	**99.44%**	**0.19%**	**0.00%**	**0.00%**	**0.01**
Alteration (+)	0.00%	0.00%	0.37%	99.44%	0.19%	0.00%	0.00%	0.01
Alteration (-)	0.00%	0.00%	0.37%	99.44%	0.19%	0.00%	0.00%	0.01
Cold period; heating period 2	**13.0%**	**15.0%**	**24.0%**	**37.0%**	**11.0%**	**0.0%**	**0.0%**	**1.04**
Alteration (+)	2.10%	13.89%	23.91%	34.25%	21.32%	4.52%	0.00%	0.88
Alteration (-)	26.01%	16.32%	25.69%	29.40%	2.58%	0.00%	0.00%	1.39

Table 7.2.4; Frequency of deviations from thermal comfort optimality for three monitoring intervals and associated P (people) values; Alteration (+/-) refers to the categories of deviations calculated considering PMV altered by the addition (+) or subtraction (-) of temperature and relative humidity maximum deviations

Conversely, during the second heating period (October –November), the deviations were mainly negative (minimum PMV -1.02, Table 7.2.1), standing for a remarkable cooling of the space (P 1.04). In this period, The air temperature was registered for 56 hours below the one outside. This condition caused a shift of the registered PMV towards negative categories -2 and -3 (PMV ≤-0.7). The readings in category *-1*, doubled compared to the ones in the first heating period. PMV categories *-2* and *-3* accounted for a total 28% of samples population compared to 0% of the readings population in the first heating period.
As it may be expected, if the PMV is subjected to positive alteration, a reduction of the deviation from the thermal quality occurs because of the significant diminishing of PMV samples within category -3 (P 0.88). Conversely, in case of PMV negative alteration, the increased population sample in the negative categories resulted in a shift of the total thermal comfort quality to the centre of the moderate category (P 1.39). It is worth mentioning that during the second heating period, the increase of relative humidity consequent to the temperature drop was not found risky for the objects. Moreover the indoor air temperature never dropped beyond the glass transition temperature.

8. Conclusions

With the purpose of detecting possible downsides of the current building microclimate management as well as for identifying microclimate management improvement solutions, it is fundamental to continuously certify the Indoor Microclimate Quality (IMQ). If this certification is based on a multi-objective assessment procedure, it facilitates to simultaneously assess the conflicting aspects of microclimate quality in heritage buildings and museums.

In this contribution we discussed the methodological aspects to be considered during data acquisition process finalized at IMQ certification. Issues regarding temporal and spatial representativeness and resolution of monitoring results were analysed.

Although results and conclusions refer to the reported case study, the research methodology may be replicated in other buildings.

The analysis pointed out that, although the monitored space was observed heterogeneous from a microclimate diagnostic point of view, it was rather homogeneous from a management one. Indeed, the hygrothermal parameters calculated from the spatial average were observed to not significantly deviate from each measurement point included in the domain. Therefore, accurate IMQ certification for movable heritage was allowed considering the target microclimate calculated from the spatial average instead of from each measurement point. The results shed some light on the possibility of optimizing number and location of measurement instruments during infield data acquisition when targeted to IMQ certification.

Results from sensitivity analysis clarified that small spatial temperature variations may result in spatial partialization of the people thermal comfort depending on the applied thermal model. This is not a minor aspect to consider during IMQ certification. Further research is solicited for identifying methodologies tailored at assessing the influence of environmental spatial heterogeneity on the actual thermal comfort sensation variation of people in motion.

In the reported case study; the alteration of ±0.71°C temperature during the warm period (considering the EN 15251 adaptive model) did not bring to comfort category variation in the space. However this occurred during the (second) heating period (considering the ISO 7730 non adaptive thermal model). In the latter case, a variation of thermal comfort quality was registered despite the environment was considerable uniform according to the standard.

In this study, we proposed a multicriteria-based model for the certification of Indoor Microclimate Quality (IMQ) for building users and cultural heritage. The model permitted an holistic understanding of the microclimate quality during different moments of the monitored year for different certification targets. Throughout the monitored period, the exhibition hall was characterized by good microclimate quality and absence of danger for the collection, caused by risky fluctuations or mechanical damage for the timber panels.

However, since a slight cooling of the space during the cold period was observed, consideration might be given to the adjustment of the temperature set-points. This is viable after a revaluation of the short hygrothermal fluctuations. On the contrary, given the perfect hygrothermal quality registered during the warm period, the installation of a cooling system in the studied exhibition hall is strongly discouraged.

9. Acknowledgments

The authors wish to thank the Vleeshuis museum director Timothy De Paepe and the former director Karel Moens for their kind support during the research. The research was financed by IWT - Instituut voor Innovatie door Wetenschap en Technologie, Belgium

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Note 1

IMQ Certification: by ***IMQ certification*** is meant the systematic verification of given microclimate parameters fulfilment to intervals of quality, performance, safety, or steadiness. The parameters benchmarks may be suggested by current standards or in field research.
Movable and immovable heritage: by ***immovable heritage*** is meant an immovable tangible cultural heritage (e.g. a building or structure) and by ***movable heritage*** is meant a movable tangible cultural heritage (e.g. archival document, works of art, collection); in *General Observations*; *Introduction*; EN 15898. In this article the authors refer to immovable heritage also as to historic building components with ***significance***.
Object: by ***object*** is meant the single manifestation of **tangible cultural heritage**; in 3.1.3; EN 15898; in this article the authors refers to object only with regard to movable heritage.
Tangible cultural heritage: by material is meant expression of ***cultural heritage***; in 3.1.2; EN 15898
Cultural heritage: by ***cultural heritage*** is meant tangible and intangible entities of ***significance*** to present and future generations; in 3.1.1; EN 15898
Value: by ***value*** is meant aspect of importance that individuals or society assign(s) to an ***object***; in 3.1.5 EN 15898
Significance: by ***significance*** is meant combination of all the ***values*** assigned to an ***object***; in 3.1.6; EN 15898

Note 2

In the 2013 monitoring campaign, the pairwise comparisons between temperature readings was observed beyond the UNI 10829 threshold only for 1 pair of sensors for less than 1% of the observations; see Fig.1 and 2 . The pairwise relative humidity difference was observed beyond the UNI 10829 threshold for two pair of sensors for 3% of the observations and less than 1% for the rest of pairwise comparisons; see Table 1. The loggers position for the 2013 monitoring campaign (from July to September) is shown in Fig. 1

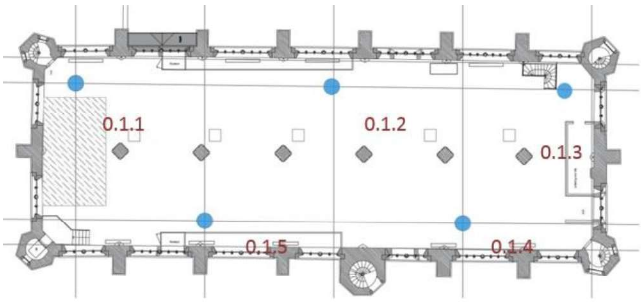

Figure 1; Location of sensors in the exhibition hall at the ground floor of the Vleeshuis museum; monitoring campaign July-September 2013

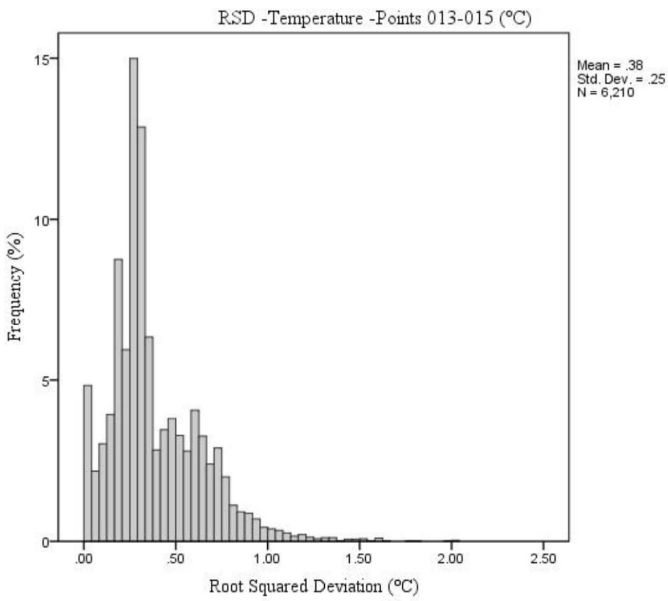

Figure 2; Root Squared Deviation –Temperature difference between sensors 013-015

	Percentiles; RSD Relative Humidity (July- September 2013)						
	5.00	10.00	25.00	50.00	75.00	90.00	95.00
RH011RH012	0.12	0.21	0.35	0.58	1.01	1.46	1.69
RH011RH013	1.02	1.35	2.03	2.63	3.14	3.72	4.08
RH011RH014	1.48	1.95	2.52	3.10	3.63	4.67	5.00
RH011RH015	1.26	1.62	2.11	2.40	2.68	3.32	4.24
RH012RH013	0.61	0.86	1.41	1.83	2.32	3.11	3.54
RH012RH014	1.06	1.46	1.97	2.47	2.98	3.39	3.61
RH012RH015	0.53	0.88	1.42	1.81	2.10	2.59	2.81
RH013RH014	0.06	0.11	0.28	0.61	1.00	1.71	2.16
RH013RH015	0.06	0.11	0.28	0.76	1.32	1.84	2.29
RH014RH015	0.08	0.15	0.44	0.86	1.33	1.85	2.19

Table 1; Percentiles of the RSD pairwise Relative Humidity difference between all the measurement points; 2013 monitoring campaign

Note 3

The calculation of daily hygrothermal fluctuations (daily cycles) is not unequivocal and by varying the calculation method, the obtained results are different; this is clearly visible in In Fig. 1 which plots the temperature daily fluctuations for the month March 2014 (point 012) calculated according to three different methods.

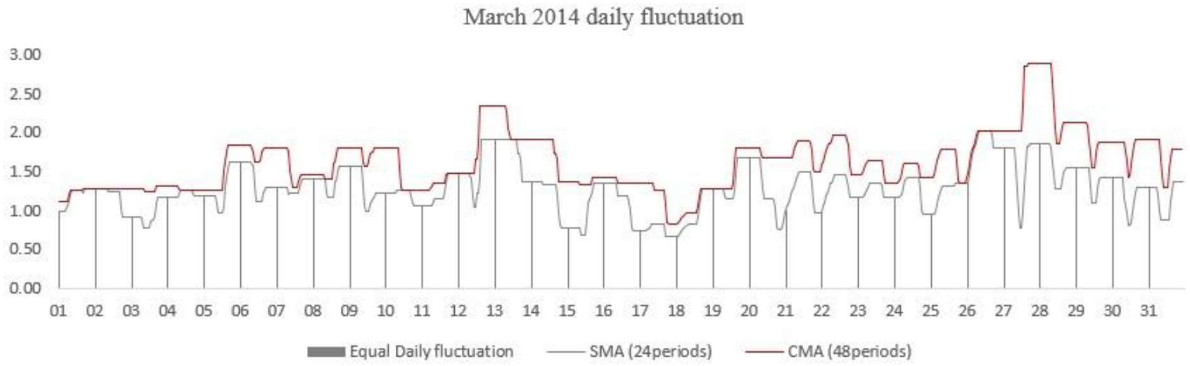

Figure 1; daily temperature fluctuations comparison; March 2014, point 012

The vertical grey bars represent the equidistant daily temperature fluctuations, calculated as the absolute difference between maximum and minimum daily temperature. The continuous smooth grey line represents the (forward) Simple Moving Average (SMA) fluctuations, calculated with a forward running average (24 period). The continuous smooth red line represents the Centred Moving Average (CMA) fluctuations calculated with a centred running average (49 period). The latter is different from the second as it is symmetrically centred (48hours + the current hour reading).

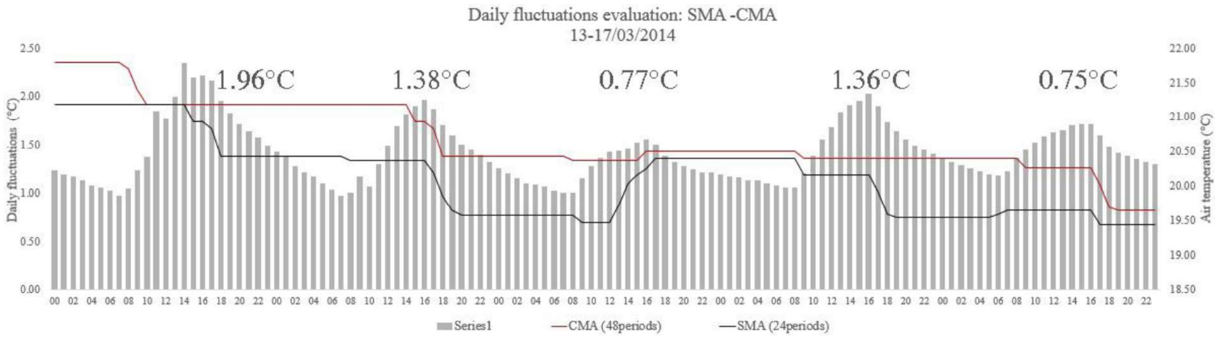

Figure 2; Daily temperature fluctuations comparison; 13-17 March 2014, point 012; Series 1 in the graph represents the hourly air temperature in point 012

Fig. 2 shows a time interval, from 13 to 17/03/2014, with regard to measurement point 012. The air temperature is plotted together with forward SMA (grey line), CMA (red line), and equidistant daily fluctuations (large numbers in black). Can be seen that the red line is less reactive than the grey one (only forward looking); this explains why CMA responds less to mono-directional variations.

By observing the grey bars representing the air temperature, can be seen that during the second day the air temperature is slightly lower than the first one; likewise during the third day. During the fourth day, the temperature is similar to the second one and during the fifth day, it decreases (though the minimum temperature increases).

Because of the temperature fluctuations decrease occurring in the third day, it can be observed (looking at the second day) that both the curves decline.

The Standard Deviation (SD) during the third day is smaller compared to the one in the second day[1]. Because the SD calculated for the SMA is smaller than the one calculated for the CMA, the daily fluctuations of the SMA drop more significantly (from 1.34°C to 0.77°C) compared to the ones of CMA (from 1.92°C to 1.38°C). This is even more visible with regard to the third day.

[1] The temperature Standard Deviation (SD) calculated according to the (forward) Simple Moving Average (SMA) decreases from 0.42°C (day 2) to 0.23°C (day 3). The SD calculated according to the Centred Moving Average (CMA), decreases from 0.53°C (day 2) to 0.35°C (day 2).

During the third day the SMA rises consistently with the thermal fluctuations in the fourth day; the SD from third to fourth day doubles[2]. Likewise, the CMA curve rises but with less intensity than the SMA; so does the SD calculated with CMA. This occurs because the CMA 'keeps memory' of the fluctuations already experienced (second day) and balances them with the ones to be yet experienced (fourth day). By doing so, the curve is more stable to environmental variations.

Because microclimate variability needs to be evaluated continuously, in the authors opinion, the Centred Moving Average (CMA) is more appropriate than other metrics. The daily fluctuations calculated on the CMA (49 periods) allow consideration of the past and coming hygrothermal fluctuations without creating discontinuities.

[2] The temperature Standard Deviation (SD) calculated according to the (forward) Simple Moving Average increases from 0.23°C (day 3) to 0.45°C (day 4). The SD calculated according to the Centred Moving Average (CMA) increases from 0.35°C (day 3) to 0.38°C (day 4).

Note 4

The model developed by Mecklenburg in [1] and included in the presented IMQ certification model, was coded with good level of approximation by P. Lankester and P. Brimblecombe in [2]; see Table 1.

Adsorption		Desorption	
Initial RH	Critical RH	Initial RH	Critical RH
10<=RH<30	1.5RH+1	10<=RH<30	0.8RH-3.33
30<RH<=40	1.0 RH+18	30<RH<= 50	0.6 RH+3.33
40<RH<=50	0.5RH+38	50<RH<=60	0.9RH-12
50<RH<=60	0.4RH+43	60<RH<=70	2.0RH-78
60<RH<=90	0.8RH+19	70<RH<=80	1.6RH-50
-	-	80<RH<=90	1.05RH-6

Table 1; Critical RH ranges for timber panels deformation elaborated according to [1]; from [2]

It is worth noting that the equations coded by P. Lankester and P. Brimblecombe identify the boundary of the elastic region of the timber panel mechanical deformation. RH fluctuations over the lines expressed by the equations, are likely to generate plastic deformation in tension or compression. These equations do not include the region of failure, which is reasonable from a preventive conservation view point.

References

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[2] P. Lankester and P. Brimblecombe, “The impact of future climate on historic interiors,” *Sci. Total Environ.*, vol. 417–418, pp. 248–254, 2012.

Note 5

Condition A (RH)	Condition A (Temp)
$\begin{cases} \Delta_{(\mathrm{RH,day})} < \Delta_{(\mathrm{RH,90})} \\ \Delta_{(RH,i)} < \Delta_{(RH,plast)} \end{cases}; \geq 90\% \ (N_1), \geq 95\% \ (N_2)$	$\begin{cases} \Delta_{(\mathrm{Temp,day})} < \Delta_{(\mathrm{Temp,90})} \\ T_{(Temp,i)} > T_{(g)} \end{cases}; \geq 90\% \ (N_1), \geq 95\% \ (N_2)$
Condition B (RH)	Condition B (Temp)
$\begin{cases} \Delta_{(\mathrm{RH,day})} > \Delta_{(\mathrm{RH,90})} \\ \Delta_{(RH,i)} < \Delta_{(RH,plast)} \end{cases}; \geq 80\% \ (N_1), \geq 95\% \ (N_2)$	$\begin{cases} \Delta_{(\mathrm{Temp,day})} < \Delta_{(\mathrm{Temp,90})} \\ T_{(Temp,i)} > T_{(g)} \end{cases}; \geq 80\% \ (N_1), \geq 95\% \ (N_2)$
Condition C (RH)	Condition C (Temp)
$\{\Delta_{(RH,i)} > \Delta_{(RH,plast)}; > 5\% \ (\mathrm{N})$	$\{T_{(Temp,i)} > T_{(g)}; > 5\% \ (\mathrm{N})$

Table 6.4.1.2 in the Text; Conditions a, b and c for short fluctuations (H); the percentage refer to the percentile of sampled data (N)

- Condition A, represents the circumstance of optimality where both short-term fluctuations and material mechanical stress do not generate any potential risk to the objects; for this reason, the incremental factor to the perturbation vector is zero.
- Condition B; represents a more typical condition, wherein recurrent short-term fluctuations are met for a lower time interval but no risk of plastic deformation for the timber panel is evidenced; the incremental factor to the perturbation vector is 0.5.
- Condition, C, is an emergency situation: independently from long and short term microclimate fluctuations, more than 5% of relative humidity fluctuations readings are potentially risky for the objects and likely to trigger plastic deformations. This occurrence makes equivalent the category to the last one (3).

Note 6

Figures 1 and 2 show the CMA and the related upper and lower bounds (calculated with the 7th and 93rd percentiles from Table 7.1.4 in the text) for the specific point 014 and for the spatial average. The maximum deviation (given by the summation of maximum short and long-term deviation between point 014 and spatial average) between point 014 and spatial average is represented by a grey stripe. This deviation (the maximum observed among the three measurement points), represents the inaccuracy of the target microclimate if calculated on the spatial average readings instead of the current readings from point 014. However this occurs in less than 5% of data population.

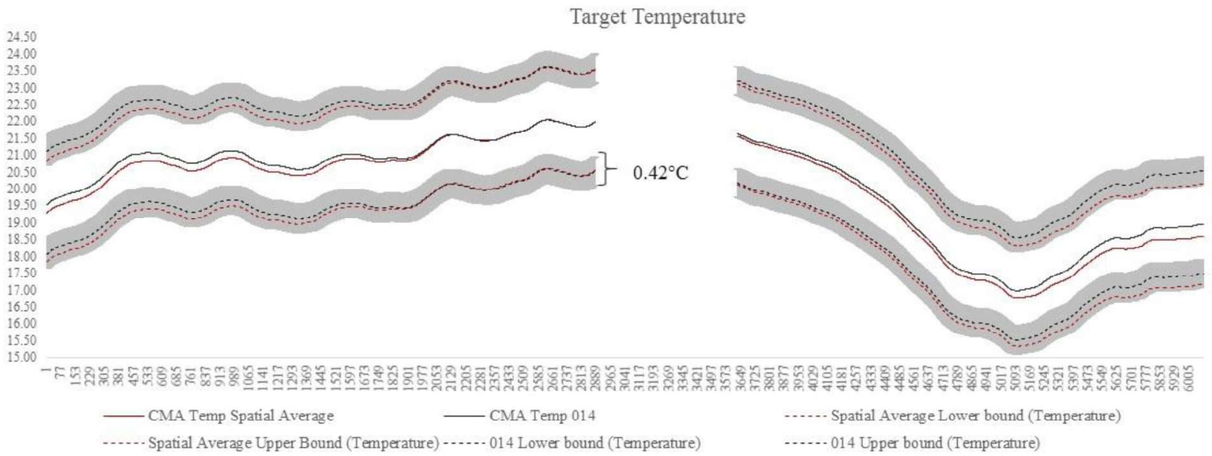

Fig. 1; Comparison Target temperature calculated with point 014 readings and with Spatial Average readings; the grey stripe represents the maximum deviation between point 014 and spatial average (0.42°C); the max deviation occurs < 5% of data population.

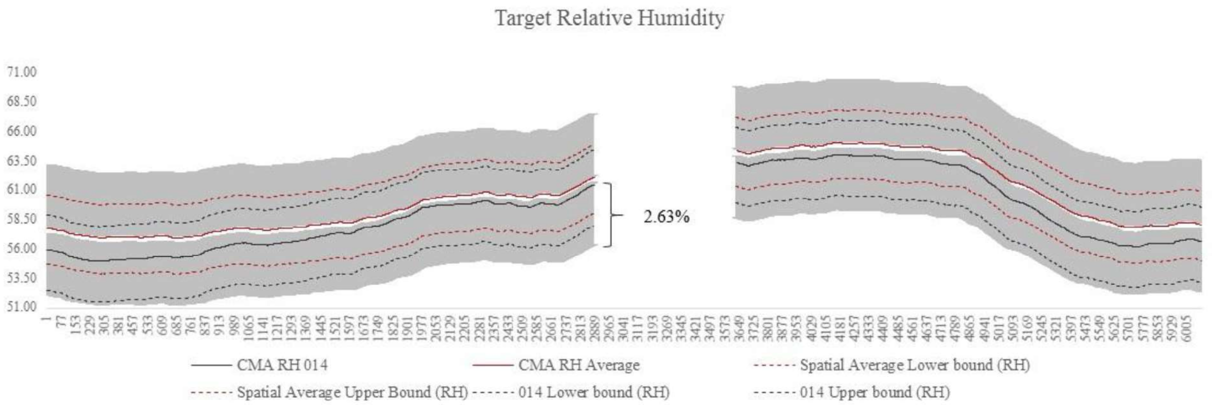

Fig. 2; Comparison Target relative humidity calculated with point 014 readings and with Spatial Average readings; the grey stripe represents the maximum deviation between point 014 and spatial average (2.63%); the max deviation occurs < 5% of data population