An integrated approach for indoor microclimate diagnosis of heritage and museum buildings : the main exhibition hall of Vleeshuis museum in Antwerp

Reference:
Litti Giovanni, Audenaert Amaryllis.- An integrated approach for indoor microclimate diagnosis of heritage and museum buildings : the main exhibition hall of Vleeshuis museum in Antw erp
Energy and buildings - ISSN 0378-7788 - 162(2018), p. 91-108
Full text (Publisher's DOI): https://doi.org/10.1016/J.ENBUILD.2017.12.014
To cite this reference: https://hdl.handle.net/10067/1475460151162165141

Manuscript Details

Manuscript number	ENB_2017_1975_R2
Title	An integrated approach for Indoor microclimate diagnosis of heritage and museum buildings: the main exhibition hall of Vleeshuis museum in Antwerp
Article type	Full Length Article

Abstract

Indoor microclimate diagnosis allows to understand the indoor-outdoor building microclimate interactions and to evaluate the extent of indoor hygrothermal variability caused by building use. Moreover, since the cumulative physical deterioration of the building envelope plays a relevant role in altering the indoor microclimate and building thermal performance, it is essential to combine both building envelope and indoor microclimate monitoring in an integrated diagnostic approach. The microclimate diagnosis of the Vleeshuis museum main exhibition hall here discussed is based on infield instrumental environmental monitoring and Infrared thermography (IRT) on the building masonries. The IRT was integrated with the analysis of the building documentation. Further, the microclimate analysis was performed by combining the conventional microclimate data analysis with statistical tests. The integrated diagnosis as presented in this study allowed to evaluate the long-term indoor microclimate variability consequent on outdoor and indoor heat and moisture loads variation as well as the identification of the sources of infiltrative water in the building masonries.

Keywords	microclimate monitoring; IRT; microclimate diagnosis; statistics applied to cultural heritage
Taxonomy	Sustainable Construction, Architectural Design, Architectural History

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Suggested reviewers	Elena Lucchi, Joanna Ferdyn-Grygierek, Alexandra Troi, Hugo Entradas Silva

Submission Files Included in this PDF

File Name [File Type]

_Cover Letter revised.docx [Cover Letter]

_Answers to the reviewers.docx [Response to Reviewers]

_Comments to the Editors.docx [Review Reports]

_Manuscript_3rd revision_Track changes.docx [Revised Manuscript with Changes Marked]

_Highlights_revised.docx [Highlights]

_Manuscript_3rd revision_NO Track changes.docx [Manuscript File]

_Supplementary Data_Figures_third sub.docx [Figure]

_Note 1 supplementary information-third sub.docx [Table]

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Research Data Related to this Submission

There are no linked research data sets for this submission. The following reason is given:
Data will be made available on request

Cover Letter

The work we present in this contribution titled: “An integrated approach for Indoor microclimate diagnosis of heritage and museum buildings: the main exhibition hall of Vleeshuis museum in Antwerp” is the result of years of studies in the Vleeshuis museum in Antwerp (Belgium). Part of the results from this long and comprehensive research were published in your journal in 2015 with an article titled: “Hygrothermal performance evaluation of traditional brick masonry in historic buildings”. Other results, related to the people thermal comfort and safety for the museum collection have been recently published in “Journal of Buildings and Environment”.

In the manuscript we introduce, by discussing results from a long term building microclimate monitoring, an integrated methodology for microclimate assessment of heritage buildings and museums. This method integrates environment monitoring, Infrared Thermography and building documentation analysis. Moreover, the data analysis we propose integrates building physics analysis with inference statistic.

In the authors opinion the latter is fundamental for discriminate among the countless climatic circumstances likely to influence the indoor building microclimate stability. Moreover it is also supportive for comparing possible causes of hygrothermal fluctuations in a confined environment. For these reasons, we believe that this approach is fundamental in the field of microclimate studies for the cultural heritage.

The analysis of the building documentation together with IRT an environmental monitoring has allowed to precisely identifying the sources of water infiltration in the building masonries. This aspect is not only fundamental in terms of building microclimate evaluation but also in terms of building envelope thermal energy assessment. Moreover, this aspect completes the study published in this journal in 2015.

We believe that the novelty of the integrated approach we have proposed (in terms of data acquisition and elaboration) as well as the obtained results could be supportive for the scientists and researchers community dealing with cultural heritage studies.

However, we are aware that the manuscript slightly exceeds the terms suggested by the journal in terms of length. We have done our best to make the article as concise as possible (also by putting table and figures extra text). For facilitate the reviewers work, the article underwent already 2 English proofreading by English native speakers.

Your sincerely

Giovanni Litti

General comments to the reviewers

Dear reviewers,

Once again we would like to thank you for the valuable support given in order to improve the quality/clearness of our work. Your comments have been integrated within this amended article version. We hope, to have satisfied your requests and to have additionally improved the quality of the submitted manuscript.
Since reviewer 2 communicated her/his agreement to publish the manuscript after our first revision, the comments reported in this report refer to the requests from reviewer 1.
The article structure has been adjusted in order to meet the requests in terms of article structure simplification. Namely, in its current version, the article is subdivided according to the canonical sections subdivision: introduction, methodology, results discussion and conclusion as requested by reviewer 1. For meeting this requirement, the article text underwent minor text- revision without modifying the contents (see Manuscript with Track changes).
It was added, as requested by reviewer 1, the trend (over time) of Air Temperature and Relative Humidity throughout the monitored period. We apologize if this request was not met in our previous revision.
Errors and wording inconsistencies pointed out by reviewer 1 have been amended as reported below in the detailed answers to the reviewer. We hope this may have increased the clarity of the text.

Independently from your decision on the manuscript, we wish to thank you all for the time invested in the reviewing process and your precious contribution.

Answers to Reviewer 1

1) With regard to your comment: "However, I consider the authors should improve some points. In my opinion the structure of the article should be simplified to: Introduction, Methodology, Results and discussion and Conclusion".
   We simplified the manuscript according to the canonical manuscript structure according to what suggested by the reviewer.

2) With regard to your comment: "In my opinion the IRT analysis does not contribute considerably to the quality of the article, or at least it is not indispensable (…) With the exception of some interesting photographs, in my opinion most of the material presented in Supplementary data is not indispensable for the understanding of the work".
   We understand the reviewer's opinion, however we believe that the performed IRT and related results are supportive for obtaining an understanding of the performed work in its totality. Indeed, the IRT results are meaningful for localising the cause of moisture infiltration in the masonries that have an influence on the indoor hygrothermal variability. This opens an important discussion (partially opened in a previous publication of the authors and often referred in this manuscript) on the long-term consequences of improper buildings restoration works on the buildings microclimate and energetic performance alteration. The here presented IRT results support the necessity of performing integrated monitoring taking into account the relation between microclimate quality (energy efficiency etc.) and building masonries technological decay. Nevertheless, the details about the IRT results are reported in a Note in Supplementary Data, making their read not mandatory to the reader.
3) With regard to your comment: "I once again ask the authors to present graphs with the evolution of temperature and relative humidity in time" As mentioned in general comments for the reviewers, the plot of indoor air temperature and relative humidity measured in the Vleeshuis museum exhibition hall have been added in the current section 3.1 Microclimate diagnosis results. We would like to apologize if the mentioned plots were not integrated before.
4) With regard to your comments: "In order to have a more detailed analysis, I recommend the following changes: a) I suggest that the Introduction, Research objectives and Limitations are join in only one chapter. b) Authors must define the importance of this type of studies and what are the goals of this paper. c) Authors can use part of the information presented in Research objectives and limitations in a summarized form. In the introduction, authors should present the developed study in summary form, as done in the third point of Research objectives and limitations. The first paragraph of the chapter Case

Study description also has useful information that should appears in the introduction. All the comments suggested by the reviewer were taken into account and the sections re-written. We hope that in this form the manuscript is more clear and better structured. The observations with regard to the importance of such a study and the research goals, although already present in the previous version, have been made more clear and synthetized. We hope to have accomplished what requested by the reviewer.

5) With regard to the comments: "- a) Authors should describe the type of building under analysis - museums, historical buildings, cultural heritage ... - in the abstract and in the first paragraph of the introduction – b) Line 3 of Introduction: I recommend authors to use "mass" instead "vapour" – c) Line 6 of Introduction: I recommend authors to use "hygrothermal" instead "thermal" – d) Authors should change the last part of the introduction as suggested below: (…).
   a) The building under investigation has been better described, especially in the introduction of the article.
   b) Mass was used instead of vapour
   c) Hygrothermal instead of thermal was used
   d) All the suggestions at point d) were considered in the article
6) With regard to the comment: a) The last two points of Research objectives and limitations and the chapter Case study description must go to the methodology chapter. b) Authors should describe the constructive solution, thermal characteristics of the elements and the relationship between glazing area / floor area.
   a) The consideration from the reviewer were integrated in the revised version of the manuscript, see current section 2.1
   b) Information on the building constructive technology as well as glazing/area fraction have been integrated in the text (current section 2.1)
7) With regard to your comment: "The encoding of the sensors presented in Table 4.1.1 could be clearer". We understand the comment of the reviewer; however we believe that the considered encoding does not constitute a problem for the results reading especially because their position and numbering is plotted in an enlarged key-plan image.
8) With regard to your comment: "Figure 4.1.2 is too small. Authors should enter the Northern indication. According to what suggested by the reviewer, the Figure was enlarged and the North indication was entered.
9) With regard to your comment: "In Chapter 4.2, 1st line, the authors speak of the North-West corner. Shouldn't it be North-East?" We thank the reviewer for this observation; there was an error in the previous version of the text. The current article version refers to the correct orientation: East.
10) With regard to your comment: "In 4.3 the authors begin to mix the terms mixing ratio (MR) and water vapour concentration. Authors should always use the same term throughout the work, because in some publications they are not calculated in the same way. We understand the concern of the reviewer, however, we would like to mention that already in the previous manuscript version it was written that (for the seek of simplicity) the term water vapour concentration and mixing ratio were used as synonyms. However, in the current version (see section 2.4), this concept is made more clear and linked with the calculation procedure given in the appendix. At section 2.4 is written: "In the article, MR is also termed, for simplicity, water vapour concentration and is calculated according to Eq. 4 in Appendix".
11) With regard to your comment: "The authors cite a water vapour production of 50 g/h/occupant. This value is too low. I recommend you to consult the BS 5250 for example. We resorted to the value of 50g/h per person of vapour production as a result of a study (referred in the text). The study considered a vapour production of people attending religious functions (activity with very low metabolic rate). The latter is, in our opinion, the closest activity to the ones considered in the study (attending concerts and looking at the exhibition).
   In the BS 5250.2011 Standard, the activity: "working in office" was the closest one to our study (table D6). However, if considering that working in office has higher metabolic rate than listening to a concert or looking at the collection (similar to book-keeping the first and similar to sitting or resting the second), the standard ISO 8996 suggests metabolic rate values of 100W/m^2 for the first and 65 W/m^2 for the second. Therefore the office activity justifies a higher per capita moisture production, 70g/h instead of 50g/h.
   According to what above mentioned, we did not vary the considered per capita moisture production, but we wish to thank the reviewer for having given us the opportunity of an additional check.
12) With regard to your comment: "In the results I do not understand why the authors still do not present a graph with the evolution of temperature and relative humidity as function of time, since they have interior and exterior data for a long period". See answer to comment 3.
13) With regard to your comment: "In addition, they could compare the values recorded with values considered acceptable for conservation". This observation was already answered in the first revision process. The assessment of the indoor microclimate quality influence on the collection hygrothermal safety was not object of the present study. Nevertheless the study asked by the reviewer was object of a

specific contribution that is now clearly mentioned in the text. See final part of the introduction in the list of objectives and limitations of the study.

14) With regard to your comment:" In 5.1 authors wrote: "As from thermal imaging on the walls, it was not evidenced risk of surface condensation during the year, the presence of moisture evaporating inwards might be caused by the natural drying of the masonry core after the moisture accumulation in winter." Until now they have not provided information to justify such information. According to the reviewer's comment the mentioned part of the text was rephrased as below reported: "From thermal imaging on the walls, it was not evidenced risk of surface condensation during the year. This because the walls surface temperature was higher than the air dew point temperature; because of this, the presence of moisture evaporating inwards might be caused by the natural drying of the masonry core after the moisture accumulation in winter".
15) With regard to your comment: "In 5.1.2. The time must be 1-24 or 0-23. If this nomenclature is maintained the authors should withdraw the pm". According to the reviewer's comment, the time format has been corrected.
16) With regard to your comment: "References: At least one of the references has an incomplete title". The wrong (incomplete) reference title has been adjusted.

General comment to the Editors

Dear Editors,

We would like to thank you for having given us the opportunity of improving our work.

We intervened on the text as asked (only) by reviewer 1. The manuscript was fitted (according to the suggestions from the reviewer) in a more conventional structure. We believe that in this new form, it is easier for the reader to follow the methodological procedure and results discussion.

Moreover, according to the reviewer's comments, the introduction was once again enlarged including research objectives and limitations (previously written in an a-part section). We believe that this new structure allows to more rapidly read and understand the presented research, its methodology and results.

We believe the revision process has given added value to our work, and this is thanks to you and all the reviewers.

The general and detailed comments to the reviewers are answered in the document: "answers to reviewers".

Your sincerely,

Giovanni Litti

An integrated approach for Indoor microclimate diagnosis of heritage and museum buildings: the main exhibition hall of Vleeshuis museum in Antwerp

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Abstract

Indoor microclimate diagnosis allows to understand the indoor-outdoor building microclimate interactions and to evaluate the extent of indoor hygrothermal variability caused by building use. Moreover, since the cumulative physical deterioration of the building envelope plays a relevant role in altering the indoor microclimate and building thermal performance, it is essential to combine both building envelope and indoor microclimate monitoring in an integrated diagnostic approach.
The microclimate diagnosis of the Vleeshuis museum main exhibition hall here discussed is based on infield instrumental environmental monitoring and Infrared thermography (IRT) on the building masonries. The IRT was integrated with the analysis of the building documentation. Further, the microclimate analysis was performed by combining the conventional microclimate data analysis with statistical tests.
The integrated diagnosis as presented in this study allowed to evaluate the long-term indoor microclimate variability consequent on outdoor and indoor heat and moisture loads variation as well as the identification of the sources of infiltrative water in the building masonries.

Keywords: microclimate monitoring; IRT; microclimate diagnosis; statistics applied to cultural heritage

Nomenclature

MR	Mixing ratio (g/kg)
Vp	water Vapour pressure (Pa)
Vps	Saturation Pressure of water Vapour (Pa)
P_{tot}	Total Air Pressure (hPa)
AH	Absolute humidity (g/m3)
T	Air Temperature (°C)
RH	Relative Humidity (%)
Δ_T	Temperature gradient inside-outside (°C)
Δ_R	Relative Humidity gradient inside-outside (%)
(in)	Inside
(out)	Outside
SE	Standard Error
CI	Confidence Interval
N	Data population

1. Introduction

Performing building indoor microclimate diagnosis means on the one hand verifying how the building interacts with its outdoor climate [1, 2] and on the other hand understanding the indoor microclimate variation consequent on variation of internal heat and mass~~vapour~~ loads [3–5]. Moreover, because the building envelope materials deterioration process plays a driving role in the indoor microclimate alteration and building energy performance [6–8], it is fundamental to evaluate both indoor building microclimate and building envelope state of conservation and hygrothermal performance [9]. Indeed, if Heat, Air and Moisture transfer through the building components is uncontrolled, not only might it cause overall building thermal performance reduction [9–12], but it may trigger indoor hygrothermal alterations with consequent risks for cultural heritage preservation and for people comfort and health [6], [13–15].

Given the existence of a cause-effect relationship between building performances, building materials state of conservation and building use, it should be favoured the implementation of holistic building monitoring and diagnosis instead of monothematic building assessment activities (e.g. energy audits). This is even more significant in case of historic, heritage buildings and museums. Indeed, in these buildings, the usual presence of non-centralized equipment, the opening of doors at each visitors entrance, the lighting system, the inconstant installation's schedule, the building physical deterioration and the long-term results effects of previous restoration works may constitute a possible source of microclimate instability or even increased building energy consumptions. As a result, global building performance can only be improved by understanding and addressing the mentioned aspects in their totality.

Nevertheless, given the large amount of data and multiple research questions at the basis of a building indoor microclimate diagnosis, statistical tools may integrate the conventional data analysis. The use of descriptive and inference statistics at support of microclimate analysis (with exploratory or confirmatory purposes) is becoming more frequent also now ordinary also in the cultural heritage science [16]. This occurs especially after the introduction, in national and European standards [17,18], of microclimate data analysis methodologies based on the support of statistics.

It should be mentioned that this support is notshould be not independent from a physical understanding of the environmental phenomena. Indeed, the physics concerned in the microclimate dynamics allows to identify the appropriate statistics to use for better analysing the problem; moreover the latter do not replace the former during the problem understanding. In other words, a correlation coefficient may express the relation between variables but it does not explain the reasons of this relationship. Nevertheless, statistical modelling may facilitate the microclimate diagnosis especially with regard to long-term monitoring wherein big amount of data are involved..

S. P. Corgnati, M. Filippi et.al, in [19,20] recurred to descriptive statistics-based indicators for globally assessing the indoor thermo-hygrometric safety of paintings during temporary exhibitions. Similar analysis supported by descriptive statistics (e.g. cumulated percentages, frequency indicators, bivariate correlations, etc.) were also undertaken by J. Ferdyn- Grygierek in [21] for evaluating the indoor climate of a large museum building and by F. Sciurpi et.al in [22] for deciding upon microclimate control strategies in an Italian museum. H.E. Silva and F. M.A. Henriques in [23] proposed a comparison between two statistical methods for the definition of safe (historic) climate target in a Spanish Portuguese church according to the EN 15757 standard and an adjusted version of the latter [24].

Other authors performed exploratory analysis for assessing specific microclimatic issues by relying on statistical inference. F. J. Garcia-Diego and M. Zarzo, in [25] applied multivariate statistics to understand the likelihood of moisture formation on a renaissance frescos in the Cathedral of Valencia, Spain. Results from Principal Components Analysis (in agreement with the ones of the restoration works) allowed identifying the presence of moisture on the fresco surface. The same multivariate analysis, was implemented by P. Merello et.al in [26] for characterizing the microclimate variability of an open-archaeological site in Pompeii, Italy, and for recognizing abnormal microclimate patterns.

The above-mentioned contributions, highlighted according to their methodology the validity given by the integration of statistical inference with canonical hygrothermal data analysis in the field of cultural heritage. This integration was a fundamental aspect considered in the present study.

The main objective of the present research is to introduce an integrated methodology for indoor microclimate assessment of heritage buildings and museums. This methodology integrates (1-year) environment monitoring, Infrared Thermography and building documentation analysis.

The performed indoor microclimate diagnosis relies on building physics analysis and inference statistics. In the authors' opinion, the latter is supportive in order to: a) discriminate among the countless climatic circumstances likely to influence the indoor building microclimate stability; b) compare possible causes of hygrothermal fluctuations or c) confirm hypothesis emerged during instrumental monitoring or data analysis.

The study of the building documentation combined with results from IRT and environmental monitoring, allowed to precisely identifying the sources of water infiltration in the building masonries. This approach not only is fundamental in terms of building microclimate evaluation but also in terms of building envelope thermal energy assessment. Indeed, it allows obtaining important insights for possible interventions targeted at the restoration or performance improvement of the building. Clearly, the mentioned contributions introduced a novel approach within the frame of preventive conservation sciences and microclimate diagnosis.

2. Research objectives and limitations

This contribution has the twofold objective of 1) proposing an integrated approach for the indoor microclimate diagnosis in historic and heritage buildings and 2) proposing a microclimate data analysis based on the integration

~~of building physic and basic statistical models.~~ The researchstudy was performed in the main exhibition hall of the Vleeshuis museum in Antwerp (~~,~~ Belgium). The Vleeshuis, is a protected monumental building in the city centre; it currently hosts a musical instruments collection in the basement and ground floor.

An introduction to the case study and to its indoor microclimate control systems is given in the section methodology (section 2). In the same section, the undertaken instrumental and analytical research methodology is described. Research results are discussed in section 3 and conclusions are drawn in section 4.

The ~~With the purpose of answering to the mentioned objectives a 1-year environmental monitoring and Infrared imaging on the building masonries were performed and combined with the analysis of documentary data from previous building restoration works. Further, the performed microclimate data analysis has integrated descriptive and inference statistical models. More specific~~specific objectives and limitations of the present study are ~~bulleted~~ listed below.

- With regard to the assessment of the building masonries~~the aim of assessing the building envelope state of conservation and its possible influence on the indoor hygrothermal variability~~, the study focusses on the following: localisation of moisture in the building masonries and identification of water infiltrative sources. Although the building envelope analyses was performed with regard to the entire building, we limit the results discussion to the North-~~West~~ East building corner (ground and first floor) as found to be the most representative for allowing a good understanding of the moisture infiltration causes and effects. This aspect of the study is based on a previous research to which we refer the reader for details on methodology and results [9].
- With regard to the assessment of ~~the aim of assessing~~ the influence of heat and moisture loads on the exhibition hall microclimate stability, the study focuses on the following: a) the effect of outdoor climate on the one indoor one;~~;~~ b) the effect of visitors on the indoor microclimate variations;~~;~~ c) the effect of climate control equipment operation and building use on the indoor hygrothermal variability; d) the effect of infiltrative air on indoor hygrothermal fluctuations.
- The specific aspects concerning the influence of the current exhibition hall microclimate quality on people comfort perception and movable cultural heritage safety are discussed by the authors in [27].
- The~~-~~ microclimate monitoring ~~here discussed~~, was performed during the year 2014-15. However, due to logging failure, data from July the 20th to September the 8th were lost, hence not included in the analysis. The outdoor environmental parameters considered in the analysis were taken from a weather station 6 km distant from the museum (Deurne).
- The exhibition hall is equipped with independent humidifiers. As it was found that the machines were not constantly in use throughout the monitored year, their influence on the indoor hygrothermal variability ~~is~~ was analysed according to the less safe scenario. In other words, t~~T~~he results with regard to this scenario represent the influence the humidifiers ~~machines~~ might have on the indoor microclimate, if constantly used ~~,~~ at their maximum power.
- ~~Further studies, aimed at~~The quantification of~~ying~~ the actual humidifiers influence of the indoor microclimate variability will be object of further research~~es~~.

2. Research methodology

In this section, the building selected as case study is presented (section 2.1) together with the methodology for the infield instrumental monitoring (section 2.2 and 2.3) and analytical procedure for the microclimate diagnosis (section 2.4).

~~3.~~2.1 Case study description

The Vleeshuis, currently museum of musical instruments, was built between 1501 and 1504 as slaughterhouse by Herman de Waghemakere (the elder). It was built to house four functions in independent levels: the slaughter space, the market, the leaving and the storage spaces. The first two functions were built respectively in the cellar and on the ground floor, while on the first floor, spaces for reception, meetings and forestry were housed. The upper four levels were used as storage. Currently the basement and ground floors host the permanent collection of musical instrument while the upper levels, except part of the second floor (used as offices), are dedicated to artifacts storage.

For the purpose of th~~e~~is study, the main exhibition hall on~~on~~ the ground floor was continuously monitored; see Figure 2.1.1~~3.1~~ (a-c). The building is technologically characterized by brick masonries and vaults at the basement and ground floor and brick masonries and timber ceilings at the upper floors. The brick masonries of the ground floor are opened by almost 220m^2 stained single glass windows (≈35% of the floor area).

The building is equipped with centralised heating system with high temperature radiators as terminals (temperature set-point 20°C)[1]. No cooling or mechanical ventilation systems is present with the only exception of an independent air heating and ventilation unit installed on the North-East~~West~~ part of the exhibition hall (see Fig. 2~~3~~.1.1.c and 2.2.1~~4.1.2~~). The air unit, without humidity control, allows an air change rate of 3500m^3/h (exhibition hall net volume ≈5300 m^3). The exhibition hall is neither equipped with humidity control system nor with temperature one.
The humidity is controlled by independent humidifiers (often found defected or not in use), while temperature regulation is allowed by the adjustment of the radiators thermostats. Nevertheless, as the radiators are located on the boundary walls -were also part of the collection is exposed- several terminals are constantly closed not to endanger the cultural objects.
In a previous study, reported by the authors in [9], it was observed that the Vleeshuis masonries are deteriorated by infiltrative water and that the moisture presence causes a remarkable masonries thermal performance reduction. By means of in-contact and semi in-contact wall hygrothermal monitoring, it was found that the thermal transmittance value on wet areas is three time higher than the one on dryer ones. Moreover, it was observed that walls drying process, is responsible for a continuous water vapour enrichment of the indoor air volume due to (partial) inwards masonry evaporation.

Fig. 2.1.1~~3.1~~.a-c (from left to right); Ground floor exhibition hall of the Vleeshuis internal view (a); example of humidifier present in the exhibition hall (b); air heating and ventilation unit integrated in a closet (similar to the showcases) on the North wall (c)

~~4. Methodology~~

~~The measurement protocol, especially with regard to the sensors location, was developed on basis of findings from a preparatory short term monitoring performed in the summer 2013 [28].~~
~~As mentioned, the performed study, was not only aimed at indoor environmental data acquisition and analysis, but also at the localisation -via infrared thermography- of the causes of the thermal discontinuities in the brick masonries and understanding their possible influence on the exhibition hall hygrothermal variability.~~
~~In a previous study, reported by the authors in [9], it was observed that the Vleeshuis masonries are deteriorated by infiltrative water and that the moisture presence causes a remarkable masonries thermal performance reduction. By means of in-contact and semi in-contact wall hygrothermal monitoring, it was found that the thermal transmittance value on wet areas is three time higher than the one on dryer ones. Moreover, it was observed that walls drying process, is responsible for a continuous water vapour enrichment of the indoor air volume due to (partial) inwards masonry evaporation.~~
Even if, in the ~~current~~ here discussed study, no direct masonry environmental monitoring was performed, it is reasonable to expect that the walls drying process, as observed in [9], triggers similar vapour evaporation in the exhibition hall and in all the spaces at the first floor where identical moisture infiltrations were observed. The problem of infiltrative water in the building masonries is not recent indeed it was already observed during restoration works in 1964 (Fig. 3 in Supplementary Data). It is worth mentioning that not only the brick masonries deterioration is supposed to affect indoor microclimate stability, but also the almost 220~~18~~ m^2 of stained glass windows, and more specifically their connection to the masonries. Indeed, due to the deterioration of the stone making up the structural frame of the glass panes, constant infiltrative heat and moisture was observed at the windows edges. Also this issue was observed during restoration works in 1964 (Fig. 1-2 in Supplementary Data)

[1] Recently the two centralised boilers present during the monitoring campaign were replaced. Nevertheless, the distribution system and terminals were not changed.

Next to the infiltrative losses via the windows, also the five building towers (especially the ones directly connected to the exhibition hall), are responsible for continuous heat loss towards outside, making the microclimate in the exhibition hall unstable and strongly dependent on the outdoor climate circumstances.

2.2 ~~4.1~~ Indoor Microclimate monitoring ~~setup~~

The environmental parameters continuously monitored in the exhibition hall and considered in the microclimate analysis are given in Table 2.2~~4.1~~.1. The measurement protocol, especially with regard to the sensors location, was developed on basis of findings from a preparatory short term monitoring performed in the summer 2013 [28].

Position code	Physical Parameter	Logger	Accuracy (of absolute reading)	Time resolution (sampling interval in min)
0.1.2-0.1.4-0.1.5	Dry bulb temperature (°C)	Hobo U12	(±0.35)	15
0.1.2-0.1.4-0.1.5	Dew temperature (°C)	Hobo U12	(± 2.5%)	15
0.1.2-0.1.4-0.1.5	Relative Humidity (%)	Hobo U12	(± 2.5%)	15
0.1.2-0.1.4-0.1.5	Light Intensity (lux)	Hobo U12	(± 2.5%)	15
0.1.2	CO2 (ppm)	Vaisala GM70	(± 2%)	15
0.1.2	Air Velocity (m/s)	MM 0038 Innova	(0.05α+0.05) **	120

** with air velocity <1m/s and 0.25α with air velocity up to 10m/s

Table 2.2.1~~4.1.1~~; Parameters continuously monitored in the exhibition hall

External environmental parameters, utilized for the microclimate analysis, were taken from the weather data station in Antwerp-Deurne (6km distant from the building), these are: dry bulb temperature (°C), dew point temperature (°C), relative humidity (%), global horizontal solar radiation (W/m^2), wind speed (m/s), wind direction (°E of N), atmospheric pressure (Pa), cloud covering (fraction).
The sensors for the indoor measurement, were installed in the exhibition hall 1.30 m above the floor. Their location as well as the location of air heating unit and humidifiers is plot in Fig. 2.2.1~~4.1.2~~. The distance between sensor 014 (entrance) and 012 (centre of the 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.

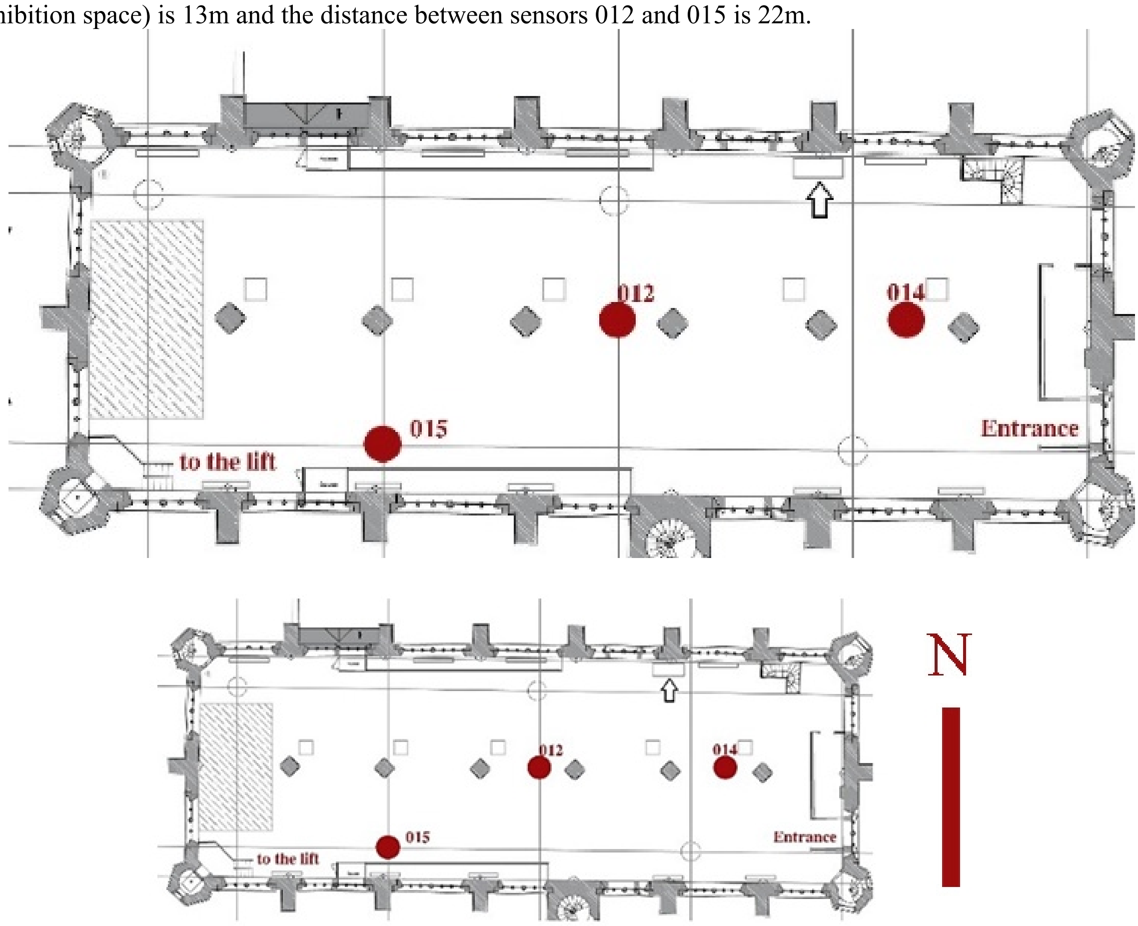

Figure 2.2.1~~4.1.2~~; Localization of sensors in the exhibition hall (red circles) air heating unit (black arrow) humidifiers (squares); the humidifiers distance from the sensor was always >2m

2.3 ~~4.2~~ Infrared Thermography (IRT)

In the North-East~~West~~ corner of the building the existing tower is not directly connected to the exhibition space, see Fig. 2.3.1~~4.2.1~~, this allowed to measure the outer masonry surface temperature distribution towards a heated and unheated space: respectively exhibition hall and tower.
The indoor-outdoor thermal imaging performed in accordance to the EN 13187 [29] and [9], allowed to localize the infiltrative water in the masonries as well as to identify the origin of the infiltrations. The latter was possible by combining Infra-Red Thermography (IRT) with analysis of building photographic documentation related to past restoration works. Namely by superimposing the IRT thermograms with the archive pictures and technical drawings of previous ~~passed~~ restoration works. The position of the thermogram discussed in section 3~~5~~.2 is reported in Fig. 2~~4~~.3~~2~~.1.

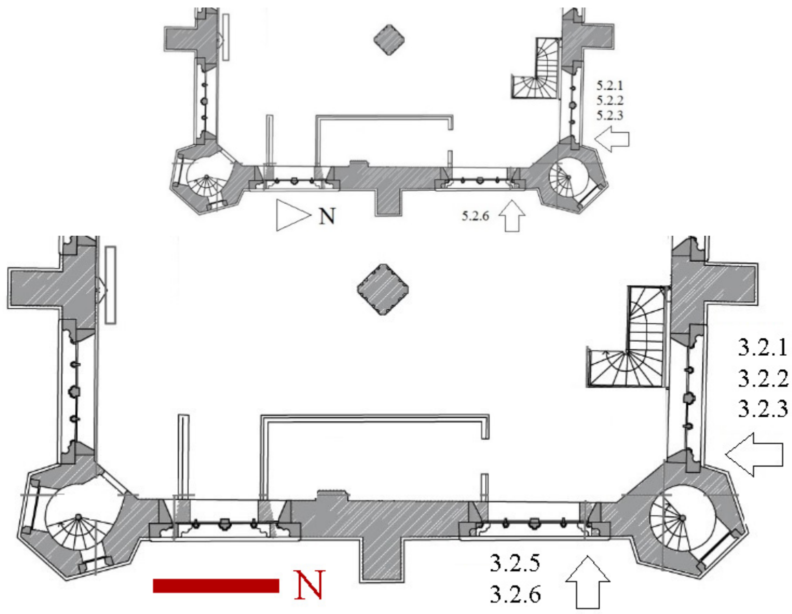

Figure 42.3.1~~2.1~~; North-East~~West~~ façade with tower; indication of IRT thermograms discussed in section 3~~5~~.2

~~4.3~~2.4 Indoor Microclimate data analysis

Based on the monitored parameters given in Table 2.2.1~~4.1.1~~, mixing ratio (g/kg) and water vapour pressure (hPa) were calculated every 15 minutes and hourly averaged; see Eq. 1 to 4 from [30] in the Appendix.
The ratio between mass of water vapour and dry air (mixing ratio, MR) allowed to analyse the air mass interactions between the indoor and outdoor environment. Indeed, because MR is invariable to both isobaric and non-isobaric and adiabatic and non-adiabatic processes (because of its independency from pressure, volume and temperature), its analysis allowed to understand the hygrothermal dynamics in the monitored exhibition space. In the article, MR is also termed ~~called~~, for simplicity, water vapour concentration and is calculated according to Eq. 4 in Appendix. ~~.~~
Inside-outside temperature, mixing ratio and relative humidity were analysed throughout the entire monitored period under conditions a) and b) reported below. Namely when the indoor air temperature and vapour pressure were higher or lower than the ones outside. For the sake of simplicity the conditions a) and b) are termed overheating and overcooling (see Eq. 1 and 2). The mentioned conditions were defined in order to better assess the exhibition hall hygrothermal patterns in case of outwards (condition a) or inwards (condition b) heat and moisture transport. According to these scenarios –meant at dichotomizing the physics of the heat and moisture transport- it were analysed the microclimate dynamics also by means of statistical tests.

Condition A: *overheating*
(heat-moisture flows towards outside)

$$\begin{cases} T_{(in)} > T_{(out)} \\ Vp_{(in)} > Vp_{(out)} \end{cases} \quad (1)$$

Condition B: *overcooling*
(heat-moisture flows towards inside)

$$\begin{cases} T_{(in)} < T_{(out)} \\ Vp_{(in)} < Vp_{(out)} \end{cases} \quad (2)$$

The possible hygrothermal instability sources present in the exhibition hall were: portable humidifiers, visitors and staff, ventilation through the entrance door, ventilation due to the air heating unit, infiltration through the envelope and moisture evaporation from the building masonries. The influence of each one of the mentioned hygrothermal disturbance was tested by combining data analysis and tests statistics. The statistical tools considered in this study are explained below.

1) *Test of mean independency (t-test).* In this study, we resorted to t-tests for observing the variation between microclimate circumstances. Indeed, bBy analysing the extent of a possible non random variation it was possible to assess the influence of e.g., people presence, doors and air-heating unit operation, air infiltration etc. on the indoor microclimate variability.
   The *t-test*, allows verifying casual inference by looking at the mean difference between statistical populations. In this study, we used this test with only one independent continuous variable per time, manipulated in two ways, and only one predicted variable per time (also continuous). The *t-test* allows analysing the influence of the manipulation of a predictor on a predicted value. In other words the test works as a regression model that predicts the outcome on basis of a group membership. If the membership to a group plays a role in varying the outcome, this will result in a significant (non-random) variation of the predicted mean.
2) *Partial correlation*. This correlation model allows observing the relationship between two variables when the effect of a third variable is held constant. The partial correlation was used in the study for looking at the relation between air water vapour concentration and air temperature by taking into account influence of the air velocity.
3) *Multiple regression model.* AThis regression model was developed for quantifying the relation of each significant environmental parameter on the variation of the exhibition hall vapour contentmixing ratio (MR). The regression model was developed on basis of indoor and outdoor parameters found to be significant both during microclimate assessment and model development. The model was developed on the least square method, and the improvement consequent on each parameter addition was evaluated by means of explained variance (R^2) and explained variance in function of the model degrees of freedom (F-test).

The effect of each heat and/or moisture source on the microclimate stability of the exhibition hall was assessed according to the methodology given below.

2.4.14.3.1 Influence of portable humidifiers

The use of portable humidifiers in the exhibition space, though continuous throughout the year, was erratic. The humidifiers were observed often defected, moved or not in use. However, during onsite inspections it was generally observed that 4 humidifiers were in use. The maximum water vapour entered in the exhibition hall by the four machines (hypotized at their maximum power) was calculated. This simplified- scenario allowed to understand the maximum influence of the humidifiers on the exhibition hall water vapour enrichment.

2.4.24.3.2 Influence of visitors and staff

The influence of visitors and staff on the possible air volume vapour enrichment, was tested by means of independent *t-test* and by analysing the hygrothermal parameters distribution throughout the monitored period.
The test was developed in two hierarchical steps: test 1 and test 2 for both cold (months 11-12-1-2) and warm (months 6-7-9) periods.
Test 1, aimed at verifying the mixing ratio mean variation between non visiting and visiting days, excluding the highly frequented concerts events (100 people on average). In case of negativity of the first test, in other words in case the mean vapour concentration during museum visiting days was found to be not significantly different from the one during closing museum days, a second test (test 2) was performed. The second test aimed at verifying the same as the first but including the concerts events, see Table 2.4.2.14.3.2.1.The second test allowed verifying whether the variation of water vapour concentration tent was insignificant also in case of short intervals with high occupation rate.

Independent t-test	continuous variable (in the model)	dummy variable (in the model)		Time interval
Test 1	Mixing Ratio_012	closing hours	visiting hours	1pm to 11pm
Test 2	Mixing Ratio_012	closing hours	visiting + concert hours	1pm to 11pm

Table 2.4.2.14.3.2.1 Independent t-Test conditions for test 1 and 2

The museum can be visited from Thursday to Sunday from 10am to 5pm; on other days the exhibition space is closed to the public. However, since in the cold period, the contribution of visitors in terms of vapour concentration enrichment was observed with a time lag in comparison with the visiting hours (see Fig.35.1.2.2), the *t- tests* were

performed considering the time interval 1pm to 11pm. This allowed taking into account the enrichment and successive dilution of vapour concentration during and after the visiting time.
From the hourly mixing ratio vapour concentration calculated on basis of the monitored indoor environmental parameters and considering a per capita water vapour production of 50g/h [31], the average vapour load produced by people during museum visits was calculated. . Further, the results were compared to the museum administration data. It is worth mentioning that 50g/h vapour production refers to people involved in activities with low metabolic rate such as attending a religious ceremony. We assume this (low) metabolic activity is not different from visiting a museum or listening to a classic concert.

2.44.3.3 Influence of ventilation due to the operating of the entrance sliding door

The ventilation rate produced by the entrance door or windows opening is supposed to be invariable throughout the year, this because the openings are not differently operated during the seasons for obvious safety reasons.
For understanding the effect of the entrance door opening on the indoor air movement, an independent *t-test* was done. The modelled dummy conditions were: museum closed and opened within the time interval 10am-5pm (museum opening hours), hence when the door is operated. The test was performed for cold and warm periods considering as continuous variable the indoor air velocity (m/s) measured in point 012 (centre of the space).

2.4.44.3.4 Influence of air infiltration and air heating unit

Even if the ventilation stays invariable between opening and closing days throughout the whole year, the infiltration rate may change with consequent influence on the air velocity inside the exhibition space and therefore on the vapour concentration.
Wallace E. et. al, in [32] observed that air infiltration rate is temperature gradient dependant and it increases in proportion of 0.0156(ach) per 1°C of temperature difference increase (indoor-outdoor).
Due to the big volume of the exhibition hall (≈5300 m^3), it was not possible to perform a blower door test. However, the influence of the air infiltration on the indoor microclimate was quantified by analysing the indoor air velocity. This approach, allowed obtaining continuous information on the air infiltration/exfiltration influence on the indoor hygrothermal conditions and at verifying the relation between air infiltration and temperature gradient. The indoor air velocity sensor was placed away from direct sources of ventilation in order to measure the whole air buoyancy of the space and to continuously detect indoor –outdoor air mass exchanges.
Due to the presence of the air-heating unit, temperature gradient and air velocity increase were unavoidably correlated. For this reason it was necessary to isolate the effect of temperature gradient increase given by the unit. Therefore, for the *t-t test* it were considered only the nocturnal hours (<10am, >5pm). In these hours, the air unit was not in use, people were absent and radiators set point temperature (during cold period) was at the lowest temperature causing negligible convective air motion. In this way, the sole influence on the indoor air velocity was attributable to the air infiltration-exfiltration (with consequent buoyancy) via windows or doors.

2.4.54.3.5 Influence of moisture in the masonries

Together with indoor environmental monitoring, an Infrared Thermography (IRT) was performed indoor and outdoor the building masonries in order to localize thermal heterogeneities caused by infiltrative water possibly influencing the exhibition hall microclimate. This analysis combined with the study of the documentation from previous restoration works allowed to identify the sources of water infiltration.

5.3. Results discussion

3.1 5.1 Microclimate diagnosis results

In this section we discuss the results from both microclimate analysis and identification of water sources in the building masonries. It is worth mentioning that the microclimate analysis results are not discussed separately - from a physical and a statistical point of view- but rather on the basis of a global understanding as allowed by the integration of the two disciplines.
The indoor building microclimate was observed to be significantly dependent on the outdoor climatic conditions for the entire monitoring period. Figures 35.1.1 and 35.1.2 plot the monthly mean outdoor and indoor temperature in overheating or overcooling conditions (see Eq. 1 and 2). The overheating occurred in all the months while overcooling occurred mainly during the warm period (June-July and September) and exceptionally at the beginning of the heating season (October and November) due to the failure of the heating system (for a total of 56 hours).

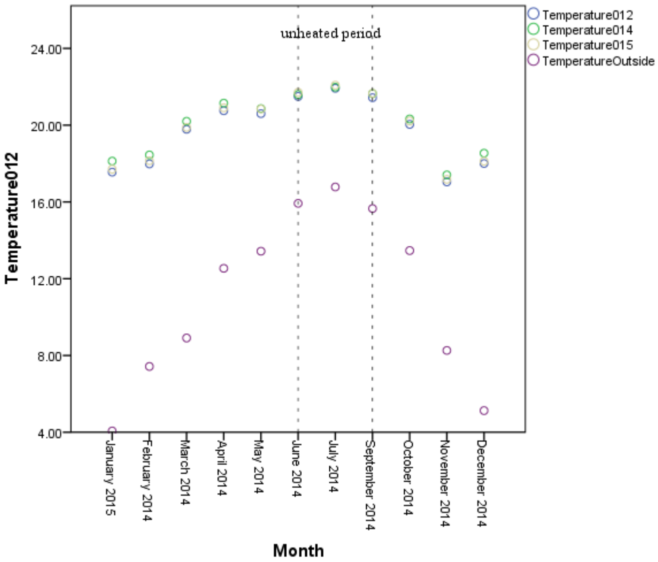

Figure 3.1.1~~5.1.1~~. Indoor temperature point 012,014,015; overheating

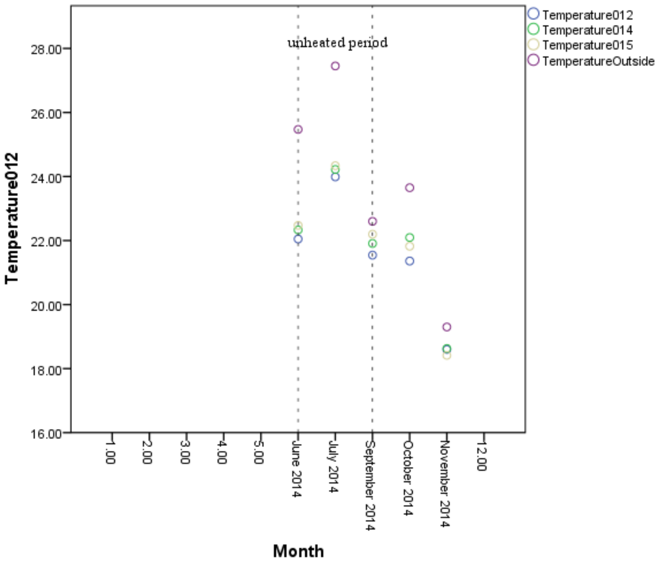

Figure 3.1.2~~5.1.2~~ Indoor temperature point 012,014,015; overcooling (the numerical terms on the x axis refer to the months not interested by overcooling)

A noteworthy cooling circumstance was registered during the warm period. Indeed, in June and July (no data for August are available), the indoor temperature was measured up to 3.5°C lower than outside. As mentioned, the building is not equipped with cooling system, hence the observed overcooling was generated by the building passive cooling. The air temperature and relative humidity trends for each measurement point with regard to the entire monitored period are shown in Fig. 3.1.3 and 3.1.4 respectively.

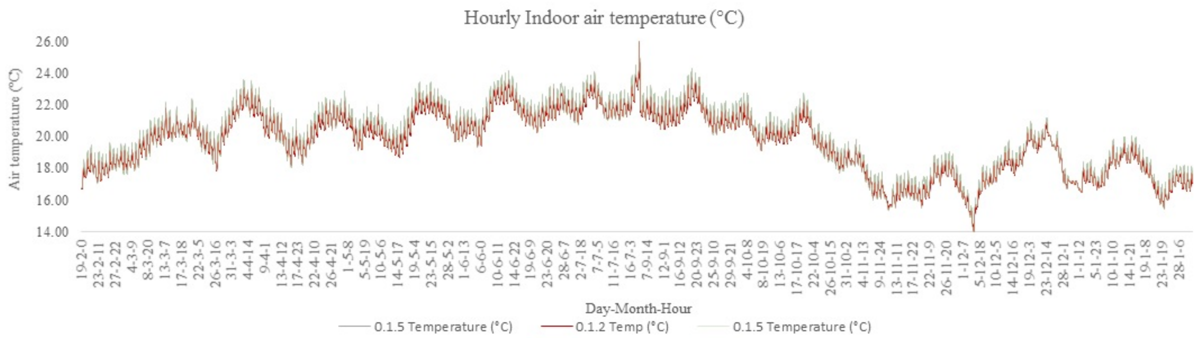

Figure 3.1.3 Indoor temperature (°C) points 012-014-015 for the entire monitored period

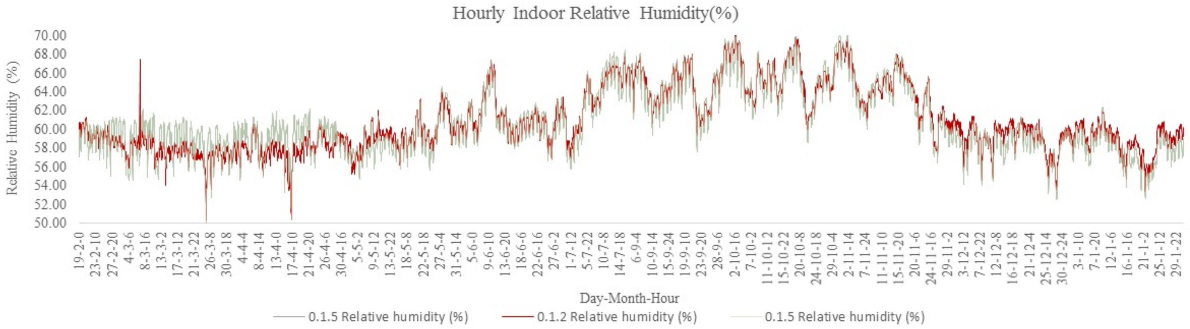

Figure 3.1.4 Indoor relative humidity (%) points 012-014-015 for the entire monitored period

In order to observe a first relationship between indoor and outdoor microclimate, the correlation between hygrothermal parameters was analysed. The correlation coefficients, of the indoor-outdoor parameters relation, are given in Tables from 3~~5~~.1.1 to 3~~5~~.1.3 respectively for cold period (overheating), warm period (overheating) and warm period (overcooling). As the mentioned correlations aimed at obtaining a global understanding of the indoor-outdoor hygrothermal relation, no distinction between museum opening or closing days is made. However, a detailed evaluation of the indoor-outdoor microclimate relationships –considering the different building use scenarios- is discussed in section 3~~5~~.1.4.

The Pearson correlation coefficients in Table 3~~5~~.1.1, illustrate the typical indoor-outdoor hygrothermal relations during cold period, while Table 3~~5~~.1.2 and 3~~5~~.1.3, plot the same relationships during warm period respectively for the case of overheating and overcooling of the exhibition space.

During the cold period, a poor correlation between outdoor and indoor temperature can be observed. This relationship is 0.365 in point 012 and it is never higher than 0.380 (point 015). The correlation, reasonably, rises during the warm period especially when the indoor temperature is lower than outside (no cooling system is present in the building). Reasonably, the weaker relation between indoor and outdoor temperature during the cold period –compared to the warm one- is attributable to the heating system effect.

Correlations (Pearson)	**Months 11-12-01-02_condition a**					
	TEMP 012	TEMP Out.	RH 012	RH Out.	MR 012	MR Out.
Temperature 012	1.000	0.365	-0.212	-0.280	0.786	0.267
Temperature Outside	0.365	1.000	0.556	-0.321	0.685	0.915
Relative Humidity012	-0.212	0.556	1.000	0.166	0.423	0.653
Relative Humidity Outside	-0.280	-0.321	0.166	1.000	-0.156	0.062
Mixing Ratio 012	0.786	0.685	0.423	-0.156	1.000	0.659
Mixing Ratio Outside	0.267	0.915	0.653	0.062	0.659	1.000

Table 3~~5~~.1.1; Pearson correlation of Temperature (TEMP), Relative Humidity (RH) and Mixing Ratio (MR) between point 012 and outside; Sig 0.01; months 11-12-1-2; overheating

Correlations (Pearson)	**Months 06-07-09_condition a**					
	TEMP 012	TEMP Out.	RH 012	RH Out.	MR 012	MR Out.
Temperature 012	1	0.592	0.093	-0.306	0.76	0.309
Temperature Outside	0.592	1	0.018	-0.717	0.426	0.239
Relative Humidity 012	0.093	0.018	1	0.511	0.711	0.723
Relative Humidity	-0.306	-0.717	0.511	1	0.125	0.497
Mixing Ratio 012	0.76	0.426	0.711	0.125	1	0.697
Mixing Ratio Outside	0.309	0.239	0.723	0.497	0.697	1

Table 3~~5~~.1.2; Pearson correlation of Temperature (TEMP), Relative Humidity (RH) and Mixing Ratio (MR) between point 012 and outside; Sig 0.01; months 06-07-09; overheating

Correlations (Pearson)	**Months 06-07-09_condition b**					
	TEMP 012	TEMP Out.	RH 012	RH Out.	MR 012	MR Out.
Temperature 012	1	0.735	0.372	-0.425	0.97	0.702
Temperature Outside	0.735	1	-0.147	-0.835	0.604	0.584
Relative Humidity 012	0.372	-0.147	1	0.415	0.581	0.334
Relative Humidity Outside	-0.425	-0.835	0.415	1	-0.258	-0.045
Mixing Ratio 012	0.97	0.604	0.581	-0.258	1	0.708
Mixing Ratio Outside	0.702	0.584	0.334	-0.045	0.708	1

Table 3~~5~~.1.3; Pearson correlation of Temperature (TEMP), Relative Humidity (RH) and Mixing Ratio (MR) between point 012 and outside; Sig 0.01; months 06-07-09; overcooling

The mentioned effect, especially during the cold period, can be additionally identified by the inverse correlation between indoor temperature and relative humidity (Pearson -0.212); similar negative correlation is calculated for the other points, maximum -0.261 (014). However, the reduction of relative humidity does not stand for water vapour reduction. Indeed the correlation between indoor mixing ratio and temperature explains rather the contrary (Pearson 0.786). This aspect, will be better discussed in section 35.1.4.
The RH decreases because the saturation vapour pressure increases as a consequence of the temperature increase. The positive and significant correlation between indoor mixing ratio and temperature, and to a lesser extent the positive correlation between indoor relative humidity and mixing ratio (Pearson 0.423) explains that the temperature triggers some addition of vapour to the air volume. This is visible in Figure 35.1.53 in which the hourly variation of temperature and mixing ratio is plotted for the cold period. Similar results were observed in [9].

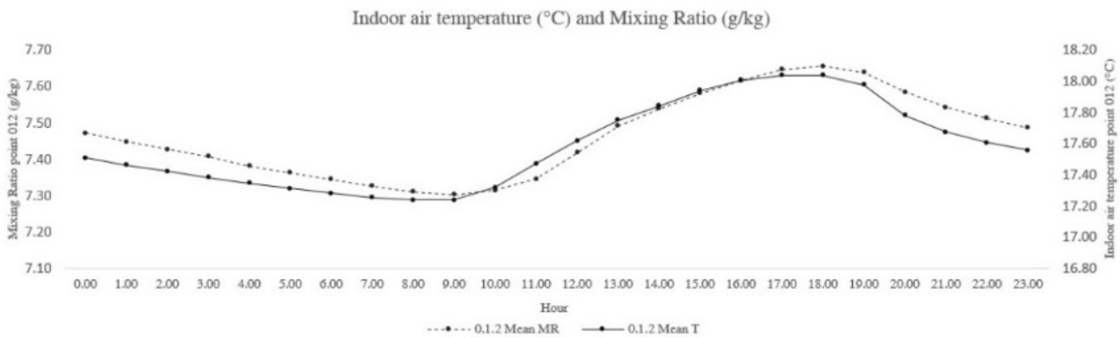

Fig. 35.1.53. Point 012, Temperature (°C) and Mixing Ratio (g/kg) hourly average over the months: February, November, and December 2014-January 2015; R 0.786

The water vapour enrichment caused by the temperature increase might be explained either by the process of evaporation of the masonries towards inside or by other sources of vapour addition combined with temperature increase, such as people, humidifiers, etc. Both the aspects will be detailed later on in the text.
During warm period (months 6-7-9), when temperature indoor is higher than outdoor (Table. 35.1.2), indoor mixing ratio correlates positively with indoor temperature (Pearson 0.76 in point 012), however this correlation is slightly lower than the cold period. This reduction can be explained by a smaller temperature gradient: Δ_T is 17.44°C and 9.80°C in cold and warm period respectively in condition a) at the 95th percentile.
It may be supposed that also during the warm period, part of the residual vapour from the moist masonries evaporates inside. When the indoor air temperature is higher than outside, condition a (Table 35.1.2), the correlation between indoor temperature and RH is zero for the above mentioned reasons (Pearson 0.09). However, when the temperature is lower inside than outsidedrops, condition b (Table 35.1.3), the RH unavoidably increases (Person 0.372).
FAs from thermal imaging on the walls, it was not evidenced risk of surface condensation during the year. This because the walls surface temperature was higher than the air dew point temperature; because of this, , the presence of moisture evaporating inwards might be caused by the natural drying of the masonry core after the moisture accumulation in winter. During the warm period when the indoor temperature is lower inside than outside (Table 35.1.3), the correlation between indoor temperature and mixing ratio rises up to 0.97. As mentioned, iIn this case, as since the temperature is lower and so is the saturation vapour pressure,, the correlation between indoor RH and temperature is positive and significant in all the points.; IIt is 0.372 in point 012 and it increases up to 0.582 in point 015.

35.1.1 Influence of humidifiers

The analysis related to the influence of humidifiers on the exhibition hall microclimate, was limited to the quantification of the maximum water vapour entered in the air volume if four humidifiers would be used continuously at the maximum power. The air recirculation rate at the given power, according to the manufacturer, is 750m^3/h, with a humidifying capacity of 2.7l/h (45% and 23°C, RH and T) and maximum room volume (per machine) of 900m^3, hence a volume coverage of 68%. With an approximation about the steadiness of the air temperature and, considering isenthalpic the air humidification from the water-based humidifiers (usually, water-based humidifiers work with isenthalpic transformation), it was estimated that the maximum moisture amount entered in the air volume per hour from the 4 humidifiers was 2.01g/kg (68% of 2.96g/kg).
Although the calculated vapour enrichment given by the humidifiers is an approximation, if looking at the high vapour concentration during the warm period (max 10.41g/kg), it might be concluded that the humidifiers use can be limited or avoided in order to keep constant vapour concentration throughout the yearseasons.

35.1.2 Influence of visitors and staff

For testing the influence of people on the indoor vapour concentration variation, a test of mean independency was run considering both museum visiting and closing days within the time interval 1-11pm23pm, during both cold and warm periods. The tested continuous variable was MR. The obtained results indicated that the presence of people, constantly contributed to the air vapour increase. This increase consistently rose with the museum visiting rate.

In the cold period, the hourly mixing ratio and also CO_2 concentration and indoor temperature during opening days were higher than during closing days only from 1pm. In the warm period, the mixing ratio during visiting days was constantly above the one of closing days. In order to compare the mean mixing ratio variation within the same time interval, the tests were run considering the time interval 1-11pm.

During the cold period and in the considered time interval (1-11pm), the mean mixing ratio was 7.52g/kg (SE 0.03) and 7.61g/kg (SE 0.02) respectively for closing and visiting days, without concert events (test 1). The difference was -0.093 g/kg (CI =-0.166, -0.021), and it was significant t(994)= -2.524, p= 0.012 (Table 35.1.2.1 and Table 35.1.2.2). The test significance (t) was calculated considering the weighted variance (pooled variance) from the two differently sized data population. Table 35.1.2.2 reports the unweighted variance, therefore the t-values (compared to the one discussed in the text) might differ by a few decimals.

Mean hourly Mixing Ratio 012 Statistics	N	Mean	Std. Deviation	Std. Error Mean	Period (months)	Interval (hours)
museum close	473	7.522	0.618	0.028	11-12-1-2	1-11pm
museum open (visiting)	627	7.615	0.594	0.024	11-12-1-2	1-11pm
museum open (visiting +concert)	649	7.609	0.586	0.023	11-12-1-2	1-11pm
museum close	341	10.061	0.638	0.035	6-7-9	1-11pm
museum open (visiting)	451	10.311	0.791	0.037	6-7-9	1-11pm
museum open (visiting +concert)	462	10.295	0.788	0.037	6-7-9	1-11pm

Table 35.1.2.1; Mixing Ratio point 012; cold period (months 11-12-1-2) and warm period (months 6-7-9); time interval 1-11pm

Although Test 1 as described in section 2.44.3.2 is verified, it is interesting discussing the results also from Test 2. Indeed, it can be observed that after including in the statistic population the opening hours related to the concerts (in addition to the ones of museum visits), the mean mixing ratio slightly decreased (Table 35.1.2.1). This occurred because of the low initial vapour concentration in the hours prior to the concerts. Figure 35.1.2.1, clearly shows this circumstance with regard to the last week of October 2014.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Low	Up
MR 012 (test 1) months 11-12-1-2	Equality of Variance assumed	3.21	0.07	-2.54	1098	0.01	-0.09	0.04	-0.17	-0.02
				-2.52	994	0.01	-0.09	0.04	-0.17	-0.02
MR 012 (test 1) months 6-7-9	Equality of Variance assumed	7.56	0.01	-4.78	790	0.00	-0.25	0.05	-0.35	-0.15
				-4.92	786	0.00	-0.25	0.05	-0.35	-0.15

Table 35.1.2.2; Independent t-test for equality of the mean (mixing ratio); Test 1, readings without concert events (1-11pm)

The concerts are performed once per month during the last of the three museum closing days, on Wednesday. In Figure 35.1.2.1, it is visible that immediately before the concert on 29 October the 29th, the exhibition space has low mixing ratio (8.36g/kg), this happened because no vapour was accumulated during the previous two closing days. Successively, during the concert hours, the mixing ratio increased up to 9.15g/kg. The air mass was enriched by 5kg of water vapour in less than three hours (the number of people participating to the event was on average 100). After the concert, the vapour started being diluted. Nevertheless, before the entrance of visitors during the successive day (15 hours later) the indoor vapour concentration (read Mixing Ratio) was still 0.19g/kg higher than the one previous to the concert. In other words, still 1.22kg of water vapour emitted from concert attenders was not expelled.

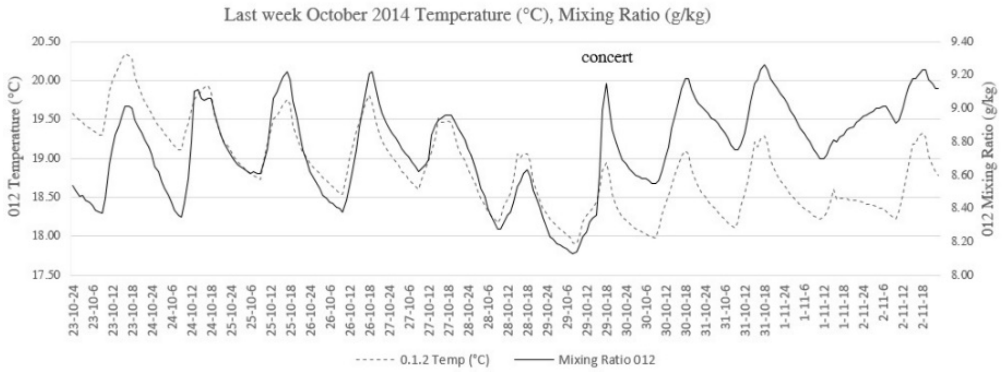

Fig. 35.1.2.1. Indoor air temperature (°C) and mixing ratio (g/kg) monitored from point 012; last week of October 2014.

The mean hourly mixing ratio and temperature in the exhibition space during the cold period, both in case of museum visiting and closing days (excluding concerts) are plotted in Figure 35.1.2.2. Although negligible, the mean air temperature during closing days is ≈0.10°C higher than the one during opening days (see Table 35.1.2.3). It should be noted that the data plotted in Table 35.1.2.3, refer to opening and closing days, without distinction between nocturnal and diurnal hours. A more detailed analysis on the nocturnal hours, hence without the influence of people and heating air unit, is discussed in section 35.1.4.

	Temperature (°C)			Mixing Ratio (g/kg)			CO2 (ppm)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
opening days (cold period)	≈17.20 9am	≈18.10 6pm	≈17.50	≈7.30 10am	≈7.70 6pm	≈7.50	≈510 10am	≈630 6pm	≈560
closing days (cold period)	≈17.30 9am	≈18.00 5pm	≈17.60	≈7.30 10am	≈7.60 5pm	≈7.45	≈495 9am	≈540 4pm	≈520
opening days (warm period)	≈21.20 6am	≈22.40 3pm	≈21.70	≈9.80 5am	≈10.40 5pm	≈10.10	≈540 10am	≈715 17pm	≈600
closing days (warm period)	≈21.10 6am	≈22.10 4pm	≈21.50	≈9.70 7am	≈10.10 5pm	≈9.90	≈500 9am	≈600 2pm	≈550

Table 35.1.2.3; Cold period (months 11-12-1-2) and Warm period (months 6-7-9); Indoor temperature, Mixing Ratio and CO_2 summary statistics for museum opening and closing days

Because of the strong relation between air temperature and mixing ratio already discussed in section 35.1, the slightly higher temperature during the closing days (compared to the opening ones) results also in a higher mixing ratio. However, during the opening days, people presence results in a faster relative increase of temperature, mixing ratio and CO_2 between 10am and 5pm. Meaning that, for long part of the day, is the rate of hygrothermal variations that attests the influence of visitors rather than the absolute value of the hygrothermal parameters. If observing the parameters hourly maximum variation, meaning the maximum parameter difference in the given time interval, it can be observed that:

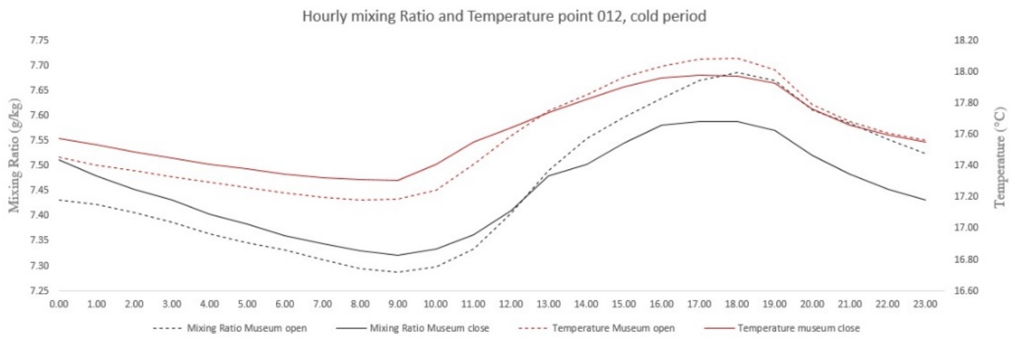

Fig. 3~~5~~.1.2.2. Mean hourly indoor mixing ratio and temperature during closing and opening hours of the museum (opening 10am-5pm); cold period (February, November, December 2014 and January 2015); point 012

- during the museum closing days, the indoor air temperature maximum variation was ≈0.60°C between 9am and 5pm, while it was ≈0.90°C between 9am and 6pm during museum opening days;
- during museum closing days, the mixing ratio maximum variation was ≈0.30g/kg between 10am and 5pm, while it was ≈0.40g/kg between 10am and 6pm during museum opening days.
- During the museum closing days, the CO_2 maximum variation was ≈47 ppm between 9am and 4pm, while it was ≈122 ppm between 10am and 6pm during museum opening days.

Clearly, from the moment the museum is open (10am), a significant increase of temperature, vapour concentration and CO_2 is registered in comparison with the closing days. But the readings of each parameter are higher than the ones registered during the closing days only from 1pm; see Figure 3~~5~~.1.2.2. The extra vapour produced by people is diluted between 6pm and 8pm. After this period, the residual vapour concentration decreases similarly (with the same slope) as the closing days.
Considering the time interval from 1pm to 6pm (before vapour dilution), the daily extra water vapour added by people to the exhibition hall air mass is ≈0.34g/kg or 2.20kg. If considering a vapour production of 50g per hours per person (see [33]), in the exhibition space during the cold period, there were on average 8people/hour.
During the warm period, again results from the independent *t-test*, confirmed, that people presence influenced the mean vapour concentration variation in the exhibition space. The mean mixing ratio was 10.06g/kg (SE 0.05) and 10.31g/kg (SE 0.05) respectively for closing and opening days, without concert events (test 1) and during the time interval 1-11pm, see Table 3~~5~~.1.2.1. The mean difference was -0.250 g/kg (CI =-0.35, -0.15), significant t(786) = -4.922, p= 2E-05, see Table 3~~5~~.1.2.2.

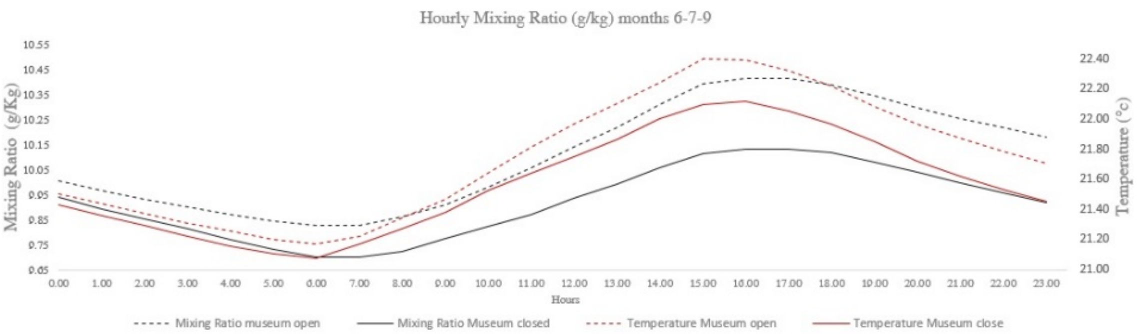

Fig. 3~~5~~.1.2.3. Mean hourly indoor mixing ratio and temperature during closing and opening hours of the museum (open from 10am to 5pm); cold period (June, July, September 2014); point 012

In Figure 3~~5~~.1.2.3, is reported the hourly mixing ratio and temperature of museum opening (dotted black and red lines) and closing (continuous black and red lines) days during the warm period. Differently from the cold period, the indoor mixing ratio during the opening hours was always higher than the closing hours, but similarly to the cold period the relative increase of temperature, mixing ratio and CO_2 was faster and more significant in presence of people as reported below. If observing the parameters hourly maximum variation, meaning the maximum parameter difference in the given time interval, it can be observed that:

- during the museum closing days, the indoor air temperature maximum variation was ≈1.00°C between 6am and 4pm, while it was ≈1.20°C between 6am and 3pm during museum opening days.
- During the museum closing days, the mixing ratio maximum variation was ≈0.40g/kg between 7am and 5pm, while it was ≈0.60g/kg between 7am and 5pm during museum opening days.
- During the museum closing days, the CO_2 maximum variation was ≈100 ppm between 9am and 2pm, while it was ≈178ppm between 10am and 5pm during museum opening days.

If considering the entire visiting time interval 10am-5pm (before vapour dilution), the added water vapour from visitors during an average visiting day in summer was ≈8.60kg (or 1.87g/kg); resulting in an average of 170 people per day or 30 person/hour. The occupation rates for the cold and warm period, calculated on basis of the measured ~~moisture~~ vapour concentration, were in agreement with the ones provided by the museum administration.

3~~5~~.1.3 Influence of ventilation due to the operating of the entrance sliding door

As described in section 42.4.~~3.~~3, the influence on the vapour concentration produced by air ventilation was assessed by observing the relation between: indoor and outdoor air velocity, air temperature, relative humidity and mixing ratio during museum opening and closing hours. Further, a test of mean independency of the indoor air velocity for museum opening and closing days during both cold and warm periods was performed. The considered time interval was 10am-5pm (museum opening hours, namely when the door is operated). According to this time interval, museum opening and closing days during the cold and warm periods were analysed.
For the cold period, the results from the independent t-test, confirmed, that the opening of the door had no influence on the mean indoor air velocity variation. The mean air velocity was 0.063m/s (SE 0.006) and 0.058 (SE 0.005) respectively for closing and opening days, without concert events and during the time interval 10am-5pm, see Table 3~~5~~.1.3.1. The mean difference was 0.005 m/s (CI =-0.012, 0.021), not significant t(79)= 0.56, p= 0.577; see Table 3~~5~~.1.3.2. Similar results were obtained also with regard to the warm period. The door opening was not significant for the mean air velocity variation. The mean air velocity was 0.054m/s (SE 0.005) and 0.058 (SE 0.004) respectively for closing and opening days, without concert events and during the time interval 10am-5pm, see Table 3~~5~~.1.3.1. The mean difference was -0.004 m/s (CI =-0.016, 0.007), not significant t(99)= -0.748, p= 0.456; see Table 3~~5~~.1.3.2.

Mean hourly Air velocity 012 Statistics

	N	Mean	Std. Deviation	Std. Error Mean	Period (months)	Interval (hours)
museum close	30	0.063	0.034	0.006	11-12-1-2	10am-5pm
museum open (visiting)	51	0.055	0.037	0.005	11-12-1-2	10am-5pm
museum close	41	0.054	0.030	0.005	6-7-9	10am-5pm
museum open (visiting)	60	0.058	0.029	0.004	6-7-9	10am-5pm

Table 3~~5~~.1.3.1; Air velocity point 012; cold period (months 11-12-1-2) and warm period (6-7-9)

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Low	Up
Air velocity 012 months (11-12-1-2)	Equality of Variance assumed	0.24	0.63	0.56	79	0.58	0.00	0.01	-0.01	0.02
				0.57	64	0.57	0.00	0.01	-0.01	0.02
Air velocity 012 months (6-7-9)	Equality of Variance assumed	0.15	0.70	-0.75	99	0.46	0.00	0.01	-0.02	0.01
				-0.75	84	0.46	0.00	0.01	-0.02	0.01

Table 3~~5~~.1.3.2; Independent t-test for equality of the mean (air velocity); readings without concert events; cold period and warm period, time interval 10am-5pm

The results from the test confirmed that the door opening had no effect on the variation of the indoor air velocity both in the cold and warm period, confirming that the ventilation rate in the exhibition space stays invariant throughout the seasons. This is also confirmed by the invariability of the mean indoor air velocity during the opening days between cold and warm periods, see Table 3~~5~~.1.3.1. It is worth noting that the indoor air velocity during the museum closing days in the cold period in the time interval 10am-5pm, is slightly higher than during the same time interval in the museum opening days~~ (difference of 0.005m/s)~~. This condition ~~is attributable~~might depend either on~~to~~ the increase of the air convection due to the heating system or on~~to~~ the increase of air infiltration or exfiltration; this aspect will be discussed in the next section.

3~~5~~.1.4 Influence of air infiltration and air heating unit

Beside the radiators from the centralized heating system, the exhibition hall has a heating and ventilation air unit (see Figure 2.2.14.1.2 and 2.1.13.1.c). The unit, located in the North-EasWest corner of the building, has no humidity control and the air is blown into the space through two outlets at the top of the unit. The air flow rate at the outlets, measured on March the 4th 2015 (2.30pm) was 3500m^3/h, air velocity was 3.16m/s, air temperature 41.5°C and relative humidity ≈16.4%. In the same moment air temperature and relative humidity in the exhibition space were only slightly heterogeneous: ≈18.70°C and ≈57.50% in point 014 (the closest to the unit), ≈18.30°C and ≈58.0% in point 012, ≈18.70°C and ≈57.0% in point 015. It is worth mentioning that, eEven if the air unit causes a slight alteration of the hygrothermal stability, this does not cause risks for the cultural objects; see [27]. Considering the seasonal time intervals, it can be observed that:

- During the cold period, the nearest sensor to the air unit 014, resulted in a slight higher temperature and lower relative humidity as well as in a slight higher standard deviation in comparison with the other points (see Table 1 in Supplementary Data). This condition describes the air unit in intermittent heating modality.
- During the warm period, the air temperature in point 014 (both in overheating and overcooling) had not substantial variation compared to the other points. This occurred because the air unit does not provide cooling. Indeed, the coolest point of the exhibition room was 012 in the middle of the space; see Table 2 and 3 in Supplementary Data. It should be noted that in all the points the increase of air temperature consequent toof the operating of the lighting system was negligible[2].

From now on, in this section we discuss the results with regard to the evaluation of building air infiltration and its influence on the indoor hygrothermal dynamics, especially with regard to mixing ratio variation.
In a study from L. Wallace [32], after continuous measurement of the building infiltration rate, it was concluded that the latter increases with indoor-outdoor temperature difference increase. Also in our study, it was observed a linear relationship between hourly temperature difference (indoor-outdoor) and indoor air velocity (R 0.80). However because the air heating unit was also responsible of temperature gradient and air velocity increase, it was necessary to remove the readings during its operation in order to avoid false correlation. If considering the readings when air heating and ventilation unit is not activated, in both cold and warm periods it is still possible to observe that indoor building microclimate is affected by air infiltration, and that the infiltration increases when the air temperature gradient indoor-outdoor increases confirming the findings from Wallace in [32]. This can be also observed in Fig. 35.1.4.1 where the hourly values of temperature difference and air velocity are plotted for the entire monitored period, during the nocturnal hours (6pm-9am). Correlation coefficient R 0.68. A more robust correlation may be expected with higher air velocity sampling frequency.

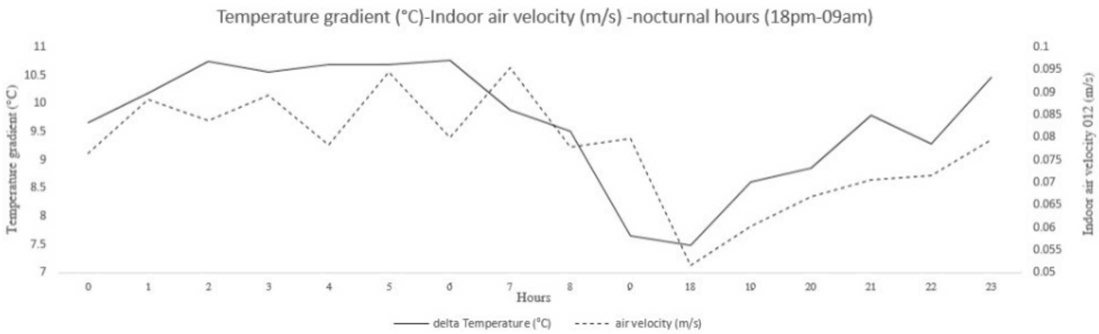

Figure 35.1.4.1; Hourly temperature gradient (°C) and air velocity (m/s) during nocturnal hours (6pm-9am) for the entire year; Pearson correlation coefficient (R) 0.68

In order to evaluate the indoor microclimate variations caused by infiltrative air, the bivariate relationship between air velocity and environmental parameters during the nocturnal time interval (6pm-9am) was quantified; both for cold and warm periods; namely, when the system was not in function; see Table 35.1.4.1. In turn, air temperature, mixing ratio, relative humidity, CO_2 and temperature difference inside-outside were correlated to the indoor air velocity. Although the correlations are statistically significant, not all of them are robust. Though Nevertheless, they allow understanding the indoor-outdoor hygrothermal dynamics. It is worth noting that the effect of the relationship between Δ_T and air velocity causes -in summer and winter- two opposite effects as below discussed.

[2] During the museum opening days in the cold period, the Pearson correlation coefficient between temperature and light intensity was respectively 0.13 in point 014, 0.17 in point 015 and 0.11 in point 012. During the summer period the light intensity had a higher influence on indoor air temperature, especially in points 014 and 015 as more exposed to the windows; the correlation coefficient was respectively 0.20 and 0.22. The R value of point 012, located in a central and always darker position,in dark was 0.07.

In the cold period (months 11-12-1-2), during nocturnal hours when the heating system is on (only radiators), the air infiltrating from outside (read air velocity) produces a lowering of the Δ_T (R -0.22; sig.0.01) meaning that infiltrative air is cooling down the indoor air temperature otherwise heated up by the radiators, see Table 35.1.4.1 (left column). Consistently the correlation between indoor temperature and indoor air velocity is negative (R=-0.22; sig.0.01); see also Table 35.1.4.2. The mentioned indoor temperature reduction is less significant during the cold period in comparison with the warm period because of the unavoidable contribution of the radiators. However, despite the mentioned slight indoor temperature reduction, the mixing ratio in the exhibition space tends to increase. This condition, apparently in contradiction with what observed in Fig. 35.1.53, is a consequence of the combination of a high temperature gradient and increase of indoor air velocity; see later in this section. Reasonably, the relative humidity increases as a consequence of the saturation water pressure decrease (consequent to the temperature reduction).
In the warm period (months 6-7-9), during the same nocturne al hours the infiltrative air rises the ΔT (R 0.33; sig. 0.01) meaning that the infiltrative air is cooling the (already cool) indoor air temperature; see Table 35.1.4.1 (right column). Consistently the air temperature of the exhibition hall decreases with the air velocity increase (R -0.77; sig. 0.01). In other words in both the periods of the year, the indoor temperature lowers with air infiltration. Further, during the warm period, because of the strong indoor temperature diminishing, also the mixing ratio lowers accordingly. What is mentioned occurs without the air unit contribution as it is not in use at night time.

	Air velocity 012 cold period, museum closing days, nocturnal hours (<10am, >5pm)	Air velocity 012 warm period, museum closing days, nocturnal hours (<10am, >5pm)
Temperature 012	-.219**	-.773**
Mixing Ratio 012	.211*	-.412**
Relative Humidity 012	.522**	.268*
CO_2 012	-.319**	-.170
ROOTSQ DT 012	-.225**	.337**

Table 35.1.4.1; Pearson correlation coefficient (R); (**) Correlation is significant at the 0.01 level (2-tailed); (*) Correlation is significant at the 0.05 level (2-tailed); nocturnal hours (<10am, >5pm); museum closing days; condition a) and b)

The different linear relationship between ventilation and mixing ratio among cold and warm period is remarkable. During the night hours in the cold period, the increase of air velocity causes an increase of vapour concentration (R 0.21), however this does not occur during the night hours in the warm period (R -0.41); see Table 35.1.4.1. This condition might be explained by the effect of air velocity on the indoor air temperature, and therefore on the mixing ratio. Indeed, in the cold period, during the nocturnal hours, although the infiltrative air enables a slight indoor temperature reduction, the temperature gradient (inside-outside) is still >23°C. In other words the indoor temperature is still far higher inside than outside, hence part of the moisture in the masonries is likely to still evaporate inwards. On the contrary, during the warm period, the air infiltration causes a substantial temperature drop. The temperature gradient is halved compared to the one during the cold period (see Table 4 in Supplementary Data), as a consequence the inwards masonry evaporation process decreases and accordingly the mixing ratio. The temperature reduction is responsible of the relative humidity increase (R 0.27).
The increase of masonries evaporation rate consequent on the temperature increase (see also [9]) observed both during the cold and warm period (diurnal hours), is evidently caused by the prevalence -within the process of masonries evaporation- of the heat term over the aerodynamic one; as observed by D. D'Agostino in [7]. However, not only the air temperature but also the air velocity boosts both vapour dilution in the exhibition space air volume and masonry evaporation. For better contrasting this phenomena, namely the contribution given by the indoor air velocity to the vapour concentration increase in the different periods of the year, the partial correlation between air temperature and mixing ratio controlled for the air velocity was analysed. The correlation was performed considering the readings from the warm and cold periods, for both museum opening and closing days, for nocturnal and diurnal hours; see Table 35.1.4.2.
In all the circumstances except one, it is possible to observe that air velocity has either no influence (on the relationship indoor temperature- vapour concentrationmixing ratio) or a positive one; this is seen by the invariability of the correlation coefficient or by its reduction in the case of partial correlation. This shows that air velocity, in the specific case, increases the relationship between air temperature and mixing ratio. This boost is clearer during closing hours in the warm months because there is less moisture extraction from the air volume[3] and a larger amount of vapour concentration compared to the cold period.

[3] The air-heating unit is off and the entrance door is closed, the only moisture subtraction is allowed by air infiltration/exfiltration.

	Closing days			
	Cold period		Warm Period	
	Pearson	Partial	Pearson	Partial
diurnal	0.750	0.749	0.622	0.524
nocturnal	0.760	0.845	0.605	0.495
	Opening days			
diurnal	0.730	0.720	0.930	0.930

Table 35.1.4.2; Pearson correlation coefficient and Partial correlation coefficient; all the correlation coefficient reported in the table are significant at 0.01 (2-tailed); nocturnal hours (<10am, >5pm); the correlated parameters are air temperature and mixing ratio, controlled for air velocity.

Only in the cold period during the nocturnal hours, it was observed the increase of correlation coefficient, from the simple correlation (R 0.76) to the partial correlation (R 0.845), meaning that the air velocity in fact tended to reduce the relationship between air temperature and mixing ratio, confirming what was explained above with regard to Table 35.1.4.1 (left column).

Namely, the infiltrative air from outside reduced the indoor air temperature by entering cold air (bearing also less vapour). This circumstance most likely reduced the moisture evaporation from the masonries and the total indoor vapour concentration. As already discussed, the increase of indoor air velocity in the monitored building, occurs when the temperature gradient (indoor-outdoor) is higher, e.g. during the nocturnal hours. This condition is valid for both warm and cold periods, see Figures 35.1.4.2 and 35.1.4.3. The mean air velocity without the influence of the air heating system (museum closing days) is 0.07 m/s and 0.09 m/s during nocturnal hours (6pm-9am) respectively in cold and warm periods and 0.059 m/s and 0.055 m/s during diurnal hours (10am-5pm) respectively in cold and warm period. During the museum opening hours (10am-5pm) the air velocity is almost invariable between cold and warm months as already observed in Table 35.1.3.1, the mean air velocity is respectively 0.056m/s and 0.058m/s[4]. The higher air velocity at night-time, explains the overall higher air velocity during the museum closing hours as reported in Table 35.1.3.1.

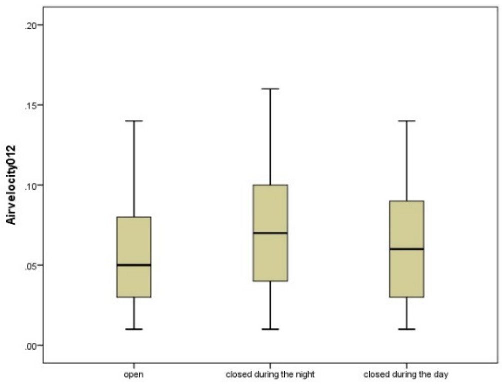

Figure 35.1.4.2; Mean indoor air velocity (012) during the cold period (months 11-12-1-2) for museum opening days-opening hours (10am-5pm), museum closing days- diurnal hours (10am-5pm) and museum closing days- nocturnal hours (6pm-9am)

The increase of the indoor air velocity (caused either by infiltration or operation of the air heating unit), enables the increase of the moisture evaporation from the exhibition hall masonries. A similar circumstance was observed by M. I. Martínez-Garrido et.al. in [11] with regard to outdoor evaporation and D. Camuffo et.al in [33] with regard to indoor masonry evaporation.

Even if higher air velocity occurs at night (see Fig. 35.1.4.2 and 35.1.4.3), the vapour concentration reaches its maximum during the museum opening hours especially during the warm period. This occurs reasonably because of the cumulative effect of masonries moisture evaporation (favoured by the operating of the air heating unit and slight higher radiators set point temperature in winter) and the additional vapour load given by people.

The latter is higher during warm periods as the visitors rate is higher. Since the humidifiers are kept with same schedule throughout the year, they give constant contribution to the air mass moisture enrichment with a maximum threshold of 2.01g/kg (see section 35.1.1).

[4] The variation of a decimal is a consequence of the use of a larger data sample size.

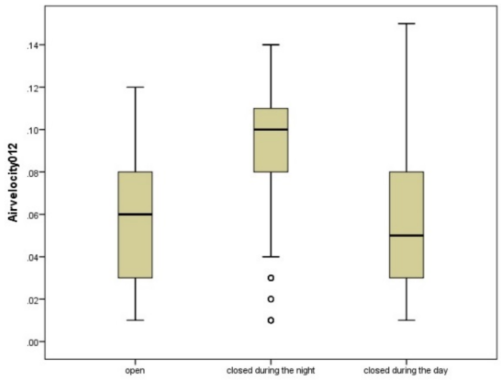

Figure 3~~5~~.1.4.3; Mean indoor air velocity (012) during the warm period (months 6-7-9) for museum opening days-opening hours (10am-5pm), museum closing days- diurnal hours (10am-5pm) and museum closing days- nocturnal hours (6pm-9am); the outliers in the graph were not considered extreme values, therefore not removed

The relative influence of indoor and outdoor parameters on the increase of air vapour content was quantified by a multiple regression model fitted to the dataset of the entire year, indiscriminately for museum opening and closing hours. The final model explains 94% of the total variance (R 0.969) and includes the following significant parameters: indoor air velocity (a_v), indoor air temperature (T_i) and outdoor mixing ratio (MR_o). The rest of the monitored or calculated environmental parameters and their (2 ways) interactions, were dominated by the three mentioned parameters; hence not significant. The Mixing Ratio (g/kg), in the museum exhibition hall air mass can be defined by means of the relation reported in (3). The Standard Error, standardized Beta coefficients and significance for each parameter are reported in Table 3~~5~~.1.4.3, while the model summary in reported in Table 5 in Supplementary Data.

$$MR_{in} = -0.64 + 0.37\,T_{in} + 2.64\,v_i + 0.28\,MR_{out} \qquad (3)$$

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
3	(Constant)	-0.638	0.089		-7.174	0.000
	Airvelocity012	2.640	0.190	0.087	13.871	0.000
	Temperature012	0.374	0.005	0.576	70.627	0.000
	Mixing Ratio Outside	0.285	0.005	0.481	58.010	0.000

a. Dependent Variable: MixingRatio012

Table 3~~5~~.1.4.3; Summary of coefficients for the final regression model

In the specific museum conditions and considering the current building use and vapour sources, the increase of indoor air velocity causes vapour concentration increase. More specifically, indoor air with a velocity of 2.64 m/s adds 1g/kg of vapour to the air mass of the space (considering constant the other predictors). It is worth noting that although air velocity is a significant variable, it only explains 2% of the total model variance, the rest is explained by the Mixing Ratio outside (12%) and by the indoor temperature (80%). This occurs because indoor air velocity causes the increase of the vapour content in the exhibition hall not “by definition”[5], but because of the combination between building equipment, management and envelope state of conservation.

Conversely, both indoor air Temperature (T_i) and outdoor Mixing Ratio (MR_o), enable always an increase of indoor vapour concentration. Their respective increase of 0.37°C and 0.29g/kg causes the increase of one unit of vapour concentration in the exhibition hall air volume (again considering one predictor per time with other predictors constant). The model diagnostic is reported in Fig. from 4 to 6 and Table 6 in Supplementary Data.

3~~5~~.2 Analysis of the masonries results

The previous sections discussed the hygrothermal variability in the exhibition hall caused, inter alia, by moisture presence in the building masonries. In this section, we discuss results regarding the identification of the water infiltrations in the masonries and possible causes of it. An IRT and documentary research was performed with this purpose. Here is reported a summary analysis regarding the North-East~~West~~ building corner. For an extended discussion on methodology and results, the reader may refer to [9].

[5] For instance in the case of nocturnal hours during the cold period the air velocity enables the mixing ratio reduction; see Table 3~~5~~.1.4.2

The mean apparent surface temperature towards the heated exhibition space was observed up to 1.6°C higher than the one towards the unheated tower, indicating the significant heat transfer through the exhibition space masonry. The surface temperature distribution was clearly dependent on the indoor air temperature layering and building geometry. Indeed, the mean surface temperature difference between heated and unheated space was observed 0.8°C at the street level (≈2.5m) and 1.6°C at the vaults level (≈7.0 m); see Figure 3~~5~~.2.1 and 3~~5~~.2.2 and Tables 7 and 8 in Supplementary Data. This occurs because inside the exhibition hall, the warm air accumulates immediately under the masonry vaults rising the temperature difference indoor-outdoor, hence outer surface temperature. Both in Figure 3~~5~~.2.1 and on the left side of Figure 3~~5~~.2.2 it can be seen a regular temperature distribution according to the masonry materials technology (bricks and sandstones). Nevertheless, this regularity is interrupted by the presence of infiltrative water generating sharp surface temperature reductions. Water infiltration was clearly identified between the first and the second floor (at the level of the second floor ceiling beams heads) and immediately above the vault level (first ceiling), under the stone kerb running around the building facades; see Fig. 3~~5~~.2.6.

Figure 5.2.3 (Table 9 in Supplementary Information), shows the same wall area as in Fig. 3~~5~~.2.2 but in presence of a sharp and irregular surface cooling caused by water infiltration. In this area, on the first floor, the inner plastered surface is strongly damaged by moisture; see Figure 3~~5~~.2.4 and Figures 7 - 10 with Tables 10 - 13 in Supplementary Information.

In Fig. 3~~5~~.2.3 (Table 9 in Supplementary Information), four horizontal lines are drawn on the damp area. Line 1 crosses a moist area on the right side of the window above the kerb, while lines 2 to 4 cross a moist area immediately under it. The minimum surface temperature measured on the four lines within the damp areas ranges between 6.7°C (line 1 and 2) and 7.2°C (line 4). Outside the damp area the surface temperature ranges between 7.7°C (line 2 and 3) and 7.9°C (line 4); (see Fig. 3~~5~~.2.2). The maximum surface temperature measured on the same lines within the damp areas ranges between 7.5°C (line 1) and 7.7°C (line 3 and 4); see Fig. 3~~5~~.2.3. While outside the damp area it ranges between 8.4°C (line 2) and 8.8°C (line 4); see Fig. 3~~5~~.2.2. Clearly, infiltrative water in the masonry is responsible for a surface cooling in all the measured points, this cooling progressively diminishes when the wall dries; namely toward the ground floor (line 4). A detailed description of the surface temperature distribution with identification of surface cooling due to infiltrative water on the North and ~~West~~ East Facades is given in Note 1 in Supplementary Information.

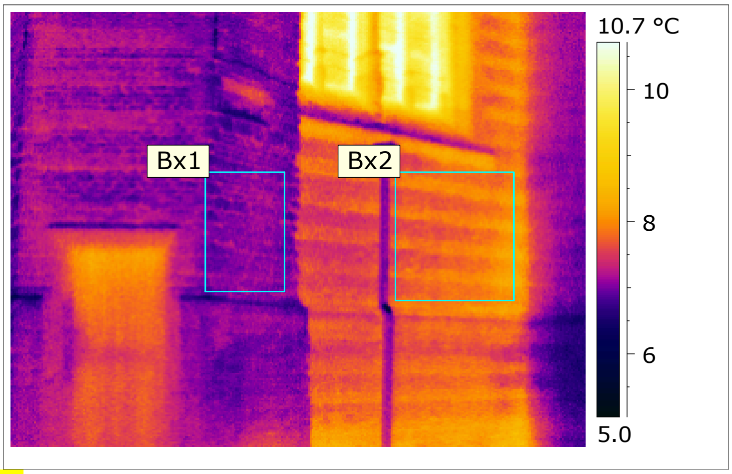

Figure 3~~5~~.2.1; IRT North-Eas~~-Wes~~t façade, street level (see corresponding Table 7 in Supplementary Data)

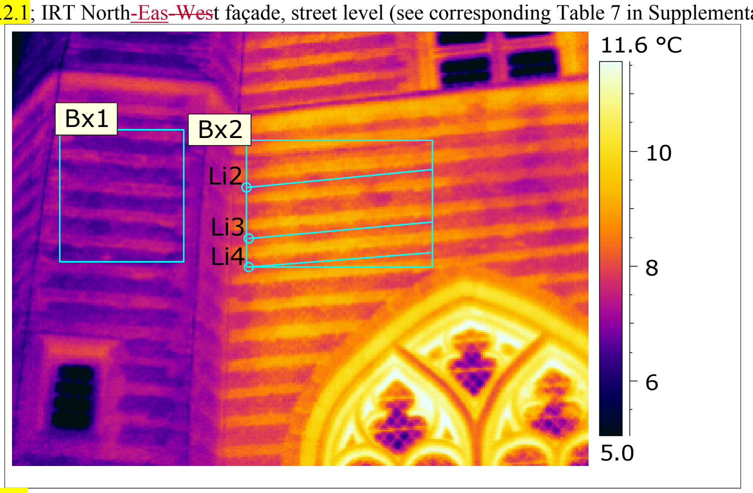

Figure ~~5~~3.2.2; IRT North-East~~West~~ façade, vaults level (see corresponding Table 8 in Supplementary Data)

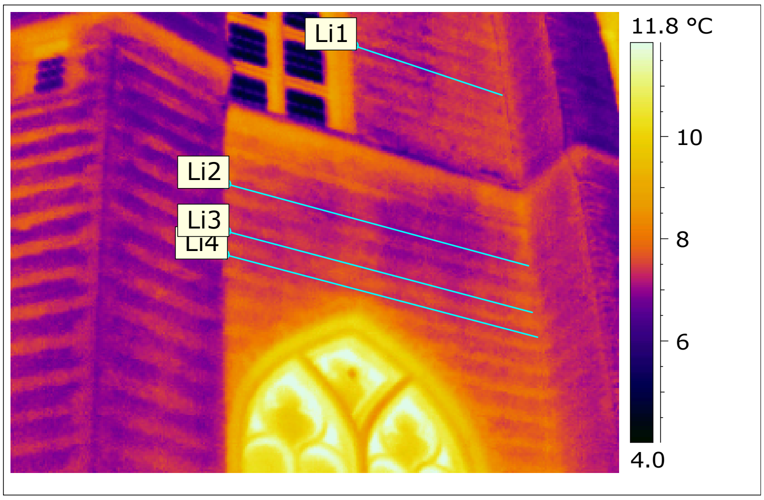

Figure 3~~5~~.2.3; IRT North-East~~West~~ façade, vaults level (see corresponding Table 9 in Supplementary Data)

Figure 3~~5~~.2.4; Room at the first floor on the North-East~~/West~~ corner; the damage due to moisture in the masonry is extended to the entire inner plaster surface (North façade), especially behind the textile and pews.

On the ~~West~~ East façade, the moisture path in the upper part (above the kerb) is identical to the one of the North façade, while the one of the lower part is sharper, see Fig. 3~~5~~.2.5 (Table 14, Fig. 11~~3~~ and Table 15 in Supplementary Data). In Fig. 3~~5~~.2.5, two horizontal lines are drawn for observing the temperature distribution alongside the wall. Line 2 is drawn on the 2nd brick area starting from the window vertex, while Line 1 is drawn on the 4th brick area. The minimum and maximum surface temperature in line 1 (above) is respectively 7.0°C and 8.2°C, while in line 2 (below) is respectively 7.2°C and 8.5°C. Both the lines have average surface temperature of 7.5°C. Clearly, minimum, maximum and mean temperature are remarkably similar to the ones observed on the N~~n~~orth façade as ~~also~~ well as the absolute surface temperature reduction in presence of water infiltrations;~~.~~ see Note 1 in supplementary information for details.

The problem of water infiltration in the Vleeshuis museum masonries is not recent. In the '60s, an extensive restoration of the building began. During the interventions, among others, the heating system was installed, the timber beams in the North-East~~West~~ corner of the building at the roof levels were consolidated by means of screwed metal profiles and all the building facades were cleaned by means of sandblasting. The external facades were finished with silicone-based hydro repellent layer (5% diluted) for avoiding driven rain infiltration. At the end of the works it was noticed that the masonry core was strongly damaged by infiltrative water. Nevertheless, interventions were not carried out in order to solve the problem neither at that time, nor later [34].

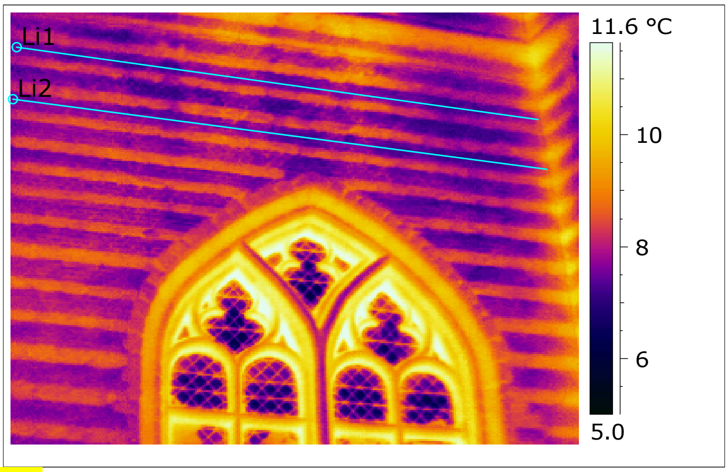

Figure 3~~5~~.2.5; IRT East~~West~~ façade, vaults level (see corresponding Table 14 in Supplementary Data)

In 2007, to secure the pedestrians from the continuous fall of stones and tiles from the building, a temporary debris collector system was installed (Fig. 3~~5~~.2.6). The suspended ring scaffold system was attached to the building facades by means of tie-rods and section bars. The sections were screwed, via metal plates, to the building masonries. Because it was ineffective, the system was re installed on a higher position in 2008 and definitively removed in 2009 [34]; Figure 3~~5~~.2.6 shows the building between the years 2007-2009 with the system installed.

Figure 3~~5~~.2.6; East~~West~~ facade; current view (upper left) and view between 2007-2009 (lower left) with debris collection system (Vleeshuis museum archive); The tie rods anchors (detail 1) and metal plates (detail 2) of the scaffold are the infiltrative water sources respectively above and below the kerb, see upper and lower IR thermogram (on the right) for detail 1 and 2

By superimposing the IRT thermograms with the building photographic documentation from the previous building restoration interventions and considering the masonries environmental monitoring results discussed in [9], it was possible to identify the metal plates and upper anchors of the tie-rods (removed in 2009) as the water infiltration sources in the building masonries. This is clearly visible if comparing Fig. 3~~5~~.2.5, Fig. 3~~5~~.2.6, and Figure 11 in Supplementary Data.

Nevertheless, in the authors opinion, it was not only the installation of the debris collecting system that brought serious damage to all the building boundary masonries (with consequent loss of energy performance [9]) and a serious threat for the housed movable heritage at the first floor, but also the lack of prompt intervention and improper restoration activities. The decision (in the years '60s) to not operate on the moistened masonries core, together with the one of adding a silicone-base waterproofing layer on the outer side of the brick facades, has worsened the scenario. The application of the hydrophobic layer has forced the inwards walls evaporation. Moreover, the evaporation was even accelerated by the heating system installed during the works.

The mentioned improper restoration measures speeded-up the decay of the building thermal and energy performance, and ~~were~~ are responsible for indoor efflorescence and mould growth as well as of possible mechanical deterioration and soiling of the artefacts attached to the walls on the first floor.

~~6.~~4. Conclusions

To detect possible building management issues and to consider building –tailored improvement options, it is of fundamental importance performing a holistic building diagnosis.

In the present contribution, we presented a comprehensive study aimed at identifying the possible influence of building envelope state of conservation as well as building and equipment usage on the indoor microclimate variability in the main exhibition hall of the Vleeshuis museum in Antwerp. The here discussed results, together with the ones published by the authors in [9] and [27], clarify the mutual interrelation between the different aspects of building performance and, implicitly, the call for a holistic approach during historic building assessments prior to the design of E~~e~~nergy and~~or~~ E~~e~~nvironmental R~~r~~etrofitting I~~i~~nterventions (EERI).

Moreover, considering the large amount of acquired data and the inherent difficulty given by the multiple research questions at the basis of each building indoor microclimate diagnosis, the conventional microclimate data analysis can be combined, with statistical tests. The resort to statistical analysis in support of physical ones allows a clear identification of the influence of tiny hygrothermal alterations on the global hygrothermal stability.

Although the discussed results report on the microclimate issues of a specific building, the implemented methodology is replicable in others. In fact, the presented procedure, enables to distinguish among sources of microclimate instability and to control the influence of building envelope and equipment performance on the building indoor microclimate. In the specific case of the Vleeshuis museum, the presented methodology allowed to understand the following:

- Since the building is not equipped with a centralized microclimate control system, it is better to tune the present equipment on basis of the internal and external hygrothermal seasonal loads rather than considering a constant schedule throughout the year. For instance, the use of portable humidifiers can be limited to the cold period because during the warm period more moisture enters the space (due to weather conditions and increased visiting rate). This option allows to~~can~~ ensure moisture stability in the exhibition hall throughout the whole year.
- The cultural events in the museum with several participants (e.g., concerts), produce sharp increase~~s~~ of water vapour concentration. It was observed that the additional moisture produced during the concerts is not efficiently extracted at the end of the events and it accumulates in the air volume. For this reason, prompt extraction of the entered moisture is necessary. In case the water vapour concentration outside the building is lower than the one inside, keeping the entrance door open (after the events) for regaining the vapour content balance as before the event, may suffice for this purpose. Otherwise, an exhausts air extractor should be considered.
- Even if the air-heating unit present in the exhibition hall was found not to provoke a strong partialization of the indoor microclimate dangerous for the housed collection, see [27], it alters the indoor hygrothermal dynamics especially by rising the inwards masonries evaporation process.
- The poor building envelope air tightness has a significant influence on the indoor microclimate stability. The air infiltration, dependent on temperature gradient indoor-outdoor, enables both lowering of indoor air temperature and increase of air velocity. During the cold period, in the nocturnal hours, the infiltrative air slows down the masonries evaporation process as a consequence of temperature reduction; similar condition was observed in the nocturnal hours during the warm period.
- The presence of moisture in the building masonries, is not a recent problem. This issue was already documented at the end of the restoration works in the years '60s. On that occasion, no prompt intervention was done. With time, water infiltration in the masonries became a severe deterioration cause.
  According to the here discussed results, the causes and sources of recent water infiltration was identified in the points in which a metal scaffold system for debris collections (removed from the building since eight years) was installed onto the building facades. This improper provisional intervention performed in 2007, has endangered almost all the cultural heritage objects present on the first floor of the building. Moreover it has triggered severe masonries deterioration processes with a significant impact on building microclimate and energy performance [9].
- Because of the high inertia of the building masonries, during the warm period, optimal hygrothermal quality is enabled in the Vleeshuis museum main exhibition hall. From this, it can be concluded that this space ~~e main exhibition hall~~ does not require any cooling system: neither for people thermal comfort improvement, nor for preventive conservation ~~reasons~~ requirements (see also [27]).

References

[1] M. Andretta, F. Coppola, and L. Seccia, "Investigation on the interaction between the outdoor environment and the indoor microclimate of a historical library," *J. Cult. Herit.*, vol. 17, pp. 75–86, 2016.

[2] J. L. Nguyen, J. Schwartz, and D. W. Dockery, “The relationship between indoor and outdoor temperature, apparent temperature, relative humidity, and absolute humidity,” *Indoor Air*, vol. 24, no. 1, pp. 103–112, 2014.

[3] D. Camuffo, E. Pagan, A. Bernardi, and F. Becherini, “The impact of heating, lighting and people in re-using historical buildings: a case study,” *J. Cult. Herit.*, vol. 5, no. 4, pp. 409–416, Oct. 2004.

[4] M. J. Varas-Muriel, M. I. Martínez-Garrido, and R. Fort, “Monitoring the thermal-hygrometric conditions induced by traditional heating systems in a historic Spanish church (12th-16th C),” *Energy Build.*, vol. 75, pp. 119–132, 2014.

[5] D. Camuffo, R. Van Grieken, H. Busse, G. Sturaro, A. Valentino, A. Bernardi, N. Blades, D. Shooter, F. Deutsch, M. Wieser, O. Kim, and U. Ulrych, “Environmental monitoring in four European museums,” *Atmos. Environ.*, vol. 1, no. 1, 2001.

[6] D. Camuffo, A. della Valle, C. Bertolin, C. Leorato, and A. Bistrot, “Humidity and environmental diagnostics in Palazzo Grimani, Venice,” in *Indoor environment and preservation, climate control in museums and historic buildings*, D. del Curto, Ed. Kermes, 2011, pp. 45–50.

[7] D. D’Agostino, “Moisture dynamics in an historical masonry structure: The Cathedral of Lecce (South Italy),” *Build. Environ.*, vol. 63, pp. 122–133, 2013.

[8] D. Camuffo, “Indoor dynamic climatology: investigations on the interactions between walls and indoor environment,” *Atmos. Environ.*, vol. 17, no. 9, pp. 1803–1809, 1983.

[9] G. Litti, S. Khoshdel, A. Audenaert, and J. Braet, “Hygrothermal performance evaluation of traditional brick masonry in historic buildings,” *Energy Build.*, vol. 105, pp. 393–411, 2015.

[10] E. Lucchi, “Thermal transmittance of historical brick masonries: A comparison among standard data, analytical calculation procedures, and in situ heat flow meter measurements,” *Energy Build.*, vol. 134, pp. 171–184, 2016.

[11] M. I. Martínez-Garrido, S. Aparicio, R. Fort, J. J. Anaya, and M. A. G. Izquierdo, “Effect of solar radiation and humidity on the inner core of walls in historic buildings,” *Constr. Build. Mater.*, vol. 51, pp. 383–394, 2014.

[12] H. S. L. C. Hens, “Envelope and fabric: heat, air and moisture metrics,” in *Applied Building Physic; Ambient Conditions, Building Performance and Materials Properties*, Second., W. A. Brand, Ed. Weinheim: Ernst & Sohn, 2012, pp. 195–248.

[13] M. Sileo, F. T. Gizzi, and N. Masini, “Low cost monitoring approach for the conservation of frescoes: The crypt of St. Francesco d’Assisi in Irsina (Basilicata, Southern Italy),” *J. Cult. Herit.*, vol. 23, pp. 89–99, 2016.

[14] C. Bonacina, P. Baggio, F. Cappelletti, P. Romagnoni, and A. G. Stevan, “The Scrovegni Chapel: The results of over 20 years of indoor climate monitoring,” *Energy Build.*, vol. 95, pp. 144–152, 2015.

[15] M. Ucci, D. Crowther, S. Pretlove, P. Biddulph, T. Oreszczyn, T. Wilkinson, G. Scadding, B. Hart, and D. Mumovic, “Indoor Air Quality and Health,” in *A handbook of Sustainable Building Design and Engineering; An integrated approach to Energy, Healt and Operational Perforformance*, 1st ed., D. Mumovic and M. Santamouris, Eds. UK-USA: Earthscan, 2012, pp. 313–323.

[16] P. Merello, M. C. Perez, J. Perez-Miralles, F. J. Garcia-Diego, A. Fernandez-Navajas, and M. Zarzo, “Basic descriptive statistical methods for monitoring and evaluation of microclimates in Cultural Heritage,” in *Science and Technology for the Conservation of Cultural Heritage*, M. A. Rogerio-Candelera, M. Lazzari, and E. Cano, Eds. London: CRC Press, Taylor and Francis Group, 2013, pp. 11–14.

[17] CTI, *UNI 10829.1999, Works of art of historical importance, Ambient conditions for conservation,*

Measurement and Analysis. Italy, 1999.

[18] CEN, *EN 15757 Conservation of Cultural Property-Specifications for temperature and relative humidity to limit climate- induces mechanical damage in organic hygroscopic materilas*, no. January. Belgium, 2010.

[19] S. P. Corgnati and M. Filippi, “Assessment of thermo-hygrometric quality in museums: Method and in-field application to the ‘ Duccio di Buoninsegna’ exhibition at Santa Maria della Scala (Siena, Italy),” *J. Cult. Herit.*, vol. 11, no. 3, pp. 345–349, 2010.

[20] S. P. Corgnati, V. Fabi, and M. Filippi, “A methodology for microclimatic quality evaluation in museums: Application to a temporary exhibit,” *Build. Environ.*, vol. 44, no. 6, pp. 1253–1260, Jun. 2009.

[21] J. Ferdyn-Grygierek, “Monitoring of indoor air parameters in large museum exhibition halls with and without air-conditioning systems,” *Build. Environ.*, vol. 107, pp. 113–126, 2016.

[22] F. Sciurpi, C. Carletti, G. Cellai, and L. Pierangioli, “Environmental monitoring and microclimatic control strategies in ‘La Specola’ museum of Florence,” *Energy Build.*, Oct. 2014.

[23] H. E. Silva and F. M. A. Henriques, “Hygrothermal analysis of historic buildings-Statistical methodologies and their applicability in temperate climates,” *Struct. Surv.*, vol. 34, no. 1, pp. 12–23, 2016.

[24] H. E. Silva and F. M. a. Henriques, “Microclimatic analysis of historic buildings: A new methodology for temperate climates,” *Build. Environ.*, vol. 82, pp. 381–387, Dec. 2014.

[25] F. J. García-Diego and M. Zarzo, “Microclimate monitoring by multivariate statistical control: The renaissance frescoes of the Cathedral of Valencia (Spain),” *J. Cult. Herit.*, vol. 11, no. 3, pp. 339–344, 2010.

[26] P. Merello, F. J. García-Diego, and M. Zarzo, “Diagnosis of abnormal patterns in multivariate microclimate monitoring: A case study of an open-air archaeological site in Pompeii (Italy),” *Sci. Total Environ.*, vol. 488–489, no. 1, pp. 14–25, 2014.

[27] G. Litti, A. Audenaert, and K. Fabbri, “Indoor Microclimate Quality (IMQ) certification in heritage and museum buildings: The case study of Vleeshuis museum in Antwerp,” *Build. Environ.*, vol. in Press, 2017.

[28] G. Litti, A. Audenaert, and J. Braet, “Indoor thermal quality in heritage buildings: combined assessment for works of art and people comfort,” in *Energy Efficient Restoration International Conference*, 2015, pp. 31–43.

[29] CEN, *NBN EN 13187 Thermal Performance of Buildings - Qualitative detection of thermal irregularities in building envelopes-Infrared method (ISO 6781:1983 modified)*. 1999, pp. 1–21.

[30] Vaisala oyj, “Humidity conversion formulas - Calculation formulas for humidity,” *Humidity Convers. Formulas*, p. 16, 2013.

[31] D. Camuffo, E. Pagan, H. Schellen, D. Limpens Neilen, R. Kozlowski, L. Bratasz, and S. Rissanen, *Church Heating and Preservation of the Cultural Heritage: A Practical Guide to the Pros and Cons of the Various Heating Systems*, Electa Mon. Milan: Electa Mondadori, 2007.

[32] L. a. Wallace, S. J. Emmerich, and C. Howard-Reed, “Continuous measurements of air change rates in an occupied house for 1 year: The effect of temperature, wind, fans and windows,” *J. Expo. Anal. Environ. Epidemiol.*, vol. 121, pp. 296–306, 2002.

[33] D. Camuffo, E. Pagan, S. Rissanen, Ł. Bratasz, R. Kozłowski, M. Camuffo, and A. della Valle, “An advanced church heating system favourable to artworks: A contribution to European standardisation,” *J. Cult. Herit.*, vol. 11, no. 2, pp. 205–219, 2010.

[34] Origin, “Museum Vleeshuis Antwerpen-Restauratie van de gevels en daken- Bouwhistorische studie,” Brussels, 2010.

7. -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 (131439).

8. Appendix

Saturation Pressure of Water vapour (V_{ps}); from [30]

$$(V_{ps}) = \frac{e^{(77.3435 + 0.0057(273(k) + T(°C)) - \frac{7235}{273(K) + T(°C)}}}{(273(K) + T(°C))^{8.2}} \text{ (Pa)} \quad (1)$$

Pressure of Water vapour (V_p); from [30]

$$V_P = V_{ps} * (RH/100); \text{ (hPa)} \quad (2)$$

Absolute humidity; from [30]

$$AH = C * V_p/T; \text{ (g/m}^3\text{)} \quad (3)$$

Mixing Ratio; from [30]

$$MR = B * V_p/(P_{tot} - V_{p)}; \text{ (g/kg); where } P_{tot} = \text{Absolute air pressure (hPa) and B= 621.9907 (g/kg)} \quad (4)$$

Highlights

1) Long term microclimate monitoring of the main exhibition hall of the Vleeshuis museum in Antwerp;
2) Indoor building microclimate monitoring based on an integrated approach targeted at evaluating the sources of hygrothermal instability in the museum exhibition space;
3) Data analysis based on statistical inference for contrasting microclimatic circumstances likely to influence indoor hygrothermal stability;
4) Infrared Thermography and building documentation analysis to identify the sources of infiltrative water in the building masonries;

An integrated approach for Indoor microclimate diagnosis of heritage and museum buildings: the main exhibition hall of Vleeshuis museum in Antwerp

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Abstract

Indoor microclimate diagnosis allows to understand the indoor-outdoor building microclimate interactions and to evaluate the extent of indoor hygrothermal variability caused by building use. Moreover, since the cumulative physical deterioration of the building envelope plays a relevant role in altering the indoor microclimate and building thermal performance, it is essential to combine both building envelope and indoor microclimate monitoring in an integrated diagnostic approach.
The microclimate diagnosis of the Vleeshuis museum main exhibition hall here discussed is based on infield instrumental environmental monitoring and Infrared thermography (IRT) on the building masonries. The IRT was integrated with the analysis of the building documentation. Further, the microclimate analysis was performed by combining the conventional microclimate data analysis with statistical tests.
The integrated diagnosis as presented in this study allowed to evaluate the long-term indoor microclimate variability consequent on outdoor and indoor heat and moisture loads variation as well as the identification of the sources of infiltrative water in the building masonries.

Keywords: microclimate monitoring; IRT; microclimate diagnosis; statistics applied to cultural heritage

Nomenclature

MR	Mixing ratio (g/kg)
Vp	water Vapour pressure (Pa)
Vps	Saturation Pressure of water Vapour (Pa)
P_{tot}	Total Air Pressure (hPa)
AH	Absolute humidity (g/m3)
T	Air Temperature (°C)
RH	Relative Humidity (%)
Δ_T	Temperature gradient inside-outside (°C)
Δ_R	Relative Humidity gradient inside-outside (%)
(in)	Inside
(out)	Outside
SE	Standard Error
CI	Confidence Interval
N	Data population

1. Introduction

Performing building indoor microclimate diagnosis means on the one hand verifying how the building interacts with its outdoor climate [1, 2] and on the other hand understanding the indoor microclimate variation consequent on variation of internal heat and mass loads [3–5]. Moreover, because the building envelope materials deterioration process plays a driving role in the indoor microclimate alteration and building energy performance [6–8], it is fundamental to evaluate both indoor building microclimate and building envelope state of conservation and hygrothermal performance [9]. Indeed, if Heat, Air and Moisture transfer through the building components is uncontrolled, not only might it cause overall building thermal performance reduction [9–12], but it may trigger indoor hygrothermal alterations with consequent risks for cultural heritage preservation and for people comfort and health [6], [13–15].

Given the existence of a cause-effect relationship between building performances, building materials state of conservation and building use, it should be favoured the implementation of holistic building monitoring and diagnosis instead of monothematic building assessment activities (e.g. energy audits). This is even more significant in case of historic, heritage buildings and museums. Indeed, in these buildings, the usual presence of non-centralized equipment, the opening of doors at each visitors entrance, the lighting system, the inconstant installation's schedule, the building physical deterioration and the long-term effects of previous restoration works may constitute a possible source of microclimate instability or even increased building energy consumptions. As a result, global building performance can only be improved by understanding and addressing the mentioned aspects in their totality.

Nevertheless, given the large amount of data and multiple research questions at the basis of a building indoor microclimate diagnosis, statistical tools may integrate the conventional data analysis. The use of descriptive and inference statistics at support of microclimate analysis (with exploratory or confirmatory purposes) is becoming more frequent also in the cultural heritage science [16]. This occurs especially after the introduction, in national and European standards [17,18], of microclimate data analysis methodologies based on the support of statistics.

It should be mentioned that this support should be not independent from a physical understanding of the environmental phenomena. Indeed, the physics concerned in the microclimate dynamics allows to identify the appropriate statistics to use for better analysing the problem; moreover the latter do not replace the former during the problem understanding. In other words, a correlation coefficient may express the relation between variables but it does not explain the reasons of this relationship. Nevertheless, statistical modelling may facilitate the microclimate diagnosis especially with regard to long-term monitoring wherein big amount of data are involved.

S. P. Corgnati, M. Filippi et.al, in [19,20] recurred to descriptive statistics-based indicators for globally assessing the indoor thermo-hygrometric safety of paintings during temporary exhibitions. Similar analysis supported by descriptive statistics (e.g. cumulated percentages, frequency indicators, bivariate correlations, etc.) were also undertaken by J. Ferdyn- Grygierek in [21] for evaluating the indoor climate of a large museum building and by F. Sciurpi et.al in [22] for deciding upon microclimate control strategies in an Italian museum. H.E. Silva and F. M.A. Henriques in [23] proposed a comparison between two statistical methods for the definition of safe (historic) climate target in a Portuguese church according to the EN 15757 standard and an adjusted version of the latter [24].

Other authors performed exploratory analysis for assessing specific microclimatic issues by relying on statistical inference. F. J. Garcia-Diego and M. Zarzo, in [25] applied multivariate statistics to understand the likelihood of moisture formation on a renaissance frescos in the Cathedral of Valencia, Spain. The same multivariate analysis, was implemented by P. Merello et.al in [26] for characterizing the microclimate variability of an open-archaeological site in Pompeii, Italy, and for recognizing abnormal microclimate patterns.

The above-mentioned contributions, highlighted according to their methodology the validity given by the integration of statistical inference with canonical hygrothermal data analysis in the field of cultural heritage. This integration was a fundamental aspect considered in the present study.

The main objective of the present research is to introduce an integrated methodology for indoor microclimate assessment of heritage buildings and museums. This methodology integrates (1-year) environment monitoring, Infrared Thermography and building documentation analysis.

The performed indoor microclimate diagnosis relies on building physics analysis and inference statistics. In the authors' opinion, the latter is supportive in order to: a) discriminate among the countless climatic circumstances likely to influence the indoor building microclimate stability; b) compare possible causes of hygrothermal fluctuations or c) confirm hypothesis emerged during instrumental monitoring or data analysis.

The study of the building documentation combined with results from IRT and environmental monitoring, allowed to precisely identifying the sources of water infiltration in the building masonries. This approach not only is fundamental in terms of building microclimate evaluation but also in terms of building envelope thermal energy assessment. Indeed, it allows obtaining important insights for possible interventions targeted at the restoration or performance improvement of the building.

The research was performed in the main exhibition hall of the Vleeshuis museum in Antwerp (Belgium). The Vleeshuis, is a protected monumental building in the city centre; it currently hosts a musical instruments collection in the basement and ground floor.

An introduction to the case study and to its indoor microclimate control systems is given in the section methodology (section 2). In the same section, the undertaken instrumental and analytical research methodology is described. Research results are discussed in section 3 and conclusions are drawn in section 4. The specific objectives and limitations of the present study are listed below.

- With regard to the assessment of the building masonries, the study focusses on the following: localisation of moisture in the building masonries and identification of water infiltrative sources. Although the building envelope analyses was performed with regard to the entire building, we limit the results discussion to the North-East building corner (ground and first floor) as found to be the most representative for allowing a good understanding of the moisture infiltration causes and effects. This aspect of the study is based on a previous research to which we refer the reader for details on methodology and results [9].

- With regard to the assessment of the influence of heat and moisture loads on the exhibition hall microclimate stability, the study focuses on the following: a) the effect of outdoor climate on the one indoor one; b) the effect of visitors on the indoor microclimate variations; c) the effect of climate control equipment operation and building use on the indoor hygrothermal variability; d) the effect of infiltrative air on indoor hygrothermal fluctuations. The specific aspects concerning the influence of the current exhibition hall microclimate quality on people comfort perception and movable cultural heritage safety are discussed by the authors in [27].
- The microclimate monitoring, was performed during the year 2014-15. However, due to logging failure, data from July the 20th to September the 8th were lost, hence not included in the analysis. The outdoor environmental parameters considered in the analysis were taken from a weather station 6 km distant from the museum (Deurne).
- The exhibition hall is equipped with independent humidifiers. As it was found that the machines were not constantly in use throughout the monitored year, their influence on the indoor hygrothermal variability was analysed according to the less safe scenario. In other words, the results with regard to this scenario represent the influence the humidifiers might have on the indoor microclimate, if constantly used at their maximum power.

The quantification of the actual humidifiers influence of the indoor microclimate variability will be object of further research.

2. Research methodology

In this section, the building selected as case study is presented (section 2.1) together with the methodology for the infield instrumental monitoring (section 2.2 and 2.3) and analytical procedure for the microclimate diagnosis (section 2.4).

2.1 Case study description

The Vleeshuis, currently museum of musical instruments, was built between 1501 and 1504 as slaughterhouse by Herman de Waghemakere (the elder). It was built to house four functions in independent levels: the slaughter space, the market, the leaving and the storage spaces. The first two functions were built respectively in the cellar and on the ground floor, while on the first floor, spaces for reception, meetings and forestry were housed. The upper four levels were used as storage. Currently the basement and ground floors host the permanent collection of musical instrument while the upper levels, except part of the second floor (used as offices), are dedicated to artifacts storage.

For the purpose of the study, the main exhibition hall on the ground floor was continuously monitored; see Figure 2.1.1 (a-c). The building is technologically characterized by brick masonries and vaults at the basement and ground floor and brick masonries and timber ceilings at the upper floors. The brick masonries of the ground floor are opened by almost 220m^2 stained single glass windows (≈35% of the floor area).

The building is equipped with centralised heating system with high temperature radiators as terminals (temperature set-point 20°C)[1]. No cooling or mechanical ventilation systems is present with the only exception of an independent air heating and ventilation unit installed on the North-East part of the exhibition hall (see Fig. 2.1.1.c and 2.2.1). The air unit, without humidity control, allows an air change rate of 3500m^3/h (exhibition hall net volume ≈5300 m^3). The exhibition hall is neither equipped with humidity control system nor with temperature one.

The humidity is controlled by independent humidifiers (often found defected or not in use), while temperature regulation is allowed by the adjustment of the radiators thermostats. Nevertheless, as the radiators are located on the boundary walls -were also part of the collection is exposed- several terminals are constantly closed not to endanger the cultural objects.

In a previous study, reported by the authors in [9], it was observed that the Vleeshuis masonries are deteriorated by infiltrative water and that the moisture presence causes a remarkable masonries thermal performance reduction. By means of in-contact and semi in-contact wall hygrothermal monitoring, it was found that the thermal transmittance value on wet areas is three time higher than the one on dryer ones. Moreover, it was observed that walls drying process, is responsible for a continuous water vapour enrichment of the indoor air volume due to (partial) inwards masonry evaporation.

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[1] Recently the two centralised boilers present during the monitoring campaign were replaced. Nevertheless, the distribution system and terminals were not changed.

Fig. 2.1.1.a-c (from left to right); Ground floor exhibition hall of the Vleeshuis internal view (a); example of humidifier present in the exhibition hall (b); air heating and ventilation unit integrated in a closet (similar to the showcases) on the North wall (c)

Even if, in the here discussed study, no direct masonry environmental monitoring was performed, it is reasonable to expect that the walls drying process, as observed in [9], triggers similar vapour evaporation in the exhibition hall and in all the spaces at the first floor where identical moisture infiltrations were observed. The problem of infiltrative water in the building masonries is not recent indeed it was already observed during restoration works in 1964 (Fig. 3 in Supplementary Data). It is worth mentioning that not only the brick masonries deterioration is supposed to affect indoor microclimate stability, but also the almost 220 m^2 of stained glass windows, and more specifically their connection to the masonries. Indeed, due to the deterioration of the stone making up the structural frame of the glass panes, constant infiltrative heat and moisture was observed at the windows edges. Also this issue was observed during restoration works in 1964 (Fig. 1-2 in Supplementary Data)
Next to the infiltrative losses via the windows, also the five building towers (especially the ones directly connected to the exhibition hall), are responsible for continuous heat loss towards outside, making the microclimate in the exhibition hall unstable and strongly dependent on the outdoor climate circumstances.

2.2 Indoor Microclimate monitoring

The environmental parameters continuously monitored in the exhibition hall and considered in the microclimate analysis are given in Table 2.2.1. The measurement protocol, especially with regard to the sensors location, was developed on basis of findings from a preparatory short term monitoring performed in the summer 2013 [28].

Position code	Physical Parameter	Logger	Accuracy (of absolute reading)	Time resolution (sampling interval in min)
0.1.2-0.1.4-0.1.5	Dry bulb temperature (°C)	Hobo U12	(±0.35)	15
0.1.2-0.1.4-0.1.5	Dew temperature (°C)	Hobo U12	(± 2.5%)	15
0.1.2-0.1.4-0.1.5	Relative Humidity (%)	Hobo U12	(± 2.5%)	15
0.1.2-0.1.4-0.1.5	Light Intensity (lux)	Hobo U12	(± 2.5%)	15
0.1.2	CO2 (ppm)	Vaisala GM70	(± 2%)	15
0.1.2	Air Velocity (m/s)	MM 0038 Innova	(0.05α+0.05) **	120

** with air velocity <1m/s and 0.25α with air velocity up to 10m/s

Table 2.2.1; Parameters continuously monitored in the exhibition hall

External environmental parameters, utilized for the microclimate analysis, were taken from the weather data station in Antwerp-Deurne (6km distant from the building), these are: dry bulb temperature (°C), dew point temperature (°C), relative humidity (%), global horizontal solar radiation (W/m^2), wind speed (m/s), wind direction (°E of N), atmospheric pressure (Pa), cloud covering (fraction).
The sensors for the indoor measurement, were installed in the exhibition hall 1.30 m above the floor. Their location as well as the location of air heating unit and humidifiers is plot in Fig. 2.2.1. The distance between sensor 014 (entrance) and 012 (centre of the 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.

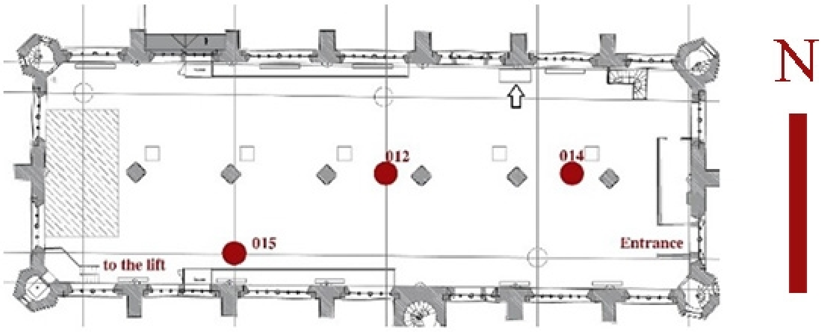

Figure 2.2.1; Localization of sensors in the exhibition hall (red circles) air heating unit (black arrow) humidifiers (squares); the humidifiers distance from the sensor was always >2m

2.3 Infrared Thermography (IRT)

In the North-East corner of the building the existing tower is not directly connected to the exhibition space, see Fig. 2.3.1, this allowed to measure the outer masonry surface temperature distribution towards a heated and unheated space: respectively exhibition hall and tower.
The indoor-outdoor thermal imaging performed in accordance to the EN 13187 [29] and [9], allowed to localize the infiltrative water in the masonries as well as to identify the origin of the infiltrations. The latter was possible by combining Infra-Red Thermography (IRT) with analysis of building photographic documentation related to past restoration works. Namely by superimposing the IRT thermograms with the archive pictures and technical drawings of previous restoration works. The position of the thermogram discussed in section 3.2 is reported in Fig. 2.3.1.

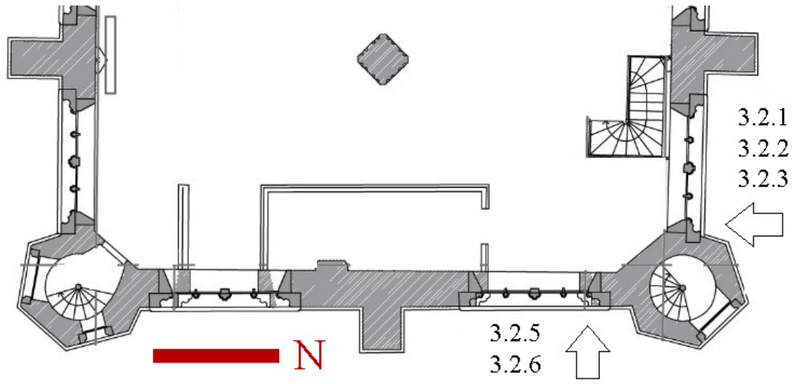

Figure 2.3.1; North-East façade with tower; indication of IRT thermograms discussed in section 3.2

2.4 Indoor Microclimate data analysis

Based on the monitored parameters given in Table 2.2.1, mixing ratio (g/kg) and water vapour pressure (hPa) were calculated every 15 minutes and hourly averaged; see Eq. 1 to 4 from [30] in the Appendix.
The ratio between mass of water vapour and dry air (mixing ratio, MR) allowed to analyse the air mass interactions between the indoor and outdoor environment. Indeed, because MR is invariable to both isobaric and non-isobaric and adiabatic and non-adiabatic processes (because of its independency from pressure, volume and temperature), its analysis allowed to understand the hygrothermal dynamics in the monitored exhibition space. In the article, MR is also termed, for simplicity, water vapour concentration and is calculated according to Eq. 4 in Appendix.
Inside-outside temperature, mixing ratio and relative humidity were analysed throughout the entire monitored period under conditions a) and b) reported below. Namely when the indoor air temperature and vapour pressure were higher or lower than the ones outside. For the sake of simplicity the conditions a) and b) are termed overheating and overcooling (see Eq. 1 and 2). The mentioned conditions were defined in order to better assess the exhibition hall hygrothermal patterns in case of outwards (condition a) or inwards (condition b) heat and moisture transport. According to these scenarios –meant at dichotomizing the physics of the heat and moisture transport- it were analysed the microclimate dynamics also by means of statistical tests.

Condition A: *overheating*
(heat-moisture flows towards outside)

$$\begin{cases} T_{(in)} > T_{(out)} \\ Vp_{(in)} > Vp_{(out)} \end{cases} \quad (1)$$

Condition B: *overcooling*
(heat-moisture flows towards inside)

$$\begin{cases} T_{(in)} < T_{(out)} \\ Vp_{(in)} < Vp_{(out)} \end{cases} \quad (2)$$

The possible hygrothermal instability sources present in the exhibition hall were: portable humidifiers, visitors and staff, ventilation through the entrance door, ventilation due to the air heating unit, infiltration through the envelope and moisture evaporation from the building masonries. The influence of each one of the mentioned hygrothermal disturbance was tested by combining data analysis and tests statistics. The statistical tools considered in this study are explained below.

1) *Test of mean independency (t-test).* In this study, we resorted to t-tests for observing the variation between microclimate circumstances. Indeed, by analysing the extent of a possible non random variation it was possible to assess the influence of e.g., people presence, doors and air-heating unit operation, air infiltration etc. on the indoor microclimate variability.
The *t-test*, allows verifying casual inference by looking at the mean difference between statistical populations. In this study, we used this test with only one independent continuous variable per time, manipulated in two ways, and only one predicted variable per time (also continuous). The *t-test* allows analysing the influence of the manipulation of a predictor on a predicted value. In other words the test works as a regression model that predicts the outcome on basis of a group membership. If the membership to a group plays a role in varying the outcome, this will result in a significant (non-random) variation of the predicted mean.
2) *Partial correlation*. This correlation model allows observing the relationship between two variables when the effect of a third variable is held constant. The partial correlation was used in the study for looking at the relation between air water vapour concentration and air temperature by taking into account influence of the air velocity.
3) *Multiple regression model.* A regression model was developed for quantifying the relation of each significant environmental parameter on the variation of the exhibition hall mixing ratio (MR). The regression model was developed on basis of indoor and outdoor parameters found to be significant both during microclimate assessment and model development. The model was developed on the least square method, and the improvement consequent on each parameter addition was evaluated by means of explained variance (R^2) and explained variance in function of the model degrees of freedom (F-test).

The effect of each heat and/or moisture source on the microclimate stability of the exhibition hall was assessed according to the methodology given below.

2.4.1 Influence of portable humidifiers

The use of portable humidifiers in the exhibition space, though continuous throughout the year, was erratic. The humidifiers were observed often defected, moved or not in use. However, during onsite inspections it was generally observed that 4 humidifiers were in use. The maximum water vapour entered in the exhibition hall by the four machines (hypotized at their maximum power) was calculated. This simplified- scenario allowed to understand the maximum influence of the humidifiers on the exhibition hall water vapour enrichment.

2.4.2 Influence of visitors and staff

The influence of visitors and staff on the possible air volume vapour enrichment, was tested by means of independent *t-test* and by analysing the hygrothermal parameters distribution throughout the monitored period.
The test was developed in two hierarchical steps: test 1 and test 2 for both cold (months 11-12-1-2) and warm (months 6-7-9) periods.
Test 1, aimed at verifying the mixing ratio mean variation between non visiting and visiting days, excluding the highly frequented concerts events (100 people on average). In case of negativity of the first test, in other words in case the mean vapour concentration during museum visiting days was found to be not significantly different from the one during closing museum days, a second test (test 2) was performed. The second test aimed at verifying the same as the first but including the concerts events, see Table 2.4.2.1.The second test allowed verifying whether the variation of water vapour concentration was insignificant also in case of short intervals with high occupation rate.

Independent t-test	continuous variable (in the model)	dummy variable (in the model)		Time interval
Test 1	Mixing Ratio_012	closing hours	visiting hours	1pm to 11pm
Test 2	Mixing Ratio_012	closing hours	visiting + concert hours	1pm to 11pm

Table 2.4.2.1 Independent t-Test conditions for test 1 and 2

The museum can be visited from Thursday to Sunday from 10am to 5pm; on other days the exhibition space is closed to the public. However, since in the cold period, the contribution of visitors in terms of vapour concentration enrichment was observed with a time lag in comparison with the visiting hours (see Fig.3.1.2.2), the *t- tests* were performed considering the time interval 1pm to 11pm. This allowed taking into account the enrichment and successive dilution of vapour concentration during and after the visiting time.
From the hourly mixing ratio calculated on basis of the monitored indoor environmental parameters and considering a per capita water vapour production of 50g/h [31], the average vapour load produced by people during museum visits was calculated. Further, the results were compared to the museum administration data. It is worth mentioning that 50g/h vapour production refers to people involved in activities with low metabolic rate such as attending a religious ceremony. We assume this (low) metabolic activity is not different from visiting a museum or listening to a classic concert.

2.4.3 Influence of ventilation due to the operating of the entrance sliding door

The ventilation rate produced by the entrance door or windows opening is supposed to be invariable throughout the year, this because the openings are not differently operated during the seasons for obvious safety reasons.
For understanding the effect of the entrance door opening on the indoor air movement, an independent *t-test* was done. The modelled dummy conditions were: museum closed and opened within the time interval 10am-5pm (museum opening hours), hence when the door is operated. The test was performed for cold and warm periods considering as continuous variable the indoor air velocity (m/s) measured in point 012 (centre of the space).

2.4.4 Influence of air infiltration and air heating unit

Even if the ventilation stays invariable between opening and closing days throughout the whole year, the infiltration rate may change with consequent influence on the air velocity inside the exhibition space and therefore on the vapour concentration.
Wallace E. et. al, in [32] observed that air infiltration rate is temperature gradient dependant and it increases in proportion of 0.0156(ach) per 1°C of temperature difference increase (indoor-outdoor).
Due to the big volume of the exhibition hall (≈5300 m^3), it was not possible to perform a blower door test. However, the influence of the air infiltration on the indoor microclimate was quantified by analysing the indoor air velocity. This approach, allowed obtaining continuous information on the air infiltration/exfiltration influence on the indoor hygrothermal conditions and at verifying the relation between air infiltration and temperature gradient. The indoor air velocity sensor was placed away from direct sources of ventilation in order to measure the whole air buoyancy of the space and to continuously detect indoor –outdoor air mass exchanges.
Due to the presence of the air-heating unit, temperature gradient and air velocity increase were unavoidably correlated. For this reason it was necessary to isolate the effect of temperature gradient increase given by the unit. Therefore, for the *t-t test* it were considered only the nocturnal hours (<10am, >5pm). In these hours, the air unit was not in use, people were absent and radiators set point temperature (during cold period) was at the lowest temperature causing negligible convective air motion. In this way, the sole influence on the indoor air velocity was attributable to the air infiltration-exfiltration (with consequent buoyancy) via windows or doors.

2.4.5 Influence of moisture in the masonries

Together with indoor environmental monitoring, an Infrared Thermography (IRT) was performed indoor and outdoor the building masonries in order to localize thermal heterogeneities caused by infiltrative water possibly influencing the exhibition hall microclimate. This analysis combined with the study of the documentation from previous restoration works allowed to identify the sources of water infiltration.

3. Results discussion

3.1 Microclimate diagnosis results

In this section we discuss the results from both microclimate analysis and identification of water sources in the building masonries. It is worth mentioning that the microclimate analysis results are not discussed separately - from a physical and a statistical point of view- but rather on the basis of a global understanding as allowed by the integration of the two disciplines.
The indoor building microclimate was observed to be significantly dependent on the outdoor climatic conditions for the entire monitoring period. Figures 3.1.1 and 3.1.2 plot the monthly mean outdoor and indoor temperature in overheating or overcooling conditions (see Eq. 1 and 2). The overheating occurred in all the months while

overcooling occurred mainly during the warm period (June-July and September) and exceptionally at the beginning of the heating season (October and November) due to the failure of the heating system (for a total of 56 hours).

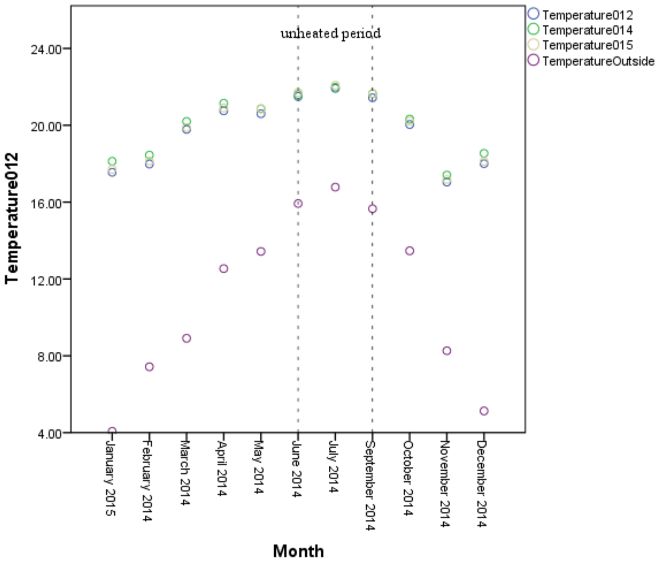

Figure 3.1.1. Indoor temperature point 012,014,015; overheating

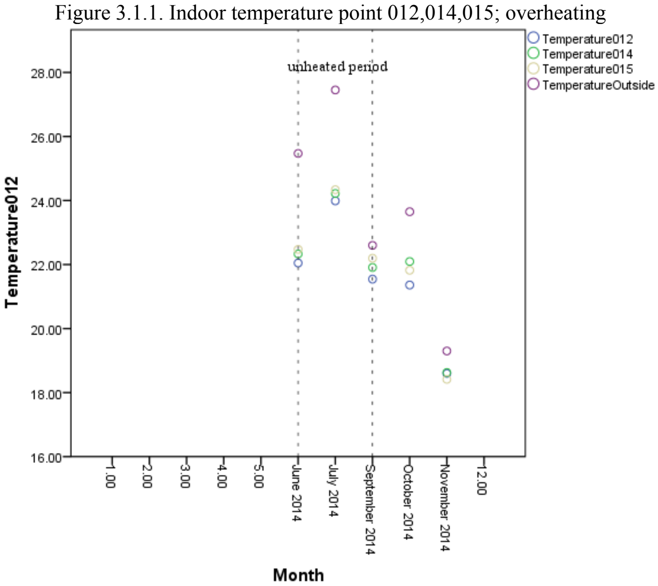

Figure 3.1.2 Indoor temperature point 012,014,015; overcooling (the numerical terms on the x axis refer to the months not interested by overcooling)

A noteworthy cooling circumstance was registered during the warm period. Indeed, in June and July (no data for August are available), the indoor temperature was measured up to 3.5°C lower than outside. As mentioned, the building is not equipped with cooling system, hence the observed overcooling was generated by the building passive cooling. The air temperature and relative humidity trends for each measurement point with regard to the entire monitored period are shown in Fig. 3.1.3 and 3.1.4 respectively.

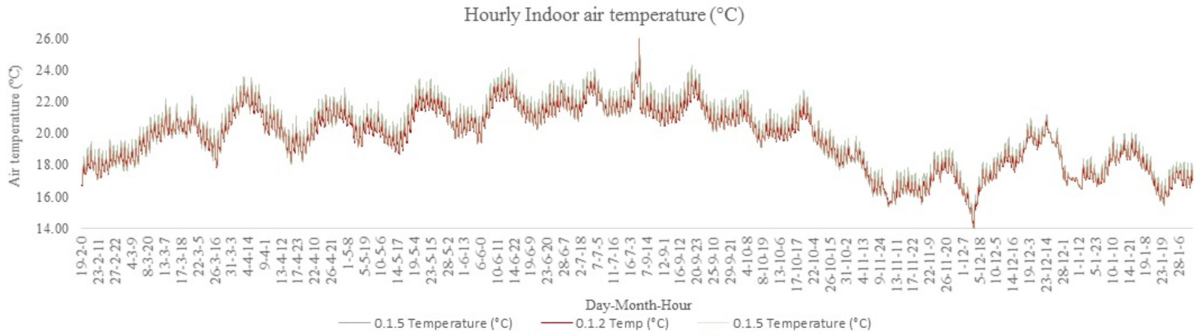

Figure 3.1.3 Indoor temperature (°C) points 012-014-015 for the entire monitored period

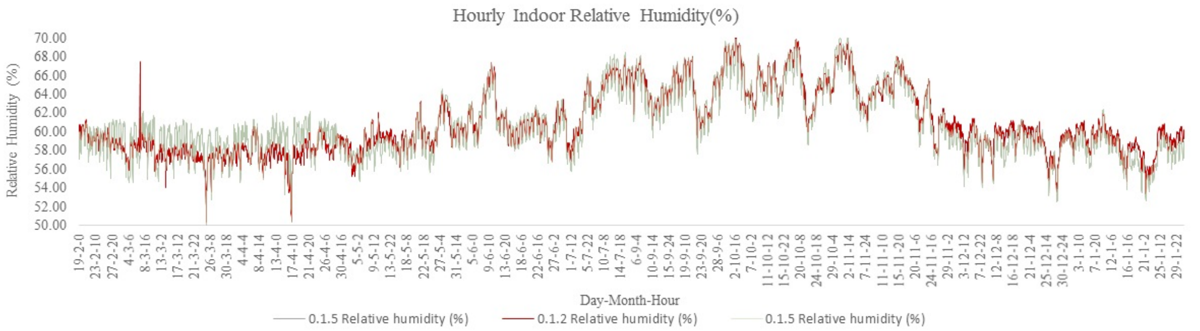

Figure 3.1.4 Indoor relative humidity (%) points 012-014-015 for the entire monitored period

In order to observe a first relationship between indoor and outdoor microclimate, the correlation between hygrothermal parameters was analysed. The correlation coefficients, of the indoor-outdoor parameters relation, are given in Tables from 3.1.1 to 3.1.3 respectively for cold period (overheating), warm period (overheating) and warm period (overcooling). As the mentioned correlations aimed at obtaining a global understanding of the indoor-outdoor hygrothermal relation, no distinction between museum opening or closing days is made. However, a detailed evaluation of the indoor-outdoor microclimate relationships –considering the different building use scenarios- is discussed in section 3.1.4.

The Pearson correlation coefficients in Table 3.1.1, illustrate the typical indoor-outdoor hygrothermal relations during cold period, while Table 3.1.2 and 3.1.3, plot the same relationships during warm period respectively for the case of overheating and overcooling of the exhibition space.

During the cold period, a poor correlation between outdoor and indoor temperature can be observed. This relationship is 0.365 in point 012 and it is never higher than 0.380 (point 015). The correlation, reasonably, rises during the warm period especially when the indoor temperature is lower than outside (no cooling system is present in the building). Reasonably, the weaker relation between indoor and outdoor temperature during the cold period –compared to the warm one- is attributable to the heating system effect.

Correlations (Pearson)	**Months 11-12-01-02_condition a**					
	TEMP 012	TEMP Out.	RH 012	RH Out.	MR 012	MR Out.
Temperature 012	1.000	0.365	-0.212	-0.280	0.786	0.267
Temperature Outside	0.365	1.000	0.556	-0.321	0.685	0.915
Relative Humidity012	-0.212	0.556	1.000	0.166	0.423	0.653
Relative Humidity Outside	-0.280	-0.321	0.166	1.000	-0.156	0.062
Mixing Ratio 012	0.786	0.685	0.423	-0.156	1.000	0.659
Mixing Ratio Outside	0.267	0.915	0.653	0.062	0.659	1.000

Table 3.1.1; Pearson correlation of Temperature (TEMP), Relative Humidity (RH) and Mixing Ratio (MR) between point 012 and outside; Sig 0.01; months 11-12-1-2; overheating

Correlations (Pearson)	**Months 06-07-09_condition a**					
	TEMP 012	TEMP Out.	RH 012	RH Out.	MR 012	MR Out.
Temperature 012	1	0.592	0.093	-0.306	0.76	0.309
Temperature Outside	0.592	1	0.018	-0.717	0.426	0.239
Relative Humidity 012	0.093	0.018	1	0.511	0.711	0.723
Relative Humidity Outside	-0.306	-0.717	0.511	1	0.125	0.497
Mixing Ratio 012	0.76	0.426	0.711	0.125	1	0.697
Mixing Ratio Outside	0.309	0.239	0.723	0.497	0.697	1

Table 3.1.2; Pearson correlation of Temperature (TEMP), Relative Humidity (RH) and Mixing Ratio (MR) between point 012 and outside; Sig 0.01; months 06-07-09; overheating

Correlations (Pearson)	Months 06-07-09_condition b					
	TEMP 012	TEMP Out.	RH 012	RH Out.	MR 012	MR Out.
Temperature 012	1	0.735	0.372	-0.425	0.97	0.702
Temperature Outside	0.735	1	-0.147	-0.835	0.604	0.584
Relative Humidity 012	0.372	-0.147	1	0.415	0.581	0.334
Relative Humidity Outside	-0.425	-0.835	0.415	1	-0.258	-0.045
Mixing Ratio 012	0.97	0.604	0.581	-0.258	1	0.708
Mixing Ratio Outside	0.702	0.584	0.334	-0.045	0.708	1

Table 3.1.3; Pearson correlation of Temperature (TEMP), Relative Humidity (RH) and Mixing Ratio (MR) between point 012 and outside; Sig 0.01; months 06-07-09; overcooling

The mentioned effect, especially during the cold period, can be additionally identified by the inverse correlation between indoor temperature and relative humidity (Pearson -0.212); similar negative correlation is calculated for the other points, maximum -0.261 (014). However, the reduction of relative humidity does not stand for water vapour reduction. Indeed the correlation between indoor mixing ratio and temperature explains rather the contrary (Pearson 0.786). This aspect, will be better discussed in section 3.1.4.
The RH decreases because the saturation vapour pressure increases as a consequence of the temperature increase. The positive and significant correlation between indoor mixing ratio and temperature, and to a lesser extent the positive correlation between indoor relative humidity and mixing ratio (Pearson 0.423) explains that the temperature triggers some addition of vapour to the air volume. This is visible in Figure 3.1.5 in which the hourly variation of temperature and mixing ratio is plotted for the cold period. Similar results were observed in [9].

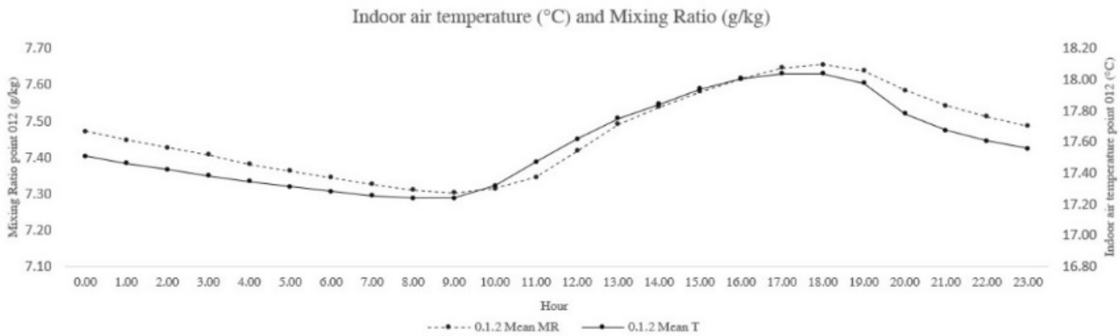

Fig. 3.1.5. Point 012, Temperature (°C) and Mixing Ratio (g/kg) hourly average over the months: February, November, and December 2014-January 2015; R 0.786

The water vapour enrichment caused by the temperature increase might be explained either by the process of evaporation of the masonries towards inside or by other sources of vapour addition combined with temperature increase, such as people, humidifiers, etc. Both the aspects will be detailed later on in the text.
During warm period (months 6-7-9), when temperature indoor is higher than outdoor (Table. 3.1.2), indoor mixing ratio correlates positively with indoor temperature (Pearson 0.76 in point 012), however this correlation is slightly lower than the cold period. This reduction can be explained by a smaller temperature gradient: Δ_T is 17.44°C and 9.80°C in cold and warm period respectively in condition a) at the 95th percentile.
It may be supposed that also during the warm period, part of the residual vapour from the moist masonries evaporates inside. When the indoor air temperature is higher than outside, condition a (Table 3.1.2), the correlation between indoor temperature and RH is zero for the above mentioned reasons (Pearson 0.09). However, when the temperature is lower inside than outside, condition b (Table 3.1.3), the RH unavoidably increases (Person 0.372).
From thermal imaging on the walls, it was not evidenced risk of surface condensation during the year. This because the walls surface temperature was higher than the air dew point temperature; because of this, the presence of moisture evaporating inwards might be caused by the natural drying of the masonry core after the moisture accumulation in winter. During the warm period when the indoor temperature is lower inside than outside (Table 3.1.3), the correlation between indoor temperature and mixing ratio rises up to 0.97. As mentioned, in this case, since the temperature is lower and so is the saturation vapour pressure, the correlation between indoor RH and temperature is positive and significant in all the points. It is 0.372 in point 012 and it increases up to 0.582 in point 015.

<u>3.1.1 Influence of humidifiers</u>

The analysis related to the influence of humidifiers on the exhibition hall microclimate, was limited to the quantification of the maximum water vapour entered in the air volume if four humidifiers would be used continuously at the maximum power. The air recirculation rate at the given power, according to the manufacturer,

is 750m^3/h, with a humidifying capacity of 2.7l/h (45% and 23°C, RH and T) and maximum room volume (per machine) of 900m^3, hence a volume coverage of 68%. With an approximation about the steadiness of the air temperature and, considering isenthalpic the air humidification from the water-based humidifiers (usually, water-based humidifiers work with isenthalpic transformation), it was estimated that the maximum moisture amount entered in the air volume per hour from the 4 humidifiers was 2.01g/kg (68% of 2.96g/kg).
Although the calculated vapour enrichment given by the humidifiers is an approximation, if looking at the high vapour concentration during the warm period (max 10.41g/kg), it might be concluded that the humidifiers use can be limited or avoided in order to keep constant vapour concentration throughout the year.

3.1.2 Influence of visitors and staff

For testing the influence of people on the indoor vapour concentration variation, a test of mean independency was run considering both museum visiting and closing days within the time interval 1-11pm, during both cold and warm periods. The tested continuous variable was MR. The obtained results indicated that the presence of people, constantly contributed to the air vapour increase. This increase consistently rose with the museum visiting rate.
In the cold period, the hourly mixing ratio and also CO_2 concentration and indoor temperature during opening days were higher than during closing days only from 1pm. In the warm period, the mixing ratio during visiting days was constantly above the one of closing days. In order to compare the mean mixing ratio variation within the same time interval, the tests were run considering the time interval 1-11pm.
During the cold period and in the considered time interval (1-11pm), the mean mixing ratio was 7.52g/kg (SE 0.03) and 7.61g/kg (SE 0.02) respectively for closing and visiting days, without concert events (test 1). The difference was -0.093 g/kg (CI =-0.166, -0.021), and it was significant $t(994)= -2.524$, $p= 0.012$ (Table 3.1.2.1 and Table 3.1.2.2). The test significance (t) was calculated considering the weighted variance (pooled variance) from the two differently sized data population. Table 3.1.2.2 reports the unweighted variance, therefore the t- values (compared to the one discussed in the text) might differ by a few decimals.

Mean hourly Mixing Ratio 012 Statistics	N	Mean	Std. Deviation	Std. Error Mean	Period (months)	Interval (hours)
museum close	473	7.522	0.618	0.028	11-12-1-2	1-11pm
museum open (visiting)	627	7.615	0.594	0.024	11-12-1-2	1-11pm
museum open (visiting +concert)	649	7.609	0.586	0.023	11-12-1-2	1-11pm
museum close	341	10.061	0.638	0.035	6-7-9	1-11pm
museum open (visiting)	451	10.311	0.791	0.037	6-7-9	1-11pm
museum open (visiting +concert)	462	10.295	0.788	0.037	6-7-9	1-11pm

Table 3.1.2.1; Mixing Ratio point 012; cold period (months 11-12-1-2) and warm period (months 6-7-9); time interval 1-11pm

Although Test 1 as described in section 2.4.2 is verified, it is interesting discussing the results also from Test 2. Indeed, it can be observed that after including in the statistic population the opening hours related to the concerts (in addition to the ones of museum visits), the mean mixing ratio slightly decreased (Table 3.1.2.1). This occurred because of the low initial vapour concentration in the hours prior to the concerts. Figure 3.1.2.1, clearly shows this circumstance with regard to the last week of October 2014.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Low	Up
MR 012 (test 1) months 11-12-1-2	Equality of Variance assumed	3.21	0.07	-2.54	1098	0.01	-0.09	0.04	-0.17	-0.02
				-2.52	994	0.01	-0.09	0.04	-0.17	-0.02
MR 012 (test 1) months 6-7-9	Equality of Variance assumed	7.56	0.01	-4.78	790	0.00	-0.25	0.05	-0.35	-0.15
				-4.92	786	0.00	-0.25	0.05	-0.35	-0.15

Table 3.1.2.2; Independent t-test for equality of the mean (mixing ratio); Test 1, readings without concert events (1-11pm)

The concerts are performed once per month during the last of the three museum closing days, on Wednesday. In Figure 3.1.2.1, it is visible that immediately before the concert on October the 29th, the exhibition space has low mixing ratio (8.36g/kg), this happened because no vapour was accumulated during the previous two closing days. Successively, during the concert hours, the mixing ratio increased up to 9.15g/kg. The air mass was enriched by 5kg of water vapour in less than three hours (the number of people participating to the event was on average 100). After the concert, the vapour started being diluted. Nevertheless, before the entrance of visitors during the successive day (15 hours later) the indoor vapour concentration (read Mixing Ratio) was still 0.19g/kg higher than the one previous to the concert. In other words, still 1.22kg of water vapour emitted from concert attenders was not expelled.

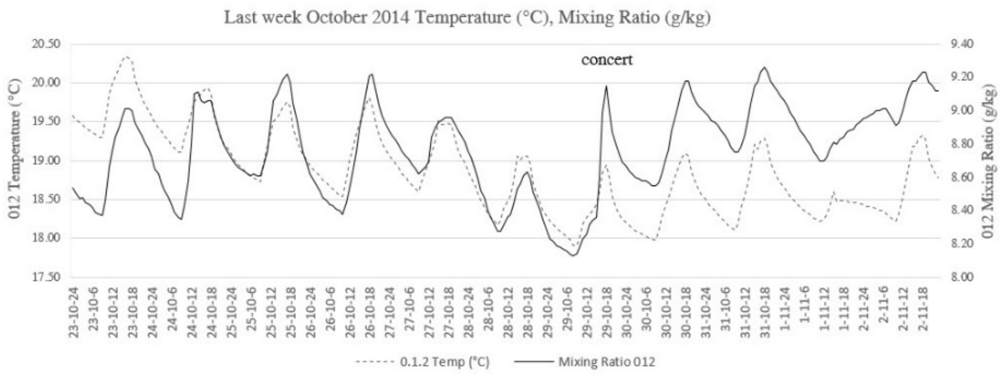

Fig. 3.1.2.1. Indoor air temperature (°C) and mixing ratio (g/kg) monitored from point 012; last week of October 2014.

The mean hourly mixing ratio and temperature in the exhibition space during the cold period, both in case of museum visiting and closing days (excluding concerts) are plotted in Figure 3.1.2.2. Although negligible, the mean air temperature during closing days is ≈0.10°C higher than the one during opening days (see Table 3.1.2.3). It should be noted that the data plotted in Table 3.1.2.3, refer to opening and closing days, without distinction between nocturnal and diurnal hours. A more detailed analysis on the nocturnal hours, hence without the influence of people and heating air unit, is discussed in section 3.1.4.

	Temperature (°C)			Mixing Ratio (g/kg)			CO2 (ppm)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
opening days (cold period)	≈17.20 9am	≈18.10 6pm	≈17.50	≈7.30 10am	≈7.70 6pm	≈7.50	≈510 10am	≈630 6pm	≈560
closing days (cold period)	≈17.30 9am	≈18.00 5pm	≈17.60	≈7.30 10am	≈7.60 5pm	≈7.45	≈495 9am	≈540 4pm	≈520
opening days (warm period)	≈21.20 6am	≈22.40 3pm	≈21.70	≈9.80 5am	≈10.40 5pm	≈10.10	≈540 10am	≈715 17pm	≈600
closing days (warm period)	≈21.10 6am	≈22.10 4pm	≈21.50	≈9.70 7am	≈10.10 5pm	≈9.90	≈500 9am	≈600 2pm	≈550

Table 3.1.2.3; Cold period (months 11-12-1-2) and Warm period (months 6-7-9); Indoor temperature, Mixing Ratio and CO_2 summary statistics for museum opening and closing days

Because of the strong relation between air temperature and mixing ratio already discussed in section 3.1, the slightly higher temperature during the closing days (compared to the opening ones) results also in a higher mixing ratio. However, during the opening days, people presence results in a faster relative increase of temperature, mixing ratio and CO_2 between 10am and 5pm. Meaning that, for long part of the day, is the rate of hygrothermal variations that attests the influence of visitors rather than the absolute value of the hygrothermal parameters. If observing the parameters hourly maximum variation, meaning the maximum parameter difference in the given time interval, it can be observed that:

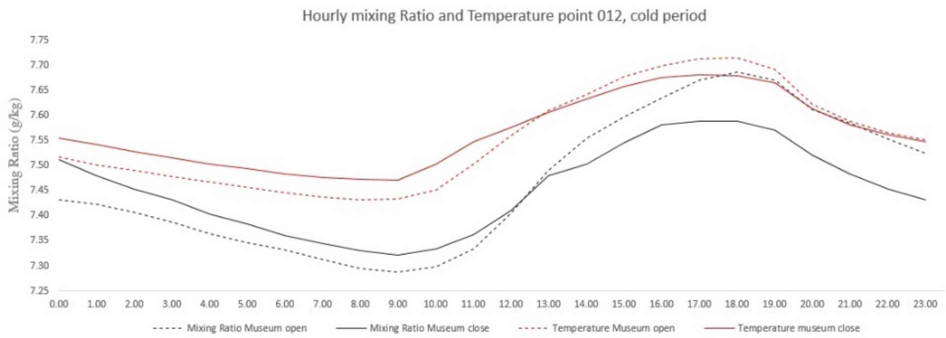

Fig. 3.1.2.2. Mean hourly indoor mixing ratio and temperature during closing and opening hours of the museum (opening 10am-5pm); cold period (February, November, December 2014 and January 2015); point 012

- during the museum closing days, the indoor air temperature maximum variation was ≈0.60°C between 9am and 5pm, while it was ≈0.90°C between 9am and 6pm during museum opening days;
- during museum closing days, the mixing ratio maximum variation was ≈0.30g/kg between 10am and 5pm, while it was ≈0.40g/kg between 10am and 6pm during museum opening days.
- During the museum closing days, the CO_2 maximum variation was ≈47 ppm between 9am and 4pm, while it was ≈122 ppm between 10am and 6pm during museum opening days.

Clearly, from the moment the museum is open (10am), a significant increase of temperature, vapour concentration and CO_2 is registered in comparison with the closing days. But the readings of each parameter are higher than the ones registered during the closing days only from 1pm; see Figure 3.1.2.2. The extra vapour produced by people is diluted between 6pm and 8pm. After this period, the residual vapour concentration decreases similarly (with the same slope) as the closing days.
Considering the time interval from 1pm to 6pm (before vapour dilution), the daily extra water vapour added by people to the exhibition hall air mass is ≈0.34g/kg or 2.20kg. If considering a vapour production of 50g per hours per person (see [33]), in the exhibition space during the cold period, there were on average 8people/hour.
During the warm period, again results from the independent *t-test*, confirmed, that people presence influenced the mean vapour concentration variation in the exhibition space. The mean mixing ratio was 10.06g/kg (SE 0.05) and 10.31g/kg (SE 0.05) respectively for closing and opening days, without concert events (test 1) and during the time interval 1-11pm, see Table 3.1.2.1. The mean difference was -0.250 g/kg (CI =-0.35, -0.15), significant $t(786) = -4.922$, $p = 2E-05$, see Table 3.1.2.2.

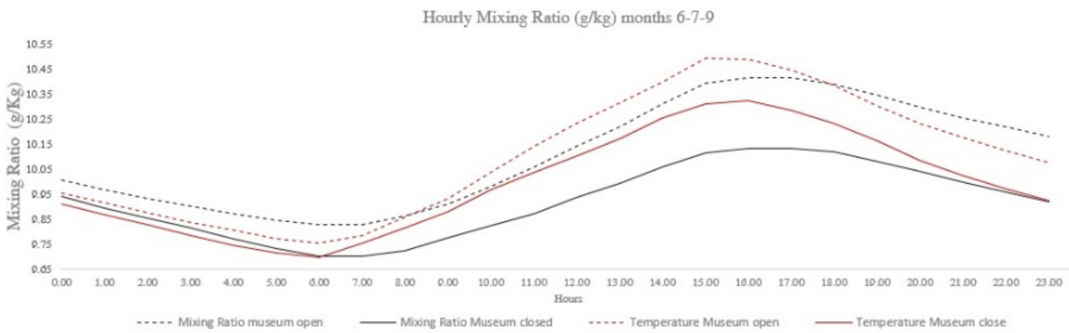

Fig. 3.1.2.3. Mean hourly indoor mixing ratio and temperature during closing and opening hours of the museum (open from 10am to 5pm); cold period (June, July, September 2014); point 012

In Figure 3.1.2.3, is reported the hourly mixing ratio and temperature of museum opening (dotted black and red lines) and closing (continuous black and red lines) days during the warm period. Differently from the cold period, the indoor mixing ratio during the opening hours was always higher than the closing hours, but similarly to the cold period the relative increase of temperature, mixing ratio and CO_2 was faster and more significant in presence of people as reported below. If observing the parameters hourly maximum variation, meaning the maximum parameter difference in the given time interval, it can be observed that:

- during the museum closing days, the indoor air temperature maximum variation was ≈1.00°C between 6am and 4pm, while it was ≈1.20°C between 6am and 3pm during museum opening days.
- During the museum closing days, the mixing ratio maximum variation was ≈0.40g/kg between 7am and 5pm, while it was ≈0.60g/kg between 7am and 5pm during museum opening days.

- During the museum closing days, the CO_2 maximum variation was ≈100 ppm between 9am and 2pm, while it was ≈178ppm between 10am and 5pm during museum opening days.

If considering the entire visiting time interval 10am-5pm (before vapour dilution), the added water vapour from visitors during an average visiting day in summer was ≈8.60kg (or 1.87g/kg); resulting in an average of 170 people per day or 30 person/hour. The occupation rates for the cold and warm period, calculated on basis of the measured vapour concentration, were in agreement with the ones provided by the museum administration.

3.1.3 Influence of ventilation due to the operating of the entrance sliding door

As described in section 2.4.3, the influence on the vapour concentration produced by air ventilation was assessed by observing the relation between: indoor and outdoor air velocity, air temperature, relative humidity and mixing ratio during museum opening and closing hours. Further, a test of mean independency of the indoor air velocity for museum opening and closing days during both cold and warm periods was performed. The considered time interval was 10am-5pm (museum opening hours, namely when the door is operated). According to this time interval, museum opening and closing days during the cold and warm periods were analysed.
For the cold period, the results from the independent t-test, confirmed, that the opening of the door had no influence on the mean indoor air velocity variation. The mean air velocity was 0.063m/s (SE 0.006) and 0.058 (SE 0.005) respectively for closing and opening days, without concert events and during the time interval 10am-5pm, see Table 3.1.3.1. The mean difference was 0.005 m/s (CI =-0.012, 0.021), not significant $t(79)= 0.56$, $p= 0.577$; see Table 3.1.3.2. Similar results were obtained also with regard to the warm period. The door opening was not significant for the mean air velocity variation. The mean air velocity was 0.054m/s (SE 0.005) and 0.058 (SE 0.004) respectively for closing and opening days, without concert events and during the time interval 10am-5pm, see Table 3.1.3.1. The mean difference was -0.004 m/s (CI =-0.016, 0.007), not significant $t(99)= -0.748$, $p= 0.456$; see Table 3.1.3.2.

Mean hourly Air velocity 012 Statistics	N	Mean	Std. Deviation	Std. Error Mean	Period (months)	Interval (hours)
museum close	30	0.063	0.034	0.006	11-12-1-2	10am-5pm
museum open (visiting)	51	0.055	0.037	0.005	11-12-1-2	10am-5pm
museum close	41	0.054	0.030	0.005	6-7-9	10am-5pm
museum open (visiting)	60	0.058	0.029	0.004	6-7-9	10am-5pm

Table 3.1.3.1; Air velocity point 012; cold period (months 11-12-1-2) and warm period (6-7-9)

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Low	Up
Air velocity 012 months (11-12-1-2)	Equality of Variance assumed	0.24	0.63	0.56	79	0.58	0.00	0.01	-0.01	0.02
				0.57	64	0.57	0.00	0.01	-0.01	0.02
Air velocity 012 months (6-7-9)	Equality of Variance assumed	0.15	0.70	-0.75	99	0.46	0.00	0.01	-0.02	0.01
				-0.75	84	0.46	0.00	0.01	-0.02	0.01

Table 3.1.3.2; Independent t-test for equality of the mean (air velocity); readings without concert events; cold period and warm period, time interval 10am-5pm

The results from the test confirmed that the door opening had no effect on the variation of the indoor air velocity both in the cold and warm period, confirming that the ventilation rate in the exhibition space stays invariant throughout the seasons. This is also confirmed by the invariability of the mean indoor air velocity during the opening days between cold and warm periods, see Table 3.1.3.1. It is worth noting that the indoor air velocity during the museum closing days in the cold period in the time interval 10am-5pm, is slightly higher than during the same time interval in the museum opening days. This condition might depend either on the increase of the air convection due to the heating system or on the increase of air infiltration or exfiltration; this aspect will be discussed in the next section.

3.1.4 Influence of air infiltration and air heating unit

Beside the radiators from the centralized heating system, the exhibition hall has a heating and ventilation air unit (see Figure 2.2.1 and 2.1.1.c). The unit, located in the North-East corner of the building, has no humidity control and the air is blown into the space through two outlets at the top of the unit. The air flow rate at the outlets, measured on March the 4th 2015 (2.30pm) was 3500m^3/h, air velocity was 3.16m/s, air temperature 41.5°C and relative humidity ≈16.4%. In the same moment air temperature and relative humidity in the exhibition space were only slightly heterogeneous: ≈18.70°C and ≈57.50% in point 014 (the closest to the unit), ≈18.30°C and ≈58.0% in point 012, ≈18.70°C and ≈57.0% in point 015. It is worth mentioning that, even if the air unit causes a slight alteration of the hygrothermal stability, this does not cause risks for the cultural objects; see [27]. Considering the seasonal time intervals, it can be observed that:

- During the cold period, the nearest sensor to the air unit 014, resulted in a slight higher temperature and lower relative humidity as well as in a slight higher standard deviation in comparison with the other points (see Table 1 in Supplementary Data). This condition describes the air unit in intermittent heating modality.
- During the warm period, the air temperature in point 014 (both in overheating and overcooling) had not substantial variation compared to the other points. This occurred because the air unit does not provide cooling. Indeed, the coolest point of the exhibition room was 012 in the middle of the space; see Table 2 and 3 in Supplementary Data. It should be noted that in all the points the increase of air temperature consequent to the operating of the lighting system was negligible[2].

From now on, in this section we discuss the results with regard to the evaluation of building air infiltration and its influence on the indoor hygrothermal dynamics, especially with regard to mixing ratio variation.
In a study from L. Wallace [32], after continuous measurement of the building infiltration rate, it was concluded that the latter increases with indoor-outdoor temperature difference increase. Also in our study, it was observed a linear relationship between hourly temperature difference (indoor-outdoor) and indoor air velocity (R 0.80). However because the air heating unit was also responsible of temperature gradient and air velocity increase, it was necessary to remove the readings during its operation in order to avoid false correlation. If considering the readings when air heating and ventilation unit is not activated, in both cold and warm periods it is still possible to observe that indoor building microclimate is affected by air infiltration, and that the infiltration increases when the air temperature gradient indoor-outdoor increases confirming the findings from Wallace in [32]. This can be also observed in Fig. 3.1.4.1 where the hourly values of temperature difference and air velocity are plotted for the entire monitored period, during the nocturnal hours (6pm-9am). Correlation coefficient R 0.68. A more robust correlation may be expected with higher air velocity sampling frequency.

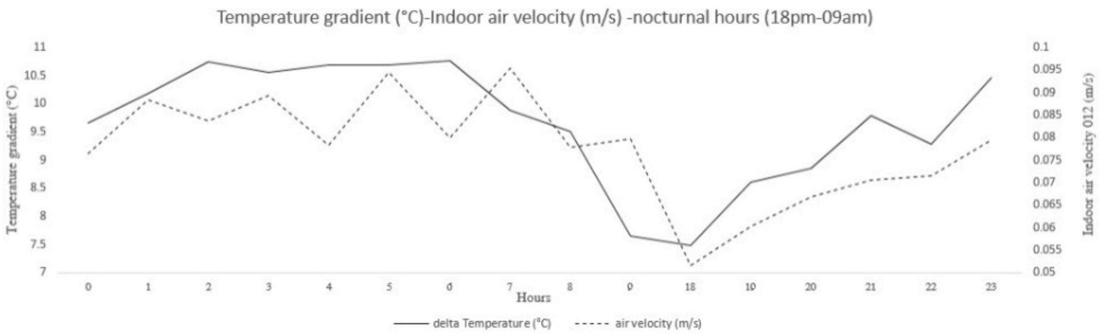

Figure 3.1.4.1; Hourly temperature gradient (°C) and air velocity (m/s) during nocturnal hours (6pm-9am) for the entire year; Pearson correlation coefficient (R) 0.68

In order to evaluate the indoor microclimate variations caused by infiltrative air, the bivariate relationship between air velocity and environmental parameters during the nocturnal time interval (6pm-9am) was quantified; both for cold and warm periods; namely, when the system was not in function; see Table 3.1.4.1. In turn, air temperature, mixing ratio, relative humidity, CO_2 and temperature difference inside-outside were correlated to the indoor air velocity. Although the correlations are statistically significant, not all of them are robust. Nevertheless, they allow

[2] During the museum opening days in the cold period, the Pearson correlation coefficient between temperature and light intensity was respectively 0.13 in point 014, 0.17 in point 015 and 0.11 in point 012. During the summer period the light intensity had a higher influence on indoor air temperature, especially in points 014 and 015 as more exposed to the windows; the correlation coefficient was respectively 0.20 and 0.22. The R value of point 012, located in a central and always darker position, was 0.07.

understanding the indoor-outdoor hygrothermal dynamics. It is worth noting that the effect of the relationship between Δ_T and air velocity causes -in summer and winter- two opposite effects as below discussed.
In the cold period (months 11-12-1-2), during nocturnal hours when the heating system is on (only radiators), the air infiltrating from outside (read air velocity) produces a lowering of the Δ_T (R -0.22; sig.0.01) meaning that infiltrative air is cooling down the indoor air temperature otherwise heated up by the radiators, see Table 3.1.4.1 (left column). Consistently the correlation between indoor temperature and indoor air velocity is negative (R=-0.22; sig.0.01); see also Table 3.1.4.2. The mentioned indoor temperature reduction is less significant during the cold period in comparison with the warm period because of the unavoidable contribution of the radiators. However, despite the mentioned slight indoor temperature reduction, the mixing ratio in the exhibition space tends to increase. This condition, apparently in contradiction with what observed in Fig. 3.1.5, is a consequence of the combination of a high temperature gradient and increase of indoor air velocity; see later in this section. Reasonably, the relative humidity increases as a consequence of the saturation water pressure decrease (consequent to the temperature reduction). In the warm period (months 6-7-9), during the same nocturne al hours the infiltrative air rises the ΔT (R 0.33; sig. 0.01) meaning that the infiltrative air is cooling the (already cool) indoor air temperature; see Table 3.1.4.1 (right column). Consistently the air temperature of the exhibition hall decreases with the air velocity increase (R -0.77; sig. 0.01). In other words in both the periods of the year, the indoor temperature lowers with air infiltration. Further, during the warm period, because of the strong indoor temperature diminishing, also the mixing ratio lowers accordingly. What is mentioned occurs without the air unit contribution as it is not in use at night time.

	Air velocity 012 cold period, museum closing days, nocturnal hours (<10am, >5pm)	Air velocity 012 warm period, museum closing days, nocturnal hours (<10am, >5pm)
Temperature 012	-.219**	-.773**
Mixing Ratio 012	.211*	-.412**
Relative Humidity 012	.522**	.268*
CO_2 012	-.319**	-.170
ROOTSQ DT 012	-.225**	.337**

Table 3.1.4.1; Pearson correlation coefficient (R); (**) Correlation is significant at the 0.01 level (2-tailed); (*) Correlation is significant at the 0.05 level (2-tailed); nocturnal hours (<10am, >5pm); museum closing days; condition a) and b)

The different linear relationship between ventilation and mixing ratio among cold and warm period is remarkable. During the night hours in the cold period, the increase of air velocity causes an increase of vapour concentration (R 0.21), however this does not occur during the night hours in the warm period (R -0.41); see Table 3.1.4.1. This condition might be explained by the effect of air velocity on the indoor air temperature, and therefore on the mixing ratio. Indeed, in the cold period, during the nocturnal hours, although the infiltrative air enables a slight indoor temperature reduction, the temperature gradient (inside-outside) is still >23°C. In other words the indoor temperature is still far higher inside than outside, hence part of the moisture in the masonries is likely to still evaporate inwards. On the contrary, during the warm period, the air infiltration causes a substantial temperature drop. The temperature gradient is halved compared to the one during the cold period (see Table 4 in Supplementary Data), as a consequence the inwards masonry evaporation process decreases and accordingly the mixing ratio. The temperature reduction is responsible of the relative humidity increase (R 0.27).
The increase of masonries evaporation rate consequent on the temperature increase (see also [9]) observed both during the cold and warm period (diurnal hours), is evidently caused by the prevalence -within the process of masonries evaporation- of the heat term over the aerodynamic one; as observed by D. D'Agostino in [7]. However, not only the air temperature but also the air velocity boosts both vapour dilution in the exhibition space air volume and masonry evaporation. For better contrasting this phenomena, namely the contribution given by the indoor air velocity to the vapour concentration increase in the different periods of the year, the partial correlation between air temperature and mixing ratio controlled for the air velocity was analysed. The correlation was performed considering the readings from the warm and cold periods, for both museum opening and closing days, for nocturnal and diurnal hours; see Table 3.1.4.2.
In all the circumstances except one, it is possible to observe that air velocity has either no influence (on the relationship indoor temperature- mixing ratio) or a positive one; this is seen by the invariability of the correlation coefficient or by its reduction in the case of partial correlation. This shows that air velocity, in the specific case, increases the relationship between air temperature and mixing ratio. This boost is clearer during closing hours in the warm months because there is less moisture extraction from the air volume[3] and a larger amount of vapour concentration compared to the cold period.

[3] The air-heating unit is off and the entrance door is closed, the only moisture subtraction is allowed by air infiltration/exfiltration.

	Closing days			
	Cold period		Warm Period	
	Pearson	Partial	Pearson	Partial
diurnal	0.750	0.749	0.622	0.524
nocturnal	0.760	0.845	0.605	0.495
	Opening days			
diurnal	0.730	0.720	0.930	0.930

Table 3.1.4.2; Pearson correlation coefficient and Partial correlation coefficient; all the correlation coefficient reported in the table are significant at 0.01 (2-tailed); nocturnal hours (<10am, >5pm); the correlated parameters are air temperature and mixing ratio, controlled for air velocity.

Only in the cold period during the nocturnal hours, it was observed the increase of correlation coefficient, from the simple correlation (R 0.76) to the partial correlation (R 0.845), meaning that the air velocity in fact tended to reduce the relationship between air temperature and mixing ratio, confirming what was explained above with regard to Table 3.1.4.1 (left column).

Namely, the infiltrative air from outside reduced the indoor air temperature by entering cold air (bearing also less vapour). This circumstance most likely reduced the moisture evaporation from the masonries and the total indoor vapour concentration. As already discussed, the increase of indoor air velocity in the monitored building, occurs when the temperature gradient (indoor-outdoor) is higher, e.g. during the nocturnal hours. This condition is valid for both warm and cold periods, see Figures 3.1.4.2 and 3.1.4.3. The mean air velocity without the influence of the air heating system (museum closing days) is 0.07 m/s and 0.09 m/s during nocturnal hours (6pm-9am) respectively in cold and warm periods and 0.059 m/s and 0.055 m/s during diurnal hours (10am-5pm) respectively in cold and warm period. During the museum opening hours (10am-5pm) the air velocity is almost invariable between cold and warm months as already observed in Table 3.1.3.1, the mean air velocity is respectively 0.056m/s and 0.058m/s[4]. The higher air velocity at night-time, explains the overall higher air velocity during the museum closing hours as reported in Table 3.1.3.1.

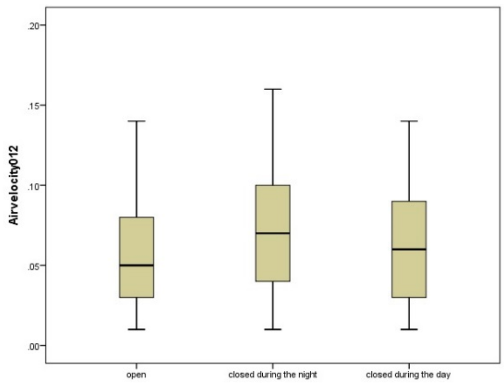

Figure 3.1.4.2; Mean indoor air velocity (012) during the cold period (months 11-12-1-2) for museum opening days-opening hours (10am-5pm), museum closing days- diurnal hours (10am-5pm) and museum closing days- nocturnal hours (6pm-9am)

The increase of the indoor air velocity (caused either by infiltration or operation of the air heating unit), enables the increase of the moisture evaporation from the exhibition hall masonries. A similar circumstance was observed by M. I. Martínez-Garrido et.al. in [11] with regard to outdoor evaporation and D. Camuffo et.al in [33] with regard to indoor masonry evaporation.

Even if higher air velocity occurs at night (see Fig. 3.1.4.2 and 3.1.4.3), the vapour concentration reaches its maximum during the museum opening hours especially during the warm period. This occurs reasonably because of the cumulative effect of masonries moisture evaporation (favoured by the operating of the air heating unit and slight higher radiators set point temperature in winter) and the additional vapour load given by people.

The latter is higher during warm periods as the visitors rate is higher. Since the humidifiers are kept with same schedule throughout the year, they give constant contribution to the air mass moisture enrichment with a maximum threshold of 2.01g/kg (see section 3.1.1).

[4] The variation of a decimal is a consequence of the use of a larger data sample size.

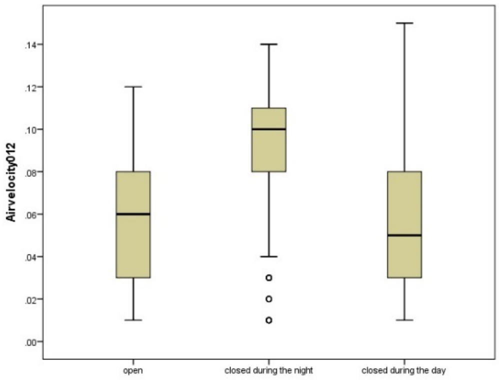

Figure 3.1.4.3; Mean indoor air velocity (012) during the warm period (months 6-7-9) for museum opening days-opening hours (10am-5pm), museum closing days- diurnal hours (10am-5pm) and museum closing days- nocturnal hours (6pm-9am); the outliers in the graph were not considered extreme values, therefore not removed

The relative influence of indoor and outdoor parameters on the increase of air vapour content was quantified by a multiple regression model fitted to the dataset of the entire year, indiscriminately for museum opening and closing hours. The final model explains 94% of the total variance (R 0.969) and includes the following significant parameters: indoor air velocity (a_v), indoor air temperature (T_i) and outdoor mixing ratio (MR_o). The rest of the monitored or calculated environmental parameters and their (2 ways) interactions, were dominated by the three mentioned parameters; hence not significant. The Mixing Ratio (g/kg), in the museum exhibition hall air mass can be defined by means of the relation reported in (3). The Standard Error, standardized Beta coefficients and significance for each parameter are reported in Table 3.1.4.3, while the model summary in reported in Table 5 in Supplementary Data.

$$\mathrm{MR_{in}} = -0.64 + 0.37\ \mathrm{T_{in}} + 2.64\ \mathrm{v_i} + 0.28\ \mathrm{MR_{out}} \qquad (3)$$

Model		Unstandardized Coefficients B	Std. Error	Standardized Coefficients Beta	t	Sig.
3	(Constant)	-0.638	0.089		-7.174	0.000
	Airvelocity012	2.640	0.190	0.087	13.871	0.000
	Temperature012	0.374	0.005	0.576	70.627	0.000
	Mixing Ratio Outside	0.285	0.005	0.481	58.010	0.000

a. Dependent Variable: MixingRatio012

Table 3.1.4.3; Summary of coefficients for the final regression model

In the specific museum conditions and considering the current building use and vapour sources, the increase of indoor air velocity causes vapour concentration increase. More specifically, indoor air with a velocity of 2.64 m/s adds 1g/kg of vapour to the air mass of the space (considering constant the other predictors). It is worth noting that although air velocity is a significant variable, it only explains 2% of the total model variance, the rest is explained by the Mixing Ratio outside (12%) and by the indoor temperature (80%). This occurs because indoor air velocity causes the increase of the vapour content in the exhibition hall not "by definition"[5], but because of the combination between building equipment, management and envelope state of conservation.
Conversely, both indoor air Temperature ($\mathrm{T_i}$) and outdoor Mixing Ratio ($\mathrm{MR_o}$), enable always an increase of indoor vapour concentration. Their respective increase of 0.37°C and 0.29g/kg causes the increase of one unit of vapour concentration in the exhibition hall air volume (again considering one predictor per time with other predictors constant). The model diagnostic is reported in Fig. from 4 to 6 and Table 6 in Supplementary Data.

3.2 Analysis of the masonries results

The previous sections discussed the hygrothermal variability in the exhibition hall caused, inter alia, by moisture presence in the building masonries. In this section, we discuss results regarding the identification of the water infiltrations in the masonries and possible causes of it. An IRT and documentary research was performed with this purpose. Here is reported a summary analysis regarding the North-East building corner. For an extended discussion on methodology and results, the reader may refer to [9].
The mean apparent surface temperature towards the heated exhibition space was observed up to 1.6°C higher than the one towards the unheated tower, indicating the significant heat transfer through the exhibition space masonry.

[5] For instance in the case of nocturnal hours during the cold period the air velocity enables the mixing ratio reduction; see Table 3.1.4.2

The surface temperature distribution was clearly dependent on the indoor air temperature layering and building geometry. Indeed, the mean surface temperature difference between heated and unheated space was observed 0.8°C at the street level (≈2.5m) and 1.6°C at the vaults level (≈7.0 m); see Figure 3.2.1 and 3.2.2 and Tables 7 and 8 in Supplementary Data. This occurs because inside the exhibition hall, the warm air accumulates immediately under the masonry vaults rising the temperature difference indoor-outdoor, hence outer surface temperature. Both in Figure 3.2.1 and on the left side of Figure 3.2.2 it can be seen a regular temperature distribution according to the masonry materials technology (bricks and sandstones). Nevertheless, this regularity is interrupted by the presence of infiltrative water generating sharp surface temperature reductions. Water infiltration was clearly identified between the first and the second floor (at the level of the second floor ceiling beams heads) and immediately above the vault level (first ceiling), under the stone kerb running around the building facades; see Fig. 3.2.6.
Figure 5.2.3 (Table 9 in Supplementary Information), shows the same wall area as in Fig. 3.2.2 but in presence of a sharp and irregular surface cooling caused by water infiltration. In this area, on the first floor, the inner plastered surface is strongly damaged by moisture; see Figure 3.2.4 and Figures 7 - 10 with Tables 10 - 13 in Supplementary Information.
In Fig. 3.2.3 (Table 9 in Supplementary Information), four horizontal lines are drawn on the damp area. Line 1 crosses a moist area on the right side of the window above the kerb, while lines 2 to 4 cross a moist area immediately under it. The minimum surface temperature measured on the four lines within the damp areas ranges between 6.7°C (line 1 and 2) and 7.2°C (line 4). Outside the damp area the surface temperature ranges between 7.7°C (line 2 and 3) and 7.9°C (line 4); (see Fig. 3.2.2). The maximum surface temperature measured on the same lines within the damp areas ranges between 7.5°C (line 1) and 7.7°C (line 3 and 4); see Fig. 3.2.3. While outside the damp area it ranges between 8.4°C (line 2) and 8.8°C (line 4); see Fig. 3.2.2. Clearly, infiltrative water in the masonry is responsible for a surface cooling in all the measured points, this cooling progressively diminishes when the wall dries; namely toward the ground floor (line 4). A detailed description of the surface temperature distribution with identification of surface cooling due to infiltrative water on the North and East Facades is given in Note 1 in Supplementary Information.

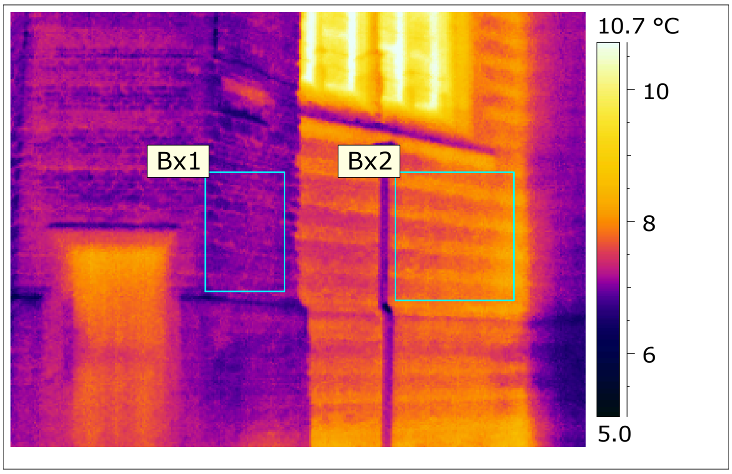

Figure 3.2.1; IRT North-East façade, street level (see corresponding Table 7 in Supplementary Data)

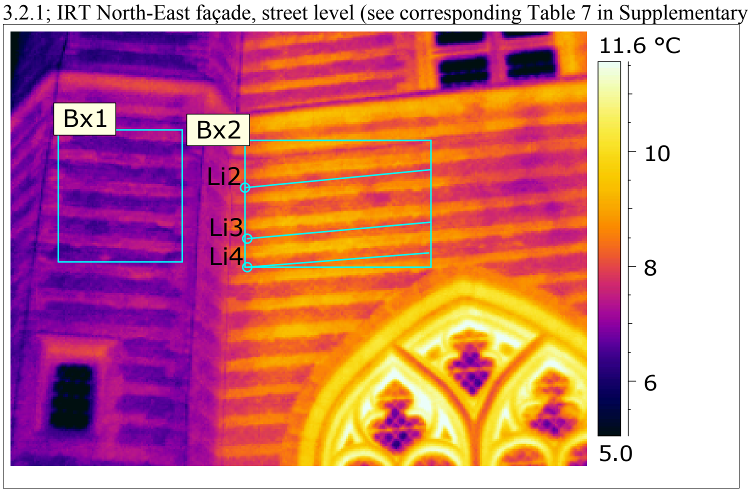

Figure 3.2.2; IRT North-East façade, vaults level (see corresponding Table 8 in Supplementary Data)

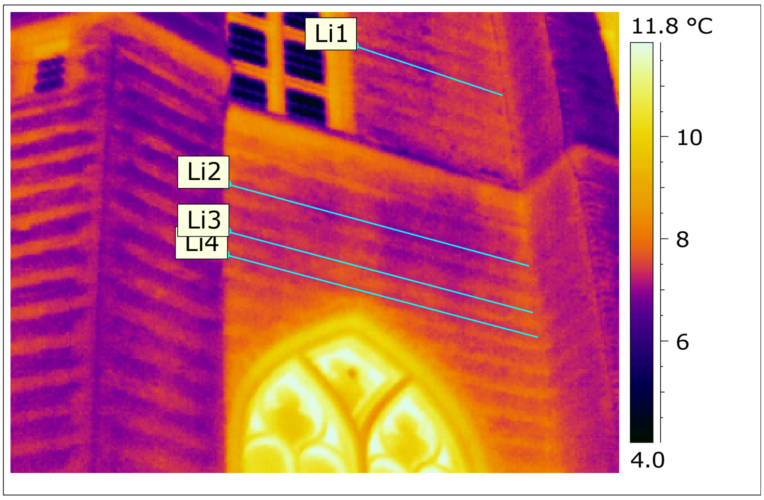

Figure 3.2.3; IRT North-East façade, vaults level (see corresponding Table 9 in Supplementary Data)

Figure 3.2.4; Room at the first floor on the North-East corner; the damage due to moisture in the masonry is extended to the entire inner plaster surface (North façade), especially behind the textile and pews.

On the East façade, the moisture path in the upper part (above the kerb) is identical to the one of the North façade, while the one of the lower part is sharper, see Fig. 3.2.5 (Table 14, Fig. 11 and Table 15 in Supplementary Data). In Fig. 3.2.5, two horizontal lines are drawn for observing the temperature distribution alongside the wall. Line 2 is drawn on the 2nd brick area starting from the window vertex, while Line 1 is drawn on the 4th brick area. The minimum and maximum surface temperature in line 1 (above) is respectively 7.0°C and 8.2°C, while in line 2 (below) is respectively 7.2°C and 8.5°C. Both the lines have average surface temperature of 7.5°C. Clearly, minimum, maximum and mean temperature are remarkably similar to the ones observed on the North façade as well as the absolute surface temperature reduction in presence of water infiltrations; see Note 1 in supplementary information for details.

The problem of water infiltration in the Vleeshuis museum masonries is not recent. In the ‘60s, an extensive restoration of the building began. During the interventions, among others, the heating system was installed, the timber beams in the North-East corner of the building at the roof levels were consolidated by means of screwed metal profiles and all the building facades were cleaned by means of sandblasting. The external facades were finished with silicone-based hydro repellent layer (5% diluted) for avoiding driven rain infiltration. At the end of the works it was noticed that the masonry core was strongly damaged by infiltrative water. Nevertheless, interventions were not carried out in order to solve the problem neither at that time, nor later [34].

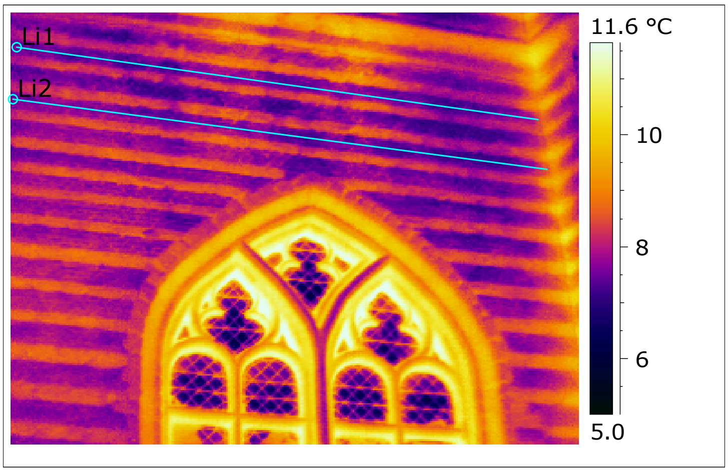

Figure 3.2.5; IRT East façade, vaults level (see corresponding Table 14 in Supplementary Data)

In 2007, to secure the pedestrians from the continuous fall of stones and tiles from the building, a temporary debris collector system was installed (Fig. 3.2.6). The suspended ring scaffold system was attached to the building facades by means of tie-rods and section bars. The sections were screwed, via metal plates, to the building masonries. Because it was ineffective, the system was re installed on a higher position in 2008 and definitively removed in 2009 [34]; Figure 3.2.6 shows the building between the years 2007-2009 with the system installed.

Figure 3.2.6; East facade; current view (upper left) and view between 2007-2009 (lower left) with debris collection system (Vleeshuis museum archive); The tie rods anchors (detail 1) and metal plates (detail 2) of the scaffold are the infiltrative water sources respectively above and below the kerb, see upper and lower IR thermogram (on the right) for detail 1 and 2

By superimposing the IRT thermograms with the building photographic documentation from the previous building restoration interventions and considering the masonries environmental monitoring results discussed in [9], it was possible to identify the metal plates and upper anchors of the tie-rods (removed in 2009) as the water infiltration sources in the building masonries. This is clearly visible if comparing Fig. 3.2.5, Fig. 3.2.6, and Figure 11 in Supplementary Data.

Nevertheless, in the authors opinion, it was not only the installation of the debris collecting system that brought serious damage to all the building boundary masonries (with consequent loss of energy performance [9]) and a serious threat for the housed movable heritage at the first floor, but also the lack of prompt intervention and improper restoration activities. The decision (in the years '60s) to not operate on the moistened masonries core, together with the one of adding a silicone-base waterproofing layer on the outer side of the brick facades, has worsened the scenario. The application of the hydrophobic layer has forced the inwards walls evaporation. Moreover, the evaporation was even accelerated by the heating system installed during the works.

The mentioned improper restoration measures speeded-up the decay of the building thermal and energy performance, and are responsible for indoor efflorescence and mould growth as well as of possible mechanical deterioration and soiling of the artefacts attached to the walls on the first floor.

4. Conclusions

To detect possible building management issues and to consider building –tailored improvement options, it is of fundamental importance performing a holistic building diagnosis.
In the present contribution, we presented a comprehensive study aimed at identifying the possible influence of building envelope state of conservation as well as building and equipment usage on the indoor microclimate variability in the main exhibition hall of the Vleeshuis museum in Antwerp. The here discussed results, together with the ones published by the authors in [9] and [27], clarify the mutual interrelation between the different aspects of building performance and, implicitly, the call for a holistic approach during historic building assessments prior to the design of Energy and Environmental Retrofitting Interventions (EERI).
Moreover, considering the large amount of acquired data and the inherent difficulty given by the multiple research questions at the basis of each building indoor microclimate diagnosis, the conventional microclimate data analysis can be combined, with statistical tests. The resort to statistical analysis in support of physical ones allows a clear identification of the influence of tiny hygrothermal alterations on the global hygrothermal stability.
Although the discussed results report on the microclimate issues of a specific building, the implemented methodology is replicable in others. In fact, the presented procedure, enables to distinguish among sources of microclimate instability and to control the influence of building envelope and equipment performance on the building indoor microclimate. In the specific case of the Vleeshuis museum, the presented methodology allowed to understand the following:

- Since the building is not equipped with a centralized microclimate control system, it is better to tune the present equipment on basis of the internal and external hygrothermal seasonal loads rather than considering a constant schedule throughout the year. For instance, the use of portable humidifiers can be limited to the cold period because during the warm period more moisture enters the space (due to weather conditions and increased visiting rate). This option allows to ensure moisture stability in the exhibition hall throughout the whole year.
- The cultural events in the museum with several participants (e.g., concerts), produce sharp increase of water vapour concentration. It was observed that the additional moisture produced during the concerts is not efficiently extracted at the end of the events and it accumulates in the air volume. For this reason, prompt extraction of the entered moisture is necessary. In case the water vapour concentration outside the building is lower than the one inside, keeping the entrance door open (after the events) for regaining the vapour content balance as before the event, may suffice for this purpose. Otherwise, an exhausts air extractor should be considered.
- Even if the air-heating unit present in the exhibition hall was found not to provoke a strong partialization of the indoor microclimate dangerous for the housed collection, see [27], it alters the indoor hygrothermal dynamics especially by rising the inwards masonries evaporation process.
- The poor building envelope air tightness has a significant influence on the indoor microclimate stability. The air infiltration, dependent on temperature gradient indoor-outdoor, enables both lowering of indoor air temperature and increase of air velocity. During the cold period, in the nocturnal hours, the infiltrative air slows down the masonries evaporation process as a consequence of temperature reduction; similar condition was observed in the nocturnal hours during the warm period.
- The presence of moisture in the building masonries, is not a recent problem. This issue was already documented at the end of the restoration works in the years ‘60s. On that occasion, no prompt intervention was done. With time, water infiltration in the masonries became a severe deterioration cause.
  According to the here discussed results, the causes and sources of recent water infiltration was identified in the points in which a metal scaffold system for debris collections (removed from the building since eight years) was installed onto the building facades. This improper provisional intervention performed in 2007, has endangered almost all the cultural heritage objects present on the first floor of the building. Moreover it has triggered severe masonries deterioration processes with a significant impact on building microclimate and energy performance [9].
- Because of the high inertia of the building masonries, during the warm period, optimal hygrothermal quality is enabled in the Vleeshuis museum main exhibition hall. From this, it can be concluded that this space does not require any cooling system: neither for people thermal comfort improvement, nor for preventive conservation requirements (see also [27]).

References

[1] M. Andretta, F. Coppola, and L. Seccia, “Investigation on the interaction between the outdoor environment and the indoor microclimate of a historical library,” *J. Cult. Herit.*, vol. 17, pp. 75–86, 2016.

[2] J. L. Nguyen, J. Schwartz, and D. W. Dockery, “The relationship between indoor and outdoor temperature, apparent temperature, relative humidity, and absolute humidity,” *Indoor Air*, vol. 24, no. 1, pp. 103–112, 2014.
[3] D. Camuffo, E. Pagan, A. Bernardi, and F. Becherini, “The impact of heating, lighting and people in re-using historical buildings: a case study,” *J. Cult. Herit.*, vol. 5, no. 4, pp. 409–416, Oct. 2004.
[4] M. J. Varas-Muriel, M. I. Martínez-Garrido, and R. Fort, “Monitoring the thermal-hygrometric conditions induced by traditional heating systems in a historic Spanish church (12th-16th C),” *Energy Build.*, vol. 75, pp. 119–132, 2014.
[5] D. Camuffo, R. Van Grieken, H. Busse, G. Sturaro, A. Valentino, A. Bernardi, N. Blades, D. Shooter, F. Deutsch, M. Wieser, O. Kim, and U. Ulrych, “Environmental monitoring in four European museums,” *Atmos. Environ.*, vol. 1, no. 1, 2001.
[6] D. Camuffo, A. della Valle, C. Bertolin, C. Leorato, and A. Bistrot, “Humidity and environmental diagnostics in Palazzo Grimani, Venice,” in *Indoor environment and preservation, climate control in museums and historic buildings*, D. del Curto, Ed. Kermes, 2011, pp. 45–50.
[7] D. D’Agostino, “Moisture dynamics in an historical masonry structure: The Cathedral of Lecce (South Italy),” *Build. Environ.*, vol. 63, pp. 122–133, 2013.
[8] D. Camuffo, “Indoor dynamic climatology: investigations on the interactions between walls and indoor environment,” *Atmos. Environ.*, vol. 17, no. 9, pp. 1803–1809, 1983.
[9] G. Litti, S. Khoshdel, A. Audenaert, and J. Braet, “Hygrothermal performance evaluation of traditional brick masonry in historic buildings,” *Energy Build.*, vol. 105, pp. 393–411, 2015.
[10] E. Lucchi, “Thermal transmittance of historical brick masonries: A comparison among standard data, analytical calculation procedures, and in situ heat flow meter measurements,” *Energy Build.*, vol. 134, pp. 171–184, 2016.
[11] M. I. Martínez-Garrido, S. Aparicio, R. Fort, J. J. Anaya, and M. A. G. Izquierdo, “Effect of solar radiation and humidity on the inner core of walls in historic buildings,” *Constr. Build. Mater.*, vol. 51, pp. 383–394, 2014.
[12] H. S. L. C. Hens, “Envelope and fabric: heat, air and moisture metrics,” in *Applied Building Physic; Ambient Conditions, Building Performance and Materials Properties*, Second., W. A. Brand, Ed. Weinheim: Ernst & Sohn, 2012, pp. 195–248.
[13] M. Sileo, F. T. Gizzi, and N. Masini, “Low cost monitoring approach for the conservation of frescoes: The crypt of St. Francesco d’Assisi in Irsina (Basilicata, Southern Italy),” *J. Cult. Herit.*, vol. 23, pp. 89–99, 2016.
[14] C. Bonacina, P. Baggio, F. Cappelletti, P. Romagnoni, and A. G. Stevan, “The Scrovegni Chapel: The results of over 20 years of indoor climate monitoring,” *Energy Build.*, vol. 95, pp. 144–152, 2015.
[15] M. Ucci, D. Crowther, S. Pretlove, P. Biddulph, T. Oreszczyn, T. Wilkinson, G. Scadding, B. Hart, and D. Mumovic, “Indoor Air Quality and Health,” in *A handbook of Sustainable Building Design and Engineering; An integrated approach to Energy, Healt and Operational Perforformance*, 1st ed., D. Mumovic and M. Santamouris, Eds. UK-USA: Earthscan, 2012, pp. 313–323.
[16] P. Merello, M. C. Perez, J. Perez-Miralles, F. J. Garcia-Diego, A. Fernandez-Navajas, and M. Zarzo, “Basic descriptive statistical methods for monitoring and evaluation of microclimates in Cultural Heritage,” in *Science and Technology for the Conservation of Cultural Heritage*, M. A. Rogerio-Candelera, M. Lazzari, and E. Cano, Eds. London: CRC Press, Taylor and Francis Group, 2013, pp. 11–14.
[17] CTI, *UNI 10829.1999, Works of art of historical importance, Ambient conditions for conservation, Measurement and Analysis*. Italy, 1999.
[18] CEN, *EN 15757 Conservation of Cultural Property-Specifications for temperature and relative humidity to limit climate- induces mechanical damage in organic hygroscopic materilas*, no. January. Belgium, 2010.
[19] S. P. Corgnati and M. Filippi, “Assessment of thermo-hygrometric quality in museums: Method and in-field application to the ‘ Duccio di Buoninsegna’ exhibition at Santa Maria della Scala (Siena, Italy),” *J. Cult. Herit.*, vol. 11, no. 3, pp. 345–349, 2010.
[20] S. P. Corgnati, V. Fabi, and M. Filippi, “A methodology for microclimatic quality evaluation in museums: Application to a temporary exhibit,” *Build. Environ.*, vol. 44, no. 6, pp. 1253–1260, Jun. 2009.
[21] J. Ferdyn-Grygierek, “Monitoring of indoor air parameters in large museum exhibition halls with and without air-conditioning systems,” *Build. Environ.*, vol. 107, pp. 113–126, 2016.
[22] F. Sciurpi, C. Carletti, G. Cellai, and L. Pierangioli, “Environmental monitoring and microclimatic control strategies in ‘La Specola’ museum of Florence,” *Energy Build.*, Oct. 2014.

[23] H. E. Silva and F. M. A. Henriques, “Hygrothermal analysis of historic buildings-Statistical methodologies and their applicability in temperate climates,” *Struct. Surv.*, vol. 34, no. 1, pp. 12–23, 2016.
[24] H. E. Silva and F. M. a. Henriques, “Microclimatic analysis of historic buildings: A new methodology for temperate climates,” *Build. Environ.*, vol. 82, pp. 381–387, Dec. 2014.
[25] F. J. García-Diego and M. Zarzo, “Microclimate monitoring by multivariate statistical control: The renaissance frescoes of the Cathedral of Valencia (Spain),” *J. Cult. Herit.*, vol. 11, no. 3, pp. 339–344, 2010.
[26] P. Merello, F. J. García-Diego, and M. Zarzo, “Diagnosis of abnormal patterns in multivariate microclimate monitoring: A case study of an open-air archaeological site in Pompeii (Italy),” *Sci. Total Environ.*, vol. 488–489, no. 1, pp. 14–25, 2014.
[27] G. Litti, A. Audenaert, and K. Fabbri, “Indoor Microclimate Quality (IMQ) certification in heritage and museum buildings: The case study of Vleeshuis museum in Antwerp,” *Build. Environ.*, vol. in Press, 2017.
[28] G. Litti, A. Audenaert, and J. Braet, “Indoor thermal quality in heritage buildings: combined assessment for works of art and people comfort,” in *Energy Efficient Restoration International Conference*, 2015, pp. 31–43.
[29] CEN, *NBN EN 13187 Thermal Performance of Buildings - Qualitative detection of thermal irregularities in building envelopes-Infrared method (ISO 6781:1983 modified)*. 1999, pp. 1–21.
[30] Vaisala oyj, “Humidity conversion formulas - Calculation formulas for humidity,” *Humidity Convers. Formulas*, p. 16, 2013.
[31] D. Camuffo, E. Pagan, H. Schellen, D. Limpens Neilen, R. Kozlowski, L. Bratasz, and S. Rissanen, *Church Heating and Preservation of the Cultural Heritage: A Practical Guide to the Pros and Cons of the Various Heating Systems*, Electa Mon. Milan: Electa Mondadori, 2007
[32] L. a. Wallace, S. J. Emmerich, and C. Howard-Reed, “Continuous measurements of air change rates in an occupied house for 1 year: The effect of temperature, wind, fans and windows,” *J. Expo. Anal. Environ. Epidemiol.*, vol. 121, pp. 296–306, 2002.
[33] D. Camuffo, E. Pagan, S. Rissanen, Ł. Bratasz, R. Kozłowski, M. Camuffo, and A. della Valle, “An advanced church heating system favourable to artworks: A contribution to European standardisation,” *J. Cult. Herit.*, vol. 11, no. 2, pp. 205–219, 2010.

[34] Origin, “Museum Vleeshuis Antwerpen-Restauratie van de gevels en daken- Bouwhistorische studie,” Brussels, 2010.

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 (131439).

Appendix

Saturation Pressure of Water vapour (V_{ps}); from [30]

$$(V_{ps}) = \frac{e^{(77.3435 + 0.0057(273(k) + T(°C)) - \frac{7235}{273(K) + T(°C)}}}{(273(K) + T(°C))^{8.2}} \text{ (Pa)} \quad (1)$$

Pressure of Water vapour (V_p); from [30]

$$V_P = V_{ps} * (RH/100); \text{ (hPa)} \quad (2)$$

Absolute humidity; from [30]

$$AH = C * V_p/T; \text{ (g/m}^3\text{)} \quad (3)$$

Mixing Ratio; from [30]

$$MR = B * V_p/(P_{tot} - V_{p)}; \text{ (g/kg); where } P_{tot} = \text{Absolute air pressure (hPa) and B= 621.9907 (g/kg)} \quad (4)$$

SUPPLEMENTARY DATA_FIGURES

Figure 1; 1964; water infiltration through the stained glasses; source Vleeshuis archive

Figure 2; 1964; water infiltration through the stained glasses and soiled masonry; source Vleeshuis archive

Figure 3; 1964; water infiltration through the vault; source Vleeshuis archive

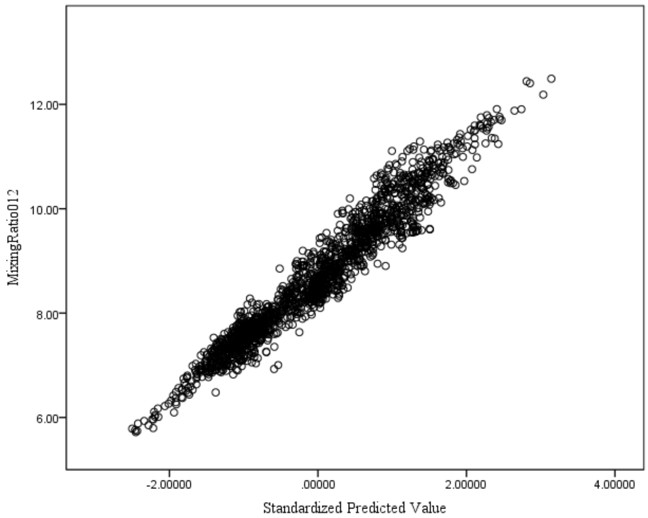

Figure 4; Test of linearity; standardized predicted values VS Mixing Ratio 012 (predicted outcome); (R 0.88)

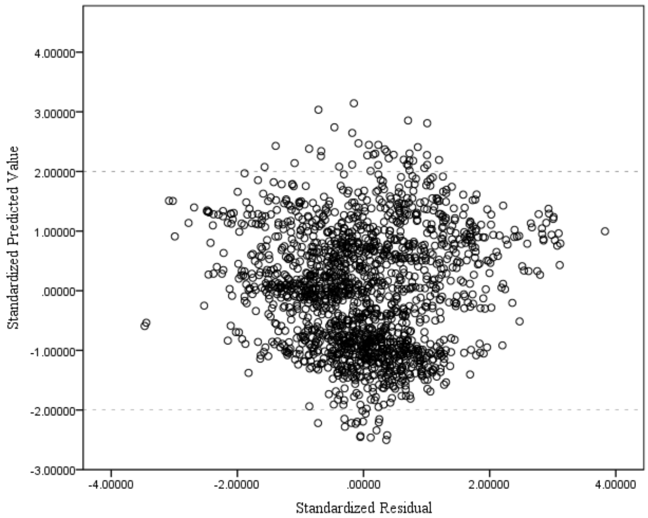

Figure 5; Test of homoscedasticity; standardized residuals VS standardized predicted outcomes

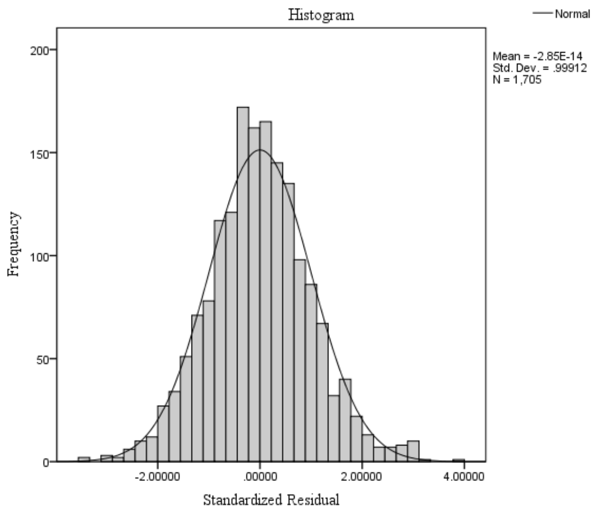

Figure 6; Test of Normality of distribution of (standardized) residuals

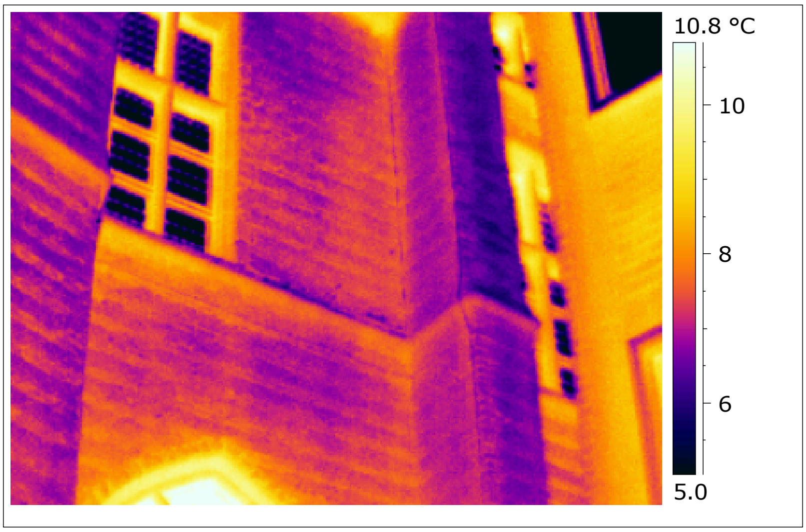

Figure 7; IRT North-East façade (see table 10 for details)

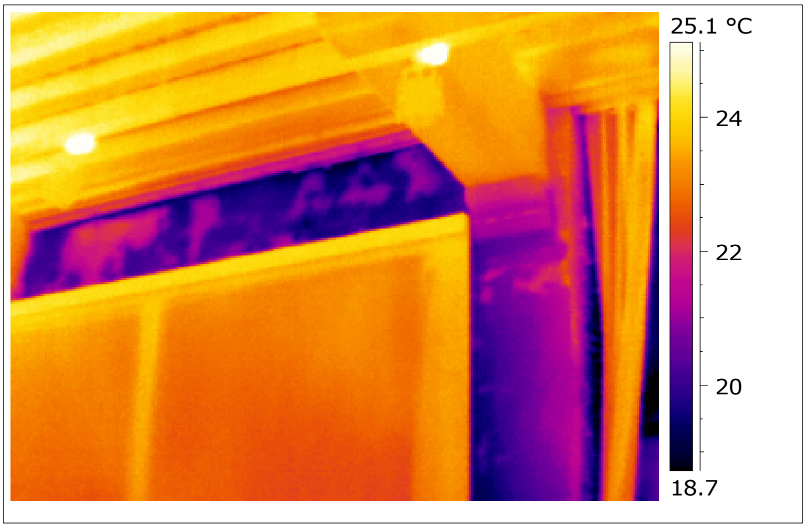

Figure 8; IRT North-East façade; indoor wall surface damage between the second and the first floor (see table 11 for details)

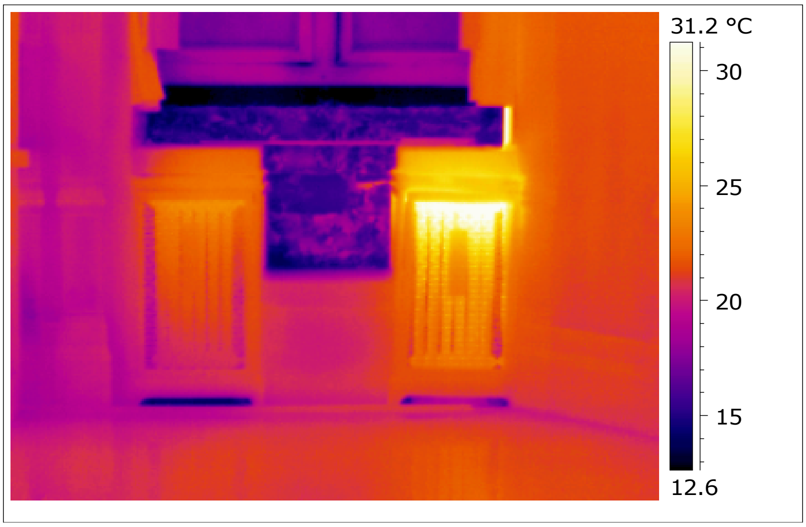

Figure 9; IRT North-East façade; indoor wall surface damage in correspondence of the window (see table 12 for details)

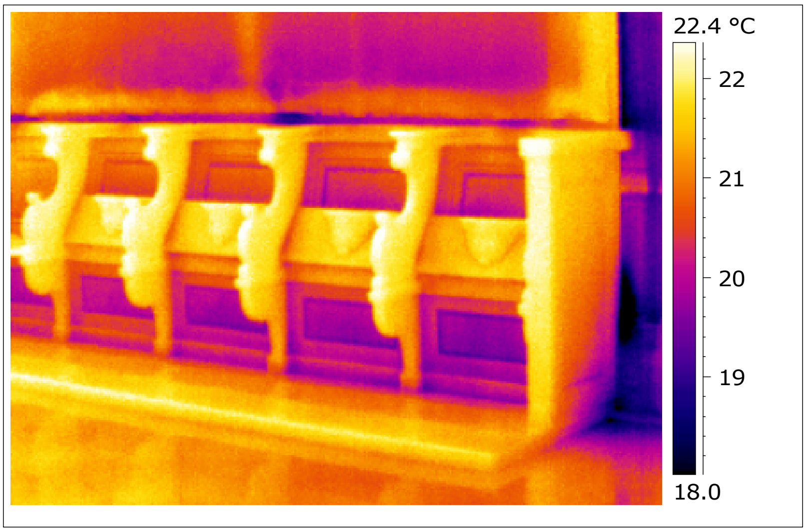

Figure 10; IRT North-East façade; surface cooling behind the textile and the pews (see table 13 for details)

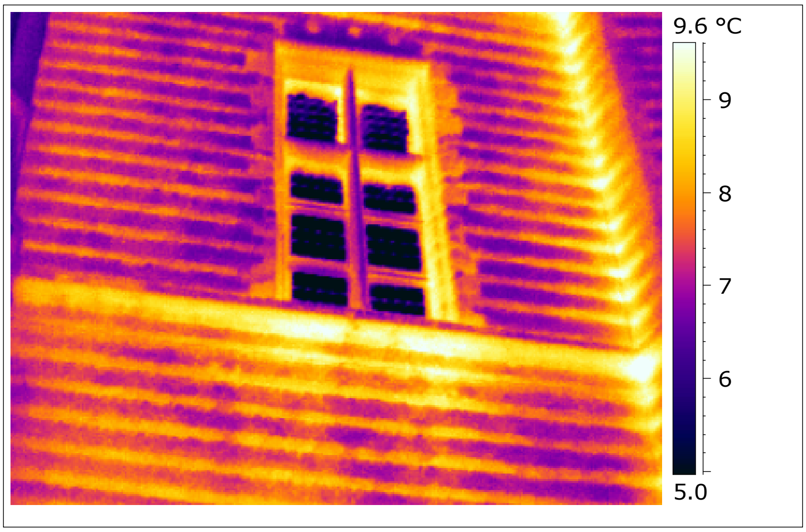

Figure 11; IRT East façade, first floor level (see table 15 for details)

Fig. 12; First floor level; typical localisation of radiators under a window on the first floor of the building. The wall is deteriorated due to inwards water infiltration and forced evaporation (accelerated by the heating system)

_Note 1_Infra Red Thermography on the North and East facades

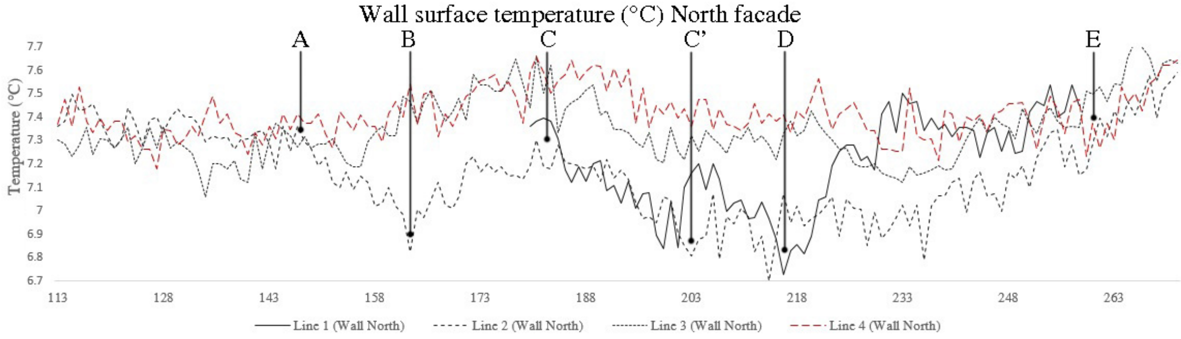

Figure 1; North façade; brick masonry courses surface temperature; Lines 1 to 4 as drawn in thermogram in Fig. 3.2.3 (in the text); the letters indicate the beginning of the moist areas; the x axis starts from the origin of the lines 2,3,4 indicated in Fig. 3.2.3 (IR thermogram cells)

In Fig. 1 (related to Fig. 3.2.3 in the text) it can be seen that all the curves have an initial value between 7.2°C and 7.5°C (line four is not present as it starts at the right side of the window) and the average surface temperature for each one of the four line in the moist area lies in the same temperature range: between 7.1°C and 7.4°C; see Table 9 in Supplementary Data.
All the four lines cross the damp area but in different points: lines 1 and 2 cross the damp above it, while lines 3 and 4 are progressively distant from it. The surface temperature curves in Fig. 1 can be explained as follows:

- The surface temperature of line 2 drops of 0.7°C when the water path is crossed (see segment A-B) and it increases again after the moist area of 0.45°C (segment B-C). This surface temperature increase might be caused by the presence of the radiators inside (Fig. 12 in Supplementary Data).
- A damp area causes a new surface temperature reduction of 0.6°C (segment C-D), and immediately afterwards the surface gradually warms up again toward the right side (segment D-E).
- Although on the right side of Figure 3.2.3 (in the text) and Fig. 1, less accurate temperature readings are expected because of border effects, it can be seen that the temperature stabilizes again around the initial average temperature.

Above the kerb, line 1 crosses another moist area.

- The surface temperature readings, start from a positive pick –occurred most likely because of the same reason observed for line 2 (internal radiators, Fig. 12 in Supplementary Data). After this, the temperature drops by 0.55°C (segment C-C').
- Due to unclear circumstances (perhaps a water path variation in the inner core of the masonry), the brick surface regains 0.33°C but the temperature trend is however not varied, indeed it decreases again by 0.48°C (segment C'-D), reaching the same surface temperature as in line 2.
- Temperature cooling for both lines 1 and 2 follows the same linear curve and reaches the lowest value of 6.7°C.
- As already mentioned, when the moist area diminishes, surface temperatures stabilizes in the range of the temperature average (segment C'-D).

The surfaces measured by the lines 3 and 4, as located further away from the damp areas (and most likely from the infiltrative water source), are less influenced by the water cooling, indeed the absolute amplitude of the temperature oscillation for the two curves is smaller than the one measured for curves 1 and 2. Nevertheless, the temperature distribution of the two areas alongside the wall (see line 3 and 4 in Fig. 1), is positively correlated to the one of the two upper areas. Pearson correlation coefficient between line 2 and line 3 and between line 3 and line 4 is R 0.32 and R 0.55 respectively.

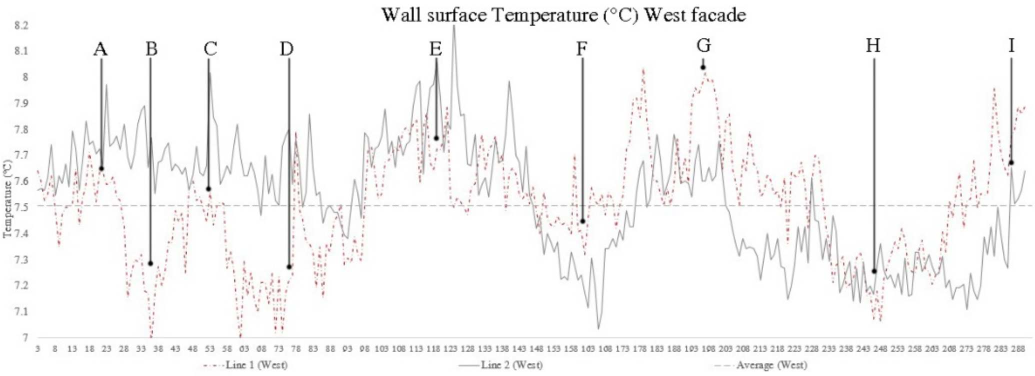

Figure 2; East façade; brick masonry courses surface temperature; Lines 1 to 2 as drawn in thermogram in Fig. 3.2.5 (in the text); the letters indicate the beginning of the larger moist areas; the x axis starts from the origin of the lines indicated in Fig. 3.2.5 (IR thermogram cells)

Similarly to what is observed on the north façade, in the initial part of the lines, before the damp areas, the surface temperature of both the lines is around the average value (±7.5°C); see Fig. 2. Further the following should be observed:

- When line 1 crosses the damp area, the temperature drops by 0.6°C (segment A-B).
- Immediately after, probably because of a water infiltration path variation, it rises back to the average value (segment B-C) and again a moist spot provokes a temperature reduction of 0.61°C (segment C-D). At this point, corresponding to the first radiator inside (Fig. 12 in Supplementary Data), surface temperature from line 1 rises of 0.85°C (segment D-E).
- When the influence of the radiators is ended the temperature decreases to the average value because no water infiltration is present (segment E-F).
- Afterwards, a second radiator behind the wall enables a temperature increase of 0.70°C (segment F-G, Fig. 12 in Supplementary Data), but still a sudden temperature cooling is observable. It is worth noting that the surface temperature reaches a higher value (than the one in point E) as the initial temperature is higher.
- The beginning of another water infiltration causes the temperature to drop of 1.0°C (segment G-H). After this point the temperature increases stabilizing around the average temperature but, again, border effects might affect the temperature readings.

Line 2, follows the same trend of line 1, therefore the considerations above discussed are still valid with the only exception being the first moist area which does not affect strongly the temperature of line 2. This may be explained by a less intense downward water infiltration flow. However, immediately after the first radiator, see point D, the trend of curve 2 is correlated to the one in 1 (R 0.52). Moreover, as already observed in line 1 (segment F-G), because the surface temperature prior to the radiator influence was around the mean value, a more significant surface temperature increase was enabled. It is also remarkable that the central water spot, provokes a more severe surface temperature cooling of line 2 compared to line 1. This might be caused by water accumulation in the masonry.

SUPPLEMENTARY DATA_TABLES

	Percentiles (months 11-12-1-2)											
	5	10	25	50	75	90	95	Mean	SE	Min	Max	S Dev
Temperature012	15.79	16.19	16.78	17.54	18.35	19.13	19.66	17.59	0.02	13.97	20.87	1.15
Temperature014	16.10	16.49	17.27	18.01	18.88	19.79	20.32	18.08	0.03	14.31	21.50	1.24
Temperature015	15.79	16.19	16.91	17.68	18.50	19.35	19.79	17.72	0.02	13.89	21.18	1.20
RelativeHumidity012	56.38	57.43	58.75	59.82	61.25	65.05	66.38	60.43	0.06	53.35	69.51	2.88
RelativeHumidity014	52.86	54.15	55.95	57.38	59.01	62.98	64.51	57.85	0.07	47.93	68.56	3.39
RelativeHumidity015	55.60	56.37	57.90	59.24	60.82	64.79	66.29	59.82	0.06	52.45	70.27	3.19

Table 1; Descriptive statistics for Temperature and Relative Humidity in the cold period (condition a)

	Percentiles (months 6-7-9_condition a)											
	5	10	25	50	75	90	95	Mean	SE	Min	Max	S Dev
Temperature012	20.29	20.54	21.02	21.52	22.09	22.56	22.88	21.54	0.02	19.41	24.23	0.78
Temperature014	20.34	20.65	21.10	21.64	22.24	22.78	23.09	21.67	0.02	19.26	24.62	0.84
Temperature015	20.35	20.63	21.14	21.71	22.36	22.89	23.26	21.75	0.02	19.32	24.68	0.88
RelativeHumidity012	58.59	59.28	60.43	61.86	64.53	66.56	67.21	62.45	0.07	56.77	69.11	2.67
RelativeHumidity014	56.00	57.75	58.99	60.45	63.10	65.70	66.48	61.03	0.08	52.33	68.71	3.06
RelativeHumidity015	58.20	58.75	60.22	61.83	64.25	66.64	67.42	62.27	0.08	55.77	69.60	2.83

Table 2; Descriptive statistics for Temperature and Relative Humidity in the warm period (condition a)

	Percentiles (months 6-7-9_condition b)											
	5	10	25	50	75	90	95	Mean	SE	Min	Max	S Dev
Temperature012	20.96	21.18	21.64	22.46	23.48	24.53	24.73	22.62	0.16	20.63	26.00	1.22
Temperature014	21.14	21.44	21.95	22.83	23.60	24.75	25.01	22.89	0.16	20.65	26.55	1.23
Temperature015	21.41	21.71	22.12	23.01	23.67	24.80	25.08	23.06	0.16	20.88	27.01	1.21
RelativeHumidity012	60.86	61.32	63.07	64.83	65.40	65.93	66.20	64.20	0.22	60.60	66.40	1.64
RelativeHumidity014	60.12	60.22	61.73	63.31	64.82	65.51	65.71	63.14	0.24	59.85	66.12	1.80
RelativeHumidity015	60.20	60.61	61.91	63.49	64.69	66.01	66.51	63.41	0.25	59.77	66.88	1.87

Table 3; Descriptive statistics for Temperature and Relative Humidity in the warm period (condition b)

moths 11-12-1-2_a	Percentiles									
	5.00	10.00	25.00	50.00	75.00	90.00	95.00	Min	Max	SD
ROOTSQ DT 012	5.81	7.08	9.09	11.82	14.04	16.01	17.44	0.22	23.41	3.53
ROOTSQ MR 012	1.02	1.32	2.00	2.70	3.36	3.76	3.98	0.01	5.38	0.92
ROOTSQ RH 012	7.09	12.19	18.42	24.07	27.94	30.45	31.69	0.10	36.58	7.32
moths 6-7-9_a										
ROOTSQ DT 012	1.00	1.81	3.89	5.84	7.56	8.98	9.80	0.02	13.54	2.64
ROOTSQ MR 012	0.22	0.48	1.04	1.70	2.54	3.06	3.34	0	5.11	0.97
ROOTSQ RH 012	1.64	3.09	8.06	16.06	23.06	26.95	28.05	0.04	33.97	8.72
moths 6-7-9_b										
ROOTSQ DT 012	0.29	0.41	1.46	3.01	4.35	5.73	6.71	0.06	7.1	1.93
ROOTSQ MR 012	0.24	0.32	0.51	0.91	1.73	2.16	2.68	0.12	3.23	0.75
ROOTSQ RH 012	0.23	0.68	2.51	5.41	9.90	16.00	17.96	0.04	20.16	5.24

Table 4; Point 012 summary statistics and percentiles for the cold (11-12-1-2) and warm (6-7-9) period in condition a) and b); Root Square of the Root Squared Error of Temperature gradient inside-outside, Mixing Ratio gradient (MR) and Relative Humidity gradient (RH)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.133[a]	0.018	0.017	1.24344	0.018	30.815	1	1703	0.000
2	.906[b]	0.821	0.821	0.53114	0.803	7631.398	1	1702	0.000
3	.969[c]	0.940	0.940	0.30786	0.119	3365.132	1	1701	0.000

Table 5; Multi regression model summary; *a. Predictors: (Constant), Airvelocity012; b. Predictors: (Constant), Airvelocity012, Temperature012; c. Predictors: (Constant), Airvelocity012, Temperature012, Mixing Ratio Outside; d. Dependent Variable: MixingRatio012*

1) Additivity and linearity; the model was tested for linear relationship between (standardized) predicted values and Mixing Ratio 012 (outcome); the resulting linear relationship was significant ($p<0.001$; R 0.88); see Fig. 4 in Supplementary Data
2) Homoscedasticity; the model was tested for homoscedasticity verifying whether the model residuals variance was constant at each level of the model predictors; no assumption violation was evidenced; see Fig. 5 in Supplementary Data
3) Normality of errors distribution; the model was tested for normality of errors distribution by means of QQ plot of the standardized residuals and a frequency-histogram graph with the normal distribution curve on it displayed. The residuals can be considered rather normally distributed; see Fig. 6 in Supplementary Data
4) Non perfect multicollinearity; the highest correlation coefficient between variables is between indoor air temperature and outdoor mixing ratio (R 0.69), the other pairwise correlation were lower than it; therefore no concern of multicollinearity is found.
5) No null- variance; as said above, the predictor with lower explained variance in the model is the indoor air velocity that however was not null. No issues of zero variance within the predictors are found.

Table 6; Summary of regression model diagnostic

Bx1 Max. Temperature	7.4 °C
Bx1 Min. Temperature	6.7 °C
Bx1 Average Temperature	7.1 °C
Bx2 Max. Temperature	8.4 °C
Bx2 Min. Temperature	7.4 °C
Bx2 Average Temperature	7.9 °C
Emissivity	0.93
Date	04/03/2014
Time	19:34
Outdoor Temperature	7°C
Outdoor Relative Humidity	82%
Indoor Temperature	19°C
Indoor Relative Humidity	58%

Table 7; Parameters Table referring to Fig.3.2.1 in the text

Bx1 Max. Temperature	7.8 °C
Bx1 Min. Temperature	6.3 °C
Bx1 Average Temperature	6.9 °C
Bx2 Max. Temperature	9.6 °C
Bx2 Min. Temperature	7.4 °C
Bx2 Average Temperature	8.5 °C
Li2 Max. Temperature	8.4 °C
Li2 Min. Temperature	7.7 °C
Li3 Max. Temperature	8.7 °C
Li3 Min. Temperature	7.7 °C
Li4 Max. Temperature	8.8 °C
Li4 Min. Temperature	7.9 °C
Li2 Average Temperature	8.1°C
Li3 Average Temperature	8.3°C
Li4 Average Temperature	8.3°C
Emissivity	0.93
Date	04/03/2014
Time	19:19
Outdoor Temperature	7°C
Outdoor Relative Humidity	82%
Indoor Temperature	19°C
Indoor Relative Humidity	58%

Table 8; Parameters Table referring to Fig. 3.2.2 in the text

Li1 Max. Temperature	7.5 °C
Li1 Min. Temperature	6.7 °C
Li2 Max. Temperature	7.6 °C
Li2 Min. Temperature	6.7 °C
Li3 Max. Temperature	7.7 °C
Li3 Min. Temperature	7.1 °C
Li4 Max. Temperature	7.7 °C
Li4 Min. Temperature	7.2 °C
Li1 Average Temperature	7.2 °C

Li2 Average Temperature	7.1 °C
Li3 Average Temperature	7.3 °C
Li4 Average Temperature	7.4 °C
Date	04/03/2014
Time	19:42
Outdoor Temperature	7°C
Outdoor Relative Humidity	82%
Indoor Temperature	19°C
Indoor Relative Humidity	58%

Table 9; Parameters Table referring to Fig. 3.2.3 in the text

Date	04/03/2014
Time	19:42
Outdoor Temperature	7°C
Outdoor Relative Humidity	82%
Indoor Temperature	19°C
Indoor Relative Humidity	58%

Table 10; Parameters Table referring to Fig. 7

Date	05/03/2014
Time	15:44
Outdoor Temperature	11.6°C
Outdoor Relative Humidity	47%
Indoor Temperature	20°C
Indoor Relative Humidity	59%
Emissivity	0.93

Table 11; Parameters Table referring to Fig. 8

Date	05/03/2014
Time	15:41
Outdoor Temperature	11.6°C
Outdoor Relative Humidity	47%
Indoor Temperature	20°C
Indoor Relative Humidity	59%
Emissivity	0.93

Table 12; Parameters Table referring to Fig. 9

Date	05/03/2014
Time	15:50
Outdoor Temperature	11.6°C
Outdoor Relative Humidity	47%
Indoor Temperature	20°C
Indoor Relative Humidity	59%

Table 13; Parameters referring to Fig. 10

Li1 Min. Temperature	7.0 °C
Li2 Min. Temperature	7.2 °C
Li1 Max. Temperature	8.2 °C
Li2 Max. Temperature	8.5 °C
Li1 Average Temperature	7.5 °C
Li2 Average Temperature	7.5°C
Li2 Emissivity	0.93
Date	04/03/2014
Time	19:29
Outdoor Temperature	7°C
Outdoor Relative Humidity	82%
Indoor Temperature	19°C
Indoor Relative Humidity	58%

Table 14; Parameters Table referring to Fig. 3.2.5 in the text

Date	04/03/2014
Time	19:29
Outdoor Temperature	7°C
Outdoor Relative Humidity	82%

Indoor Temperature	19°C
Indoor Relative Humidity	58%

Table 15; Parameters Table referring to Fig. 11