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Strategies for the deployment of microclimate sensors in spaces housing collections

Francesca Frasca[1], Elena Verticchio[1], Andrea Peiró-Vitoria[2,3], Andreas Grinde[4], Alessandro Bile[5], Claudio Chimenti[6], Cecilia Conati Barbaro[7], Gabriele Favero[8], Eugenio Fazio[5], F-J Garcia-Diego[9] and Anna Maria Siani[1*]

Abstract

The study of the microclimate is pivotal for the protection and conservation of cultural heritage. This paper describes specific procedures aimed at the deployment of microclimate sensors in spaces housing collections (e.g., museums) under different scenarios. The decision making involves a multidisciplinary discussion among museum manager, conservator and conservation scientist and implies five steps. Since the sensor's deployment depends on the number of available sensors, we have identified two possible circumstances: (a) *artwork-related deployment* (i.e., there are as many sensors as the number of artworks) and (b) *artwork-envelope-related deployment* (i.e., the number of available sensors is less than the number of artworks). The former circumstance is advisable when the artwork is often moved from a museum to another one. The latter circumstance is usually the case of permanent collections, and, according to the Museum Scenario (MS), the related procedures can be further subdivided into basic (MSI and MSII) and advanced (MSIII and MSIV). Advanced procedures are preferable over basic procedures when several time series of microclimate data have been collected for at least one calendar year in several sampling points. All these procedures make it possible to design where to deploy sensors both in the case of an initial deployment and of optimisation of already installed sensors.

Keywords: Microclimate, Sensor deployment, Artwork-related deployment, Artwork-envelope-related deployment, Preventive conservation, Decision making, Space housing collections, Museums

Introduction

The durability of artworks exposed to the outdoor and indoor climate depends on the vulnerability of the material type to specific climatic impacts. The study of the indoor climate conditions surrounding an artwork, namely the microclimate, is pivotal for the protection and conservation of cultural heritage. Indeed, agents such as temperature, humidity, air flows, light, and pollution can act on materials either independently or in synergy over a short- and/or long-term time scale, leading to direct and indirect effects, triggering and/or accelerating the rate of material degradation.

Over the years, monitoring the microclimate has become an increasingly common practise to study the agents causing climate-induced deterioration of artworks [1, 2]. Sensors devoted to microclimate monitoring in spaces housing collections (e.g., archive, church, gallery, library, museum) must comply with specific requirements in terms of their technical features and location (i.e., the measuring point), in the same way as it is recommended for stations for weather observations by the World Meteorological Organisation [3]. To the preventive

*Correspondence: annamaria.siani@uniroma1.it

[1] Department of Physics, Sapienza University of Rome, P.le Aldo Moro 5, 00185 Rome, Italy
Full list of author information is available at the end of the article

conservation purpose, specific European standards were published which recommend the minimum technical features of the sensors for measurements of temperature and relative humidity [4, 5]. However, there are neither norms nor procedures that provide a guidance to deploying sensors to monitor the environmental variables in spaces housing collections, except for suggestions to locate them as close as possible to the artwork [4, 5]. The common practice is that sensors' deployment is based on the operator's experience and competence involved in that task [6]. In the framework of preventive conservation of artworks housed in indoor spaces, very few papers describe the rationale behind the identification of the number and location of measuring points for microclimate monitoring (Table 1). It is worth noticing that: (i) methodologies for sensors deployment imply different approaches; (ii) methodologies for sensors deployment are applied to several types of spaces housing collections (e.g., church, library, museum); (iii) temperature (T) and relative humidity (RH) are the most frequently measured indoor climate variables. Although some studies have addressed the issue on the deploying sensors in other indoor environments (e.g. residential buildings, offices) [7, 8], none of them provide enough details to be straightforwardly transferred to the sensors' positioning in spaces housing collections.

This paper describes specific procedures aimed at the deployment of sensors for microclimate monitoring in spaces housing collections under different scenarios. In this context, the term "museum scenario" refers to contexts associated with the availability of collected microclimate data over a sufficiently long period (i.e., at least one calendar year or multiple years) and/or with the possibility to conduct microclimate measurements campaigns. Furthermore, based on the information on the spaces gathered during the preliminary visual inspection, the procedures proposed here make it possible to design where to deploy sensors in the case both of a first guess (or initial) deployment and of optimisation/improvement of already installed sensors. Since the sensor's deployment depends on the number of available sensors, we have identified two possible circumstances: (a) *artwork-related deployment* (i.e., there are as many sensors as the number of artworks) and (b) *artwork-envelope-related deployment* (i.e., the number of available sensors is less than the number of artworks). The former circumstance (a) is advisable when the artwork is often moved from a museum to another one. The latter circumstance (b) is usually the case of permanent collections and the related procedures can be further subdivided into basic and advanced.

This paper represents the first attempt to provide practical guidance on the deployment of sensors also through the analysis and interpretation of the measured data. This guidance would hopefully become useful to less experienced collection managers or conservation professionals embarking on installing or modifying microclimate monitoring in spaces housing collections.

The topic of this paper represented a milestone of the H2020 EU project CollectionCare–Innovative and

Table 1 Studies explaining the rationale behind the deployment of measuring points for indoor climate monitoring.

Refs.	Type of spaces housing collections	Indoor climate variables	Methodology for sensors deployment
[9]	Archaeological site	T, RH	Thermographic measurements
[10]	Castle	T, RH	Adoption of well-established criteria [6], Table 2
[11]	Church	T, RH, Ts, V	
[12]	Monastery	T, RH, CO_2	
[13]	Library	T, RH	Microclimate measurement campaigns on 2-D virtual grid
[14]	Museum	T, RH	Signal propagation and coverage of wireless sensors
[15]	Palaces	T, RH	
[16]	Archaeological site	T, RH, E, CO_2, O_2	Sampling Design method
[17]	Cathedral	T, RH	Microclimate measurement campaigns on 3-D virtual grid
[18]	Temple	T, RH, V	Lowest aesthetic impact, measuring points easily reachable
[19]	Gallery	T, RH	
[20]	Palace	T, RH, Ts	Restoration theories
[21]	Gallery	T, RH, Ts, CO_2	
[22]	Museum	T, RH	Multivariate statistics to optimise the current measuring points
[23]	Cathedral	T, RH	
[24]	Castle/Museum	T, RH	

CO_2 carbon dioxide concentration, *E* irradiance, *O_2* oxygen concentration, *RH* relative humidity, *T* temperature, *Ts* surface temperature, and *V* air flow

affordable service for the Preventive Conservation monitoring of individual Cultural Artefacts during display, storage, handling, and transport (Grant Agreement n 814624) [25].

The paper is structured into three main sections. "Methodology" Section is devoted to the description of the methodology for sensor deployment through the identification of five procedures. In "Results and discussion" Section some practical examples of the application of the procedures in real contexts are outlined. Conclusions summarise the advantages and limitations of the proposed procedures.

Methodology

A multidisciplinary discussion

Every preventive action should be based on effective multidisciplinary collaboration among different experts. Specifically, in the design of the sensors' deployment, we pinpointed three possible experts actively taking part in the decision making (Fig. 1): the manager, the conservator, and the conservation scientist. The manager could be the person in charge for the administration of the spaces housing collections, the collector, or the owner of the collection. The conservator is responsible for the preservation, treatment, and technical research of artworks. The conservation scientist is a professional with specific expertise on microclimate, data mining, and climate-induced deterioration processes.

The decision making on the sensors' deployment can involve five steps (Fig. 1):

(1) Identification of the problem

Experts *Manager, conservator, and conservation scientist.*

Scope: to understand whether the monitoring is devoted to the characterisation of the indoor climate of the whole conservation space or to the risk assessment posed by the climate to specific artworks [26].

(2) Collection of information

Experts *Manager, conservator, and conservation scientist.*

Scope: to collect all relevant information on the spaces housing collections on available sensors and on climate-sensitive or damaged artworks.

(3) Procedure for the sensors' deployment

Experts *Manager, conservator, and conservation scientist.*

Scope: to identify the most suitable procedure for sensors' deployment and possible alternatives.

(4) Implementation of actions

Experts *Conservator, and conservation scientist.*

Scope: to install sensors.

(5) Revision of the configuration

Responsible *Conservation scientist.*

Scope: to analyse environmental data collected after at least one year of monitoring and, together with the conservator, discuss upon the conservation state of selected artworks.

However, it has to be noticed that often the final decision on sensors' deployment is likely to be competing with other issues, such as the available budget to

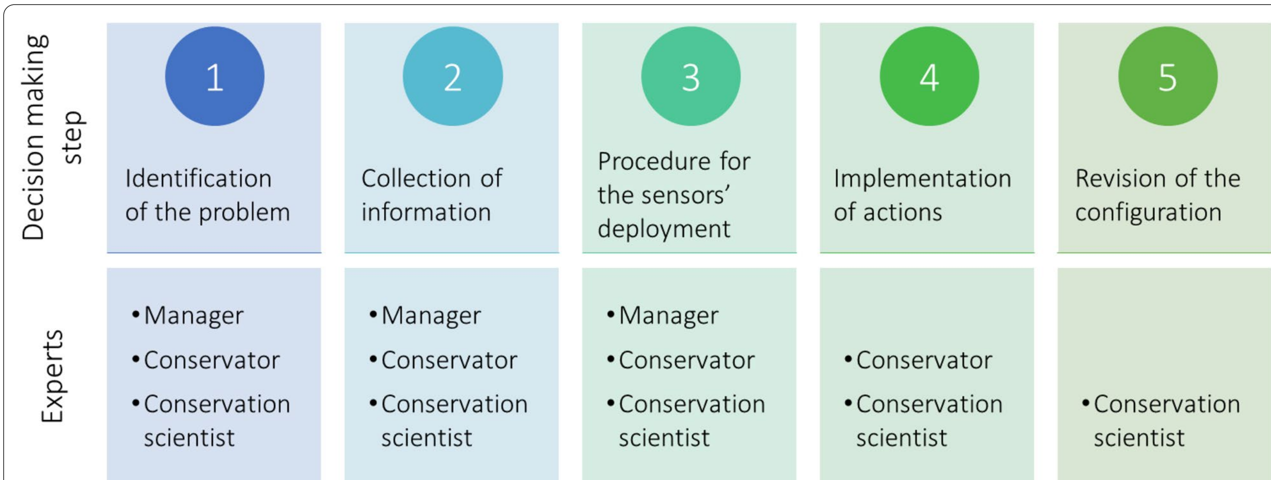

Fig. 1 Schematic workflow of the decision-making process about the microclimate monitoring design and implementation in spaces and experts involved in each step

purchase new and/or maintain existing sensors; human resources (e.g., the staff involved in implementing the decision has not skills and expertise); and technology (e.g., the lack of sensors in accordance with standards may invalidate the decision making).

How many sensors to install

A rational approach for decision making is to apply the so-called Five Ws and One H method (hereafter called 5Ws1H), widely used in journalism and research to gather information about certain topics [27]. The acronym 5Ws1H stands for the questions whose answers can help to obtain a 360° view on a given issue: Why?, What?, Where?, When?, and Who? (the five W questions) and How many? (the one H question). Steps 1 and 2 of the decision making imply the identification of the need for indoor climate monitoring and the collection of useful information. Here, it is important to clearly answer to:

- W1—Why is there a need for microclimate monitoring? The answer aims to identify the triggers which lead us to require microclimate monitoring.
- W2—What are the most relevant/informative microclimate variables to be monitored based on the climate sensitivity of artworks? The answer helps select the indoor climate variables that better match the scopes of microclimate monitoring (e.g., temperature, relative humidity, surface temperature).
- W3—Where will the microclimate monitoring take place? The answer identifies the typology of the site where the indoor climate monitoring is planned (e.g., exhibition space, storage, handling room, transport facilities).
- W4—When does the microclimate monitoring start and how long for? The answer allows to plan the timing of the monitoring period in terms of duration and sampling interval. The monitoring period might also depend on which standards [28] or guidelines [29] are considered in the assessment of the climate-induced conservation risks. One calendar year or its multiples is more advisable in the case of organic and hygroscopic materials [28], as well as a sampling frequency of at least 1 h [30].
- W5—Who is responsible for the maintenance of sensors and for data mining? The answer should help identify the people involved in contributing to the task.
- H1—How many sensors can be employed for indoor climate monitoring? The answer constitutes the premise to find a compromise among climate representativeness, conservation requirements, and the number of sensors needed and/or available.

The number of sensors for microclimate monitoring (i.e., the answer to H1) determines two circumstances (Fig. 2) that allows identifying the procedures to be followed (Step 3 of the decision making):

(1) *Artwork-related deployment* There are as many sensors as the number of artworks, thus the configuration will be named as artwork-related deployment. This circumstance, even hypothetical, would lead to unnecessary cost of purchasing the sensors and data processing, with little useful information gained. However, it could be applied when artworks are moved from one museum to another [25] and for monitoring microclimate in temporary exhibitions or in new museums.
(2) *Artwork-envelope-related deployment* A given number of sensors is set, due to limited budgets for the monitoring campaigns or for other management or decision-making reasons, thus the configuration will be designated as artwork-envelope-related deployment. It better applies to artworks permanently stored in a space housing collections and for designing and/or optimising the deployment of sensors.

In both circumstances, it is important to provide the number of artworks. The artworks selection should be done in Step 2 by the conservator through the compilation of ad hoc condition reports [31] (the selection may include climate-sensitive artworks, severely damaged objects, and other objects of interest) and/or the manager, collector, or owner of the collection, who will identify the most valuable assets for the museum. In the case of wireless sensors, signal connectivity should be tested by the conservation scientist to ensure that measurements are correctly transmitted to the gateways. Finally, the on-site visit or a virtual tour (if feasible) allows adding more details to the background information gathered through a survey to be compiled by whom oversees the space housing collections. A specific survey had already been tested and validated on CollectionCare museums (briefly described in Appendix A. The survey).

Artwork-related deployment

In the case of the artwork-related deployment, there are as many sensors as the number of artworks to be monitored.

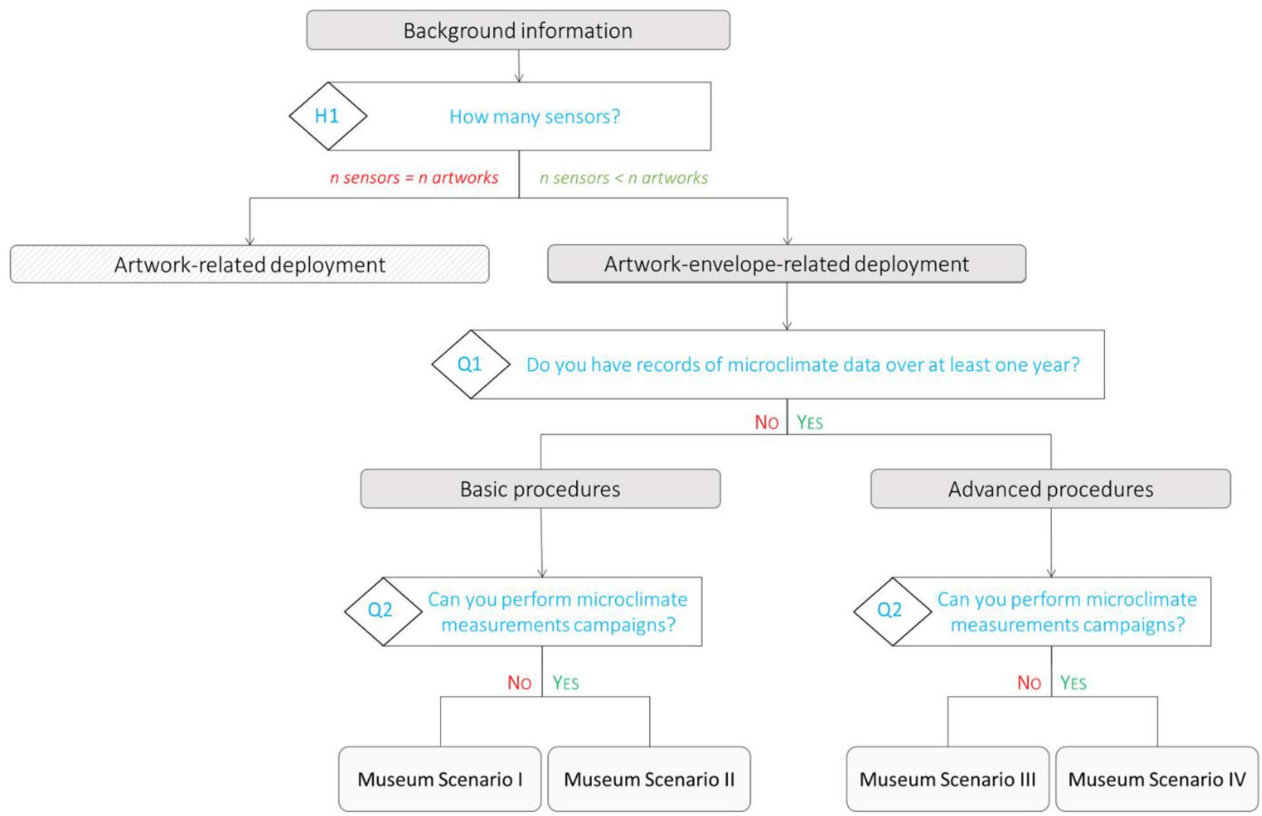

Fig. 2 Schematic workflow of the two circumstances identified by answering to the H1 question (How many sensors?) and the artwork-envelope-related deployment identified by answering to the Q1 (Do you have records of microclimate data over at least one year?) and Q2 (Can you perform microclimate measurements campaigns?)

In this circumstance, sensors should be placed near the artwork or attached to it through compatible and reversible supports [32]. This procedure is recommended every time the artwork is moved from one museum to another, because it allows to monitor its "historical" climate fingerprint [28] and provides continuous control of the climate conditions it experiences.

However, if the budget of the museum to purchase several sensors and assure their maintenance and calibration is limited, it is advisable to follow the procedures developed for the *artwork-envelope-related deployment* (Section "Artwork-envelope-related deployment").

Artwork-envelope-related deployment

In the case of the *artwork-envelope-related deployment*, only a given number of sensors is available regardless of the number of artworks to be monitored. For this reason, it is necessary to identify adequate sampling points to guarantee representativeness in the time and space of the environment surrounding individual artworks.

In this circumstance, the term "museum scenario" refers to contexts associated with the availability of collected microclimate data over a sufficiently long period (i.e., at least one calendar year or multiple years) and/or with the possibility to conduct microclimate measurements campaigns. Four Museum Scenarios were identified (Fig. 2). The classification of the museum into its corresponding most suitable Museum Scenario can be done by answering two closed-ended questions:

(1) Do you have records of microclimate data over at least one year?
(2) Can you perform microclimate measurements campaigns?

If the answer to (Q1) is No, the protocol is based on the Basic procedures. Basic procedures are conceived as prime installation of sensors for microclimate monitoring. The choice of the Museum Scenario depends on the answer to (Q2): if No, the procedure is related to Museum Scenario I ("Museum scenario I" Section), otherwise the procedure is Museum Scenario II ("Museum scenario II" section).

If the answer to (Q1) is Yes, the protocol is based on Advanced procedures. Advanced procedures are proposed for fine-tuning the location of sensors if already installed in the spaces, and/or to identify new sampling points for additional sensors. To apply advanced procedures, it is necessary to analyse historical microclimate data collected for at least one calendar year. The choice of the Museum Scenario depends on the answer to (Q2): if No, the procedure is related to Museum Scenario III ("Museum scenario III" section), otherwise the procedure is Museum Scenario IV ("Museum scenario IV" section)

Museum scenario I

In Museum Scenario I (MSI), records of microclimate data have not been collected either continuously or occasionally, and measurement campaigns cannot be planned nor performed (e.g., portable thermo-hygrometric instruments are not available). As it is not possible to evaluate the historic climate and its variability in time and space, sensors should be placed considering where climate-vulnerable artworks are exhibited and the features of the building envelope. We identify two possible procedures:

(a) *"As many sensors as the number of rooms"*: sensors can be deployed in the middle of each exhibition room [26], all at the same height, and assuming no spatial gradients or vertical stratification of microclimate variables. This approach is feasible if at least as many sensors as the number of exhibition rooms are available.

(b) *"As many sensors as the number of climate blocks"*: sensors can be deployed in the middle of each room representative of a climate block. This approach was borrowed from ASHRAE *Standard* 90.1 [33], which defines a method to identify the thermal zoning of residential spaces in the field of dynamic energy modelling. The standard suggests that rooms characterised by the same orientations or internal gains, or ceiling/floor loads may be reasonably grouped into one single thermal block without losing information on the individual rooms. Each climate block is representative of all rooms with the same features. As an example, the space housing collections could be arranged into a given number of climate blocks grouping the rooms located on the same floor, with the same internal gains (heat and moisture sources/sinks) and placed along the same orientation of the main axis of the building, hence assuming homogeneous climate conditions.

Museum scenario II

In Museum Scenario II (MSII), records of microclimate data have not been collected either continuously or occasionally, but microclimate measurements campaigns have been conducted and/or can be planned. In order to map and characterise the microclimate in a horizontal/vertical cross section of the exhibition space, discrete measurements of air temperature and relative humidity should be taken at specific points of a virtual equally spaced grid using portable instruments in accordance with standards [4, 5]. Measurements should be repeated for some days over the year to study whether the results are representative of the situation [6]. Then, the spatial distribution of temperature and humidity can be constructed in the form of contour maps, using professional contouring software. In this way, it is possible to characterise the indoor climate behaviour by identifying patterns with significant climate variability and those characterised by climate homogeneity, those mostly affected by outdoor climate or those with other relevant phenomena. In fact, it was demonstrated that visualisation of the spatial distribution of the microclimate variables improves the identification of heat or moisture source/sinks [5]. In addition, it allows the examination of conditions favouring vertical/horizontal transport of air masses, including gaseous pollutants and particulate matter, useful for the conservation risk assessment of the individual artwork.

Museum scenario III

In Museum Scenario III (MSIII), records of microclimate data have been collected over at least one calendar year, but measurements campaigns cannot be planned nor performed (as portable thermo-hygrometric instruments are not available), thus the spatial distribution and the gradients of microclimatic parameters remain unknown. In this case, it is possible to evaluate the historical indoor climate and its variability (i.e., the climate in which an object has always been kept or has been kept for a long period of time and to which it has acclimatised), and sensors can be deployed considering the location where climate-sensitive artworks are exhibited as well as the features of the building envelope. The approach of MSIII is advisable to refine the location of sensors in the first-guess installation after having collected microclimate data over at least one calendar year.

The procedure entails the application of univariate and multivariate statistical methods on multi-year microclimate data (if available) with the aim to determine an objective classification of climate blocks [24], representing a further step of what done in MSI. The first step is an objective assessment of the data quality by using specific indexes to perform reliable data analysis: Completeness Index (CoI), Continuity Index (CI), and Microclimatic Quality Index (MQI). Details on the above indexes and their use can be found in [24, 34]. The second step includes the application of univariate and multivariate statistical methods to microclimate data. The former approach (e.g., box-and-whiskers plot) allows a synthetic visualisation of microclimate behaviour, a quick comparison among microclimate data within the same room or for visualising microclimate differences among rooms. The latter approach (e.g., Principal Components Analysis, Cluster Analysis) allows to aggregate microclimate observations recorded in different spaces housing collections for an objective classification of climate blocks. These methods have already demonstrated a satisfactory capability for classifying microclimate data with very similar characteristics (i.e., microclimate patterns) and proved to be an effective tool in identifying the proper number of sensors and their setting in microclimate monitoring programmes in museums [22–24, 35–37]. Recently, new approaches on microclimate analysis (e.g., machine learning [38]) have been explored and could have a potential application to the sensors' deployment.

Museum scenario IV

In Museum Scenario IV (MSIV), records of microclimate data have been collected over at least one calendar year and microclimate measurements campaigns have been conducted and/or can be planned. The procedure for the deployment of sensors combines the outcomes from the procedure adopted for MSIII and from the microclimate measurements campaigns described in MSII. The combined approach allows to further fine-tune the deployment of the sensors, highlighting better the temporal variability of the historic climate and the areas with gradients of temperature and moisture, which may have direct influence on the deterioration mechanisms of cultural objects.

Some advisable practices

The design stage of a microclimate monitoring is a challenging step. Over recent years, some advisable practices have been identified.

As a rule of thumb, when the aim of the monitoring is to assess the microclimate behaviour of a space housing collections, sensors must be deployed in a position that avoids the influence of unwanted sources, such as air flows or solar radiation, heating/cooling or humidity control systems, and distant from doors and windows [39]. However, if the climate sensitive artwork is exposed directly to these disturbances, measurements must be also taken at these sampling points.

Another important aspect is related to the presence of Heating, Ventilation, and Air -Conditioning (HVAC) systems for tight microclimate control. When microclimate is tightly controlled, the microclimate monitoring might be redundant unless for detecting the failure of the HVAC systems [40].

Moreover, sensors should have a sufficiently broad operative range to measure the whole climate variability. As an example, if an artwork is located close to a window, an adequate light sensor should be capable of detecting high luminous exposure [13], or if an artwork is located in a very humid space, sensors for RH measurements should not encounter condensation issues [41].

In the case of wireless sensors, it is also important to evaluate indoor signal propagation. Indeed, transmission can be affected by construction materials of the building (e.g., reinforced concrete), object materials (e.g., metal),

Table 2 Summary of advisable and not advisable practices

Advisable	Not Advisable
To finalise the purpose of the microclimate monitoring	To start a microclimate monitoring without a clear purpose
To define the appropriate climate variables to record in relation with the material of the preserved artworks	To collect arbitrary climate variables without any relation to the material of artworks
To choose sensors with features recommended by the European standards	To choose sensors with poor features (e.g., high uncertainty), not calibrated, and with low performance
To carry out the calibration of sensors with a reference instrument or compare all sensors among them before starting a monitoring campaign, to guarantee the comparability and reliability of recorded data	To use sensors with different metrological features and inconsistent time response
To install sensors in sampling points representative of real conditions	To deploy sensors close to disturbing climate factors, or local constraints or obstacles
To evaluate indoor signal propagation of wireless sensing system	To deploy sensors close to heavy masonries, underground rooms, etc. without first checking the correct data transmission in that area
To reduce the visual impact	To deploy sensors along visitors' passageways

or long distances between sensors and gateway, among others.

Finally, sensors used in cultural sites should minimise the visual impact and the risk of theft or damage along the visitors' passageways [14]. Indeed, the practice is to deploy sensors in more hidden places, entailing low representativeness of the climate behaviour even in small-sized rooms, and a possible misinterpretation of the microclimate, particularly when sensors are located in the corners [22].

These and other possible desirable requirements should be discussed and agreed upon with the conservation space's manager together with professional conservators.

Table 2 provides a list of advisable and not advisable practices that should be considered in the operational procedure of positioning sensors.

Table 3 Museum Scenario (MS) associated with museums involved in CollectionCare project according to the answers provided by museum staff (May 2019) to the questions Q1 and Q2 (Fig. 2)

Museum name	Acronym	Q1	Q2	Museum Scenario
Alava Arms Museum of Diputación Foral de Álava (Álava, Spain)	DFA_AAM	No	No	MSI
Alava Fine Arts Museum of Diputación Foral de Álava (Álava, Spain)	DFA_AFAM	No	No	MSI
National Historical Museum. Historical and Ethnological Society of Greece (Athens, Greece)	IEEE	No	No	MSI
Institut Valencià de Cultura (Valencia, Spain)	IVC	No	No	MSI
Musical Instruments Museum, Royal Museums of Art and History (Brussels, Belgium)	KMKG	No	No	MSI
Ethnographic Open-Air Museum of Latvia (Riga, Latvia)	OALM	No	No	MSI
The Danish Royal Collection. Rosenborg (Copenhagen, Denmark)	RDC[a]	Yes	No	MSIII
The Danish Royal Collection. Rosenborg (Copenhagen, Denmark)	RDC[a]	Yes	Yes	MSIV
Museum of Informatics of the School of Informatics (University of Valencia, Spain)	UPV	No	No	MSI
Museo delle Origini (Sapienza University of Rome, Italy)	URO1	No	Yes	MSII

Museums used as case studies are highlighted in bold

Q1) Do you have records of microclimate data over at least 1 year?

Q2) Can you perform microclimate field measurements?

[a] At the beginning of the project, RDC was associated with MSIII. During the project, microclimate field campaigns were conducted and hence RDC was associated with MSIV

Table 4 Application of the 5Ws1H method to museums involved in CollectionCare project

Questions	Answers
W1–Why is there a need for microclimate monitoring?	Conservation risk assessment of the spaces housing collections
W2–What are the most relevant/informative microclimate variables to be monitored based on the climate-sensitivity of artworks?	Temperature (T), relative humidity (RH)
W3–Where will the microclimate monitoring take place?	Exhibition and/or storage spaces
W4–When does the microclimate monitoring start and how long for?	Period: multi-year observations Sampling intervals: 15–60 min[a]
W5–Who is responsible for the maintenance of sensors and for data mining?	Museum staff and conservation scientists
H1–How many sensors can be employed for microclimate monitoring?	*n* sensors of temperature (T) and relative humidity (RH)

[a] The sampling interval varies according to the rate of short-term fluctuations that pose a risk to climate-sensitive artworks [6, 30]

Results and discussions

In this section, the procedures previously described will be presented through their application to the nine museum partners of the CollectionCare project (Table 3) that were used as case studies. In this project, climate-sensitive artworks include paper, metal and wooden objects and canvas paintings [25].

The procedure for the *artwork-related deployment*, as hypothetical circumstance,will be not shown, since it includes that each artwork were associated with its own sensor.

For the procedures of the *artwork-envelope-related deployment*, the museum partners were associated with the corresponding Museum Scenario (Table 3) based on the answers gathered by an ad hoc questionnaire.

Table 4 summarises the outcomes of the 5Ws1H method focused on the needs to the museum partners of CollectionCare project. In this project, one objective was devoted to the definition of operative procedures for the deployment of sensors in spaces, tailored to monitor ambient microclimate (mainly temperature and relative humidity) which may have direct influence on the deterioration of artworks. The procedures were put in the field during the demonstration phase of the project teaming up with all museum staff (i.e., the person in charge for the museum), conservators and conservation scientists. In this phase, we employed the wireless sensors developed in the framework of the CollectionCare project and performed connectivity tests (e.g., radio frequency tests) to ensure that collected data were correctly transmitted to the gateways.

Artwork-envelope-related deployment

In this circumstance, the number of sensors is less than the number of climate-sensitive artworks selected by museum staff and conservators. The deployment of sensors for each Museum Scenario is shown taking into account the number of available sensors for the specific museum.

Museum scenario I

The results for Alava Arms Museum of Diputación Foral de Álava (Álava, Spain) are here shown as an example of the application of MSI. Five sensors (named from S1 to S5) were available. The museum was divided into three climate blocks, corresponding to the two exhibition rooms (ground and first floors) and the storage rooms. The location of sensors was identified in five distinct areas (Fig. 3):

Fig. 3 Artwork-envelope-related deployment – Museum Scenario I: Alava Arms Museum of Diputación Foral de Álava (Álava, Spain). Green circle indicates sensor, black solid rectangle artwork. The alphanumeric code identifies the artwork

- Sensors S1 and S2 were placed in the first room close to the artworks D005 and D012, respectively. On the ground floor, most artworks are located in the showcases, except for two climate-vulnerable artworks in the centre of the room: D005 beneath the stairwell and D012 beneath the open slab between the ground and first floors. Here, the two sensors deployed in correspondence with the above-mentioned artworks can reasonably collect different hygrothermal conditions due to the combined effect of the stairwells and the building orientation.
- Sensors S3 and S4 were placed close to the artworks D001/D015 inside the same showcase and outside in the room, respectively. On the first floor, most artworks are exhibited inside the showcases. In this case, two sensors were deployed, one inside the showcase (S03) and one outside the showcase (S04), that would allow us to understand heat and moisture exchanges between the room and the showcase [40].
- Sensor S5 was placed in the centre of the attic storage room. In this room is stored a selected paper artwork on a planar and is the most unfavourable room from a climate point of view.

Museum scenario II

Museo delle Origini (Rome, Italy) was associated with MSII. Measurements of T and RH were collected through portable instruments manufactured by Rotronic© (model HygroPalm, uncertainty ± 0.2°C for T and 1.0% for RH at 23 ± 5°C). Several microclimate field campaigns were conducted to identify representative sampling points to evaluate the spatial distribution of heat and moisture. The microclimate field measurements were carried out on the horizontal cross-sections of the museum on a 2 m × 2 m regular grid at 1.5 m above the floor (Fig. 4a) during different times of the day (morning/afternoon) since 2016. Microclimate contour maps were elaborated from T and RH observations. For the sake of brevity, Fig. 4b–c show the microclimate field campaign conducted in November 2019, as it showed a similar microclimate pattern with the previous campaigns. A decreasing temperature tendency was observed along the south-east north-west direction of the exhibition spaces, with a thermal minimum in proximity to the east side close to the large window of the museum (Fig. 4b). The temperature tends to increase in the more internal areas. Concerning the RH distribution, a more homogenous pattern can be noted with low variability within 3.0% (Fig. 4c). For this museum, only 4 sensors were available (named from S1 to S4). Therefore, the location of sensors was identified in four distinct areas characterising the climate variability around the climate-sensitive artworks selected by the conservator, as shown in Fig. 5:

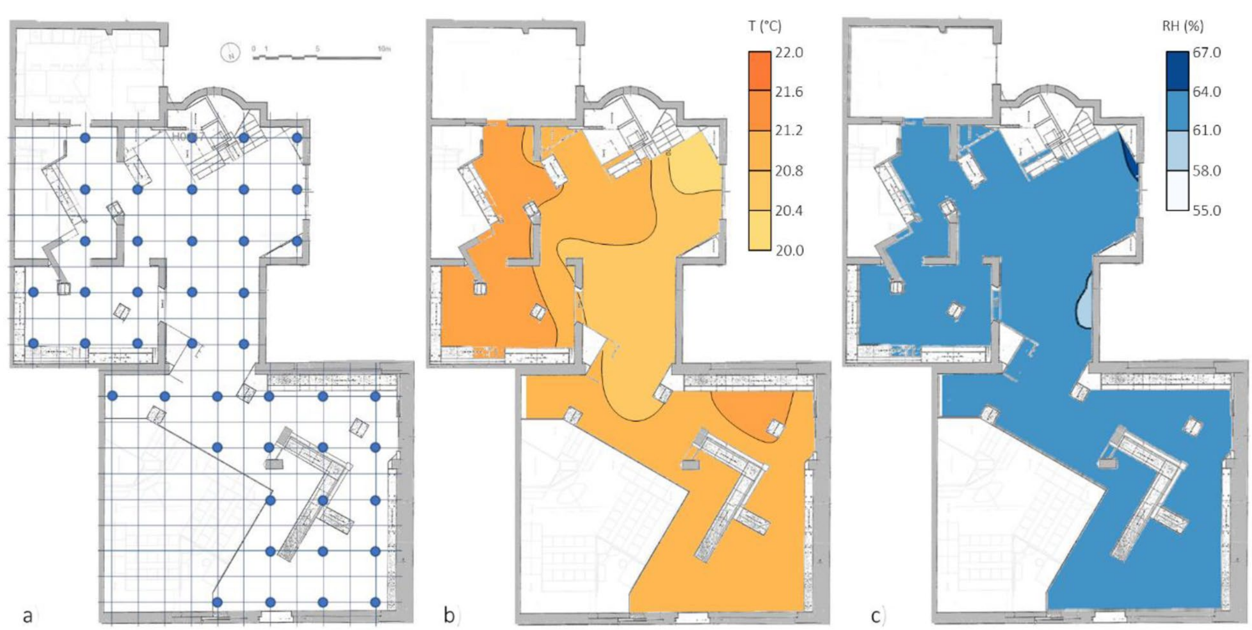

Fig. 4 Steps to draw microclimate maps applied to Museo delle Origini (Rome, Italy): **a** Virtual grid superimposed on the plan where vertices are the sampling points; **b** Horizontal map of air temperature (at 0.4 °C intervals); **c** Horizontal map of relative humidity (at 3.0% intervals). Microclimate field campaign was performed in November 2019

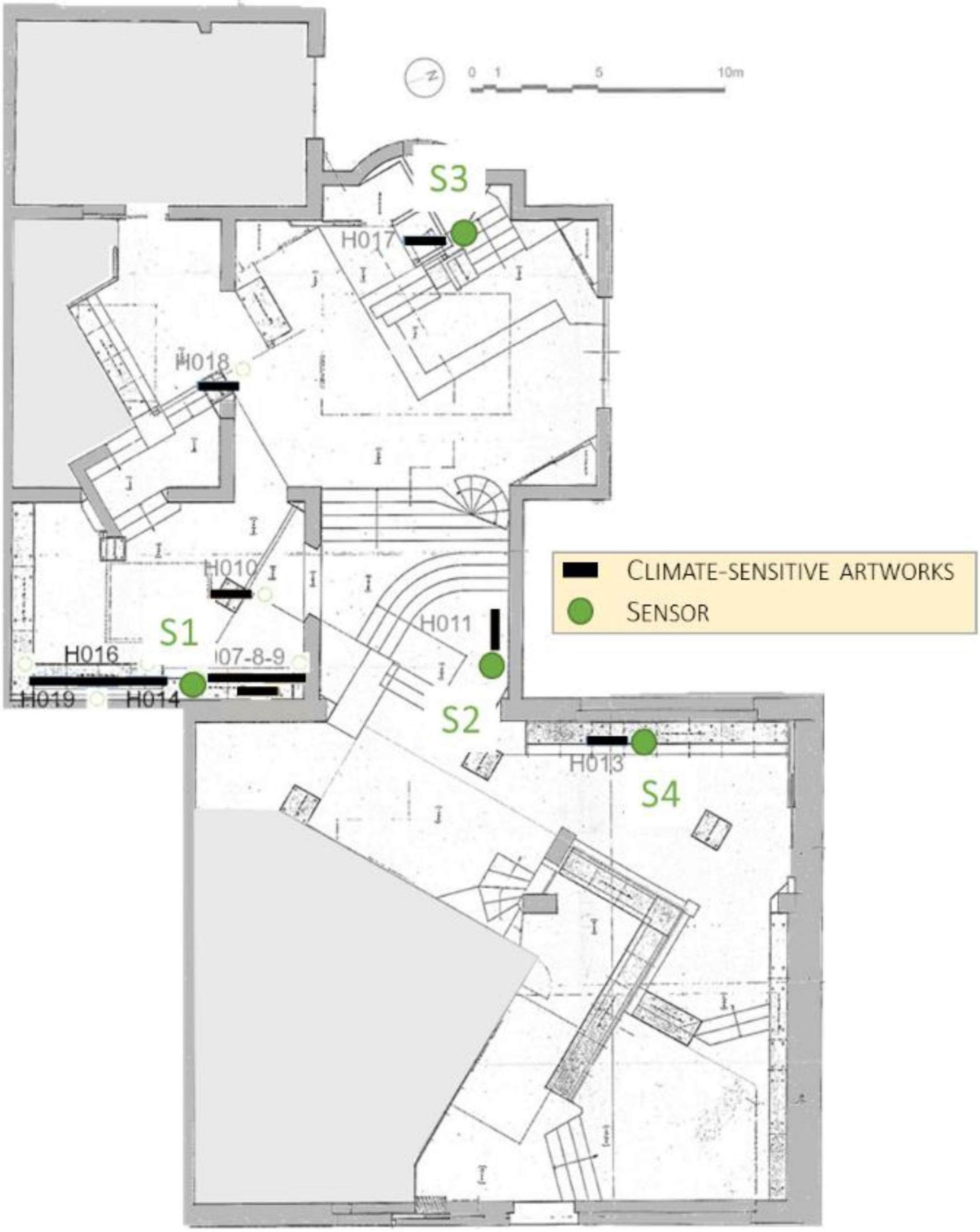

Fig. 5 Artwork-envelope-related deployment–Museum Scenario II: Museo delle Origini (Rome, Italy). Green circle indicates sensor, black solid rectangle artwork. The alphanumeric code identifies the artwork

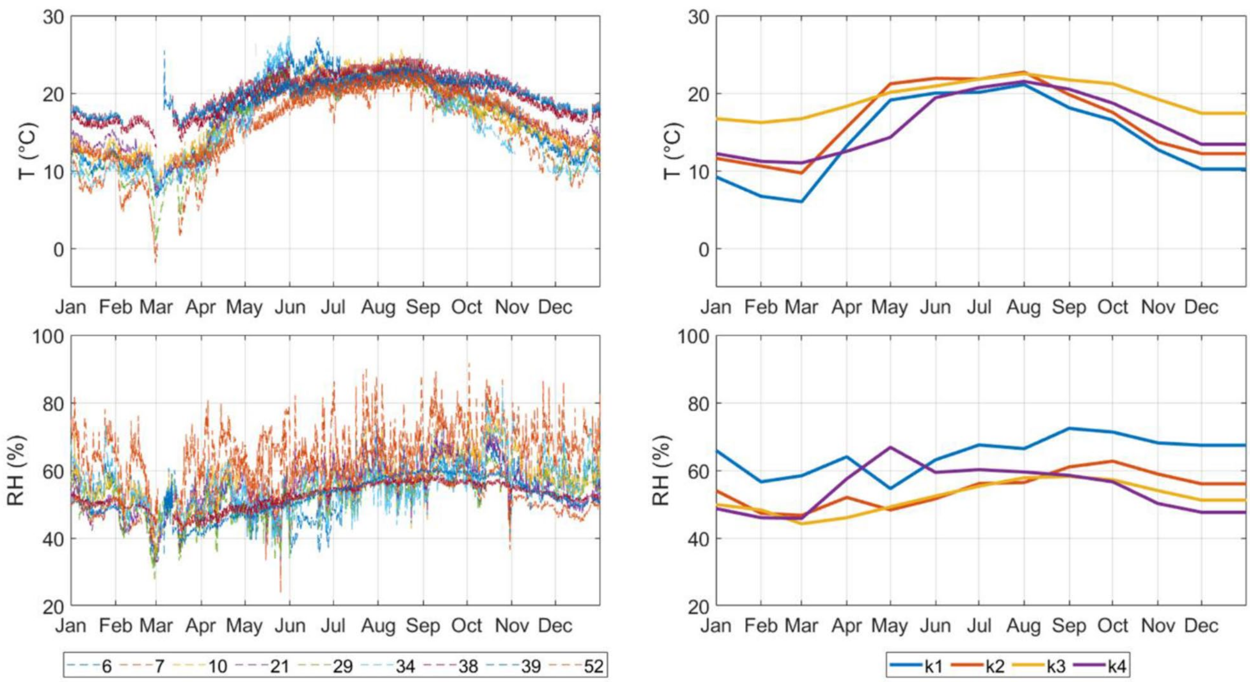

Fig. 6 Left panels. Time evolution of observations of temperature (T) and relative humidity (RH) over a whole calendar year in each room of Danish Royal Collection (Copenhagen, Denmark) coded by numbers. Right panels. Time evolution of T and RH centroids of four room climate blocks identified with k-mean Cluster Analysis [24]: k1 includes room 7*; k2 includes rooms 6, 10*, 21, 29, 34; k3 includes rooms 38* and 39; k4 includes room 52*. Asterisk indicates the room with the microclimate conditions representative of its corresponding cluster

- Sensor S1 was placed in the warm area surrounding metal and wooden artworks and potentially responsible for degradation.
- Sensor S2 was placed in the low MR area where the wooden artwork H011 is exhibited.
- Sensor S3 was placed in the thermal minimum, where the metal artwork H017 is exhibited.
- Sensor S4 was placed in a different hygrothermal area with respect to the above conditions and where the metal artwork H013 is located.

Museum scenario III

The museum Danish Royal Collection—Rosenborg (Copenhagen, Denmark) was associated with MSIII. For the sake of brevity, in this paper we show only the classification of climate blocks obtained through the Cluster Analysis. Cluster Analysis allowed to identify four climate blocks as the best number cluster [24]. Figure 6 compares time evolution of T and RH hourly observations (left panels) and time evolution of T and RH centroids (right panels) after the application of the k-mean Cluster Analysis. In this way, it is possible to obtain an objective representation of microclimate patterns of the museum useful to optimise the deployment of the current measuring points. For this museum, ten sensors were available (named from S1 to S10) and were located as shown in Fig. 7. The sensors already located in the representative room of each cluster (S5 in room 7 for k1; S6 in room 10 for k2, S2 in room 38 for k3 and S1 in room 52 for k4) were left in their original positions. The remaining six sensors were moved in other rooms without sensors, close to the selected climate-sensitive artworks. This allows to investigate microclimate conditions surrounding additional artworks in spaces not yet monitored, demonstrating how few sensors can be reasonably moved and deployed to get meaningful information.

Museum scenario IV

The Danish Royal Collection—Rosenborg (Copenhagen, Denmark) is also associated with MSIV. Measurements of T and RH were collected through portable instruments manufactured by Rotronic© (model HygroPalm, uncertainty ± 0.2°C for T and 1.0% for RH at 23 ± 5°C). Microclimate measurements campaigns were conducted in 2021 and 2022 during different times of the day (morning/afternoon) to evaluate the spatial distribution of heat and moisture. The microclimate field measurements

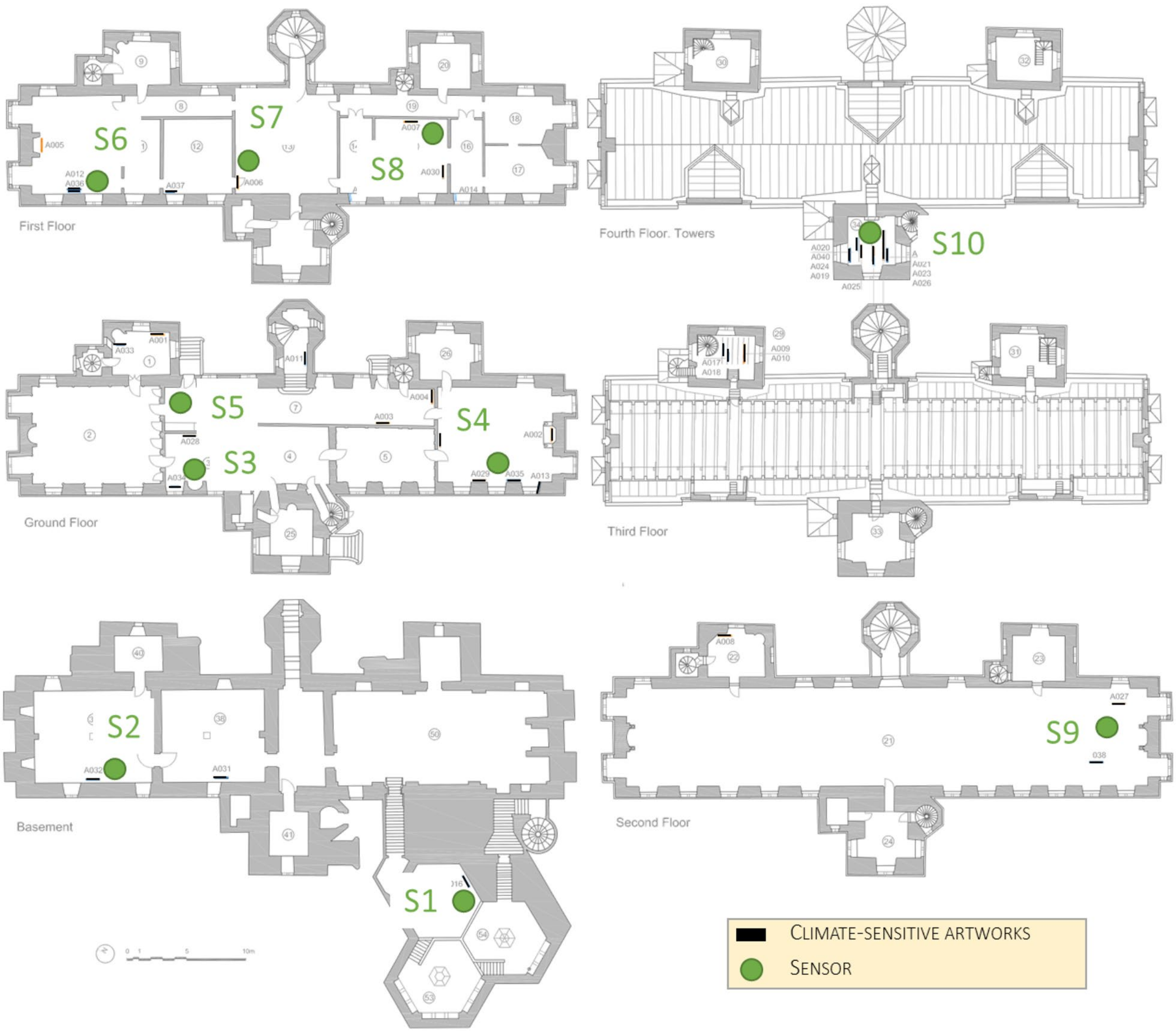

Fig. 7 Artwork-envelope-related deployment–Museum Scenario III: The Danish Royal Collection—Rosenborg (Copenhagen, Denmark). Green circle indicates sensor, black solid rectangle artwork. The alphanumeric code identifies the artwork

were carried out on the horizontal cross-sections of the museum on a 4 m × 4 m regular grid at 1.5 m above the floor. The microclimate contour maps elaborated from T and RH observations highlighted that both T and RH tended to be stable over the exhibition spaces varying less than 1 °C for T and 5.0% for RH (Fig. 8a–b). For the sake of brevity, Fig. 8a–b show the microclimate mapping extracted from the microclimate field campaign conducted in May 2022, as it showed a similar microclimate pattern with the previous campaigns.

The microclimate maps were used to fine tune the deployment suggested through the MSIII procedure. Indeed, due to the stability observed in Room 7 (ground floor, central position), it was possible to move S5 from north-east to south-east side to monitor microclimate conditions closer to selected artworks (Fig. 9). Moreover, as microclimate behaviour in Room 10 (first floor, NW side of the building) is similar to the adjoining rooms, S6 was moved to Room 2 (ground floor), thus increasing the knowledge of microclimate in an unexplored room.

Conclusions

The microclimate monitoring in spaces housing collections needs to be carefully designed. This paper provides practical guidance for the deployment of sensors for microclimate monitoring in spaces housing

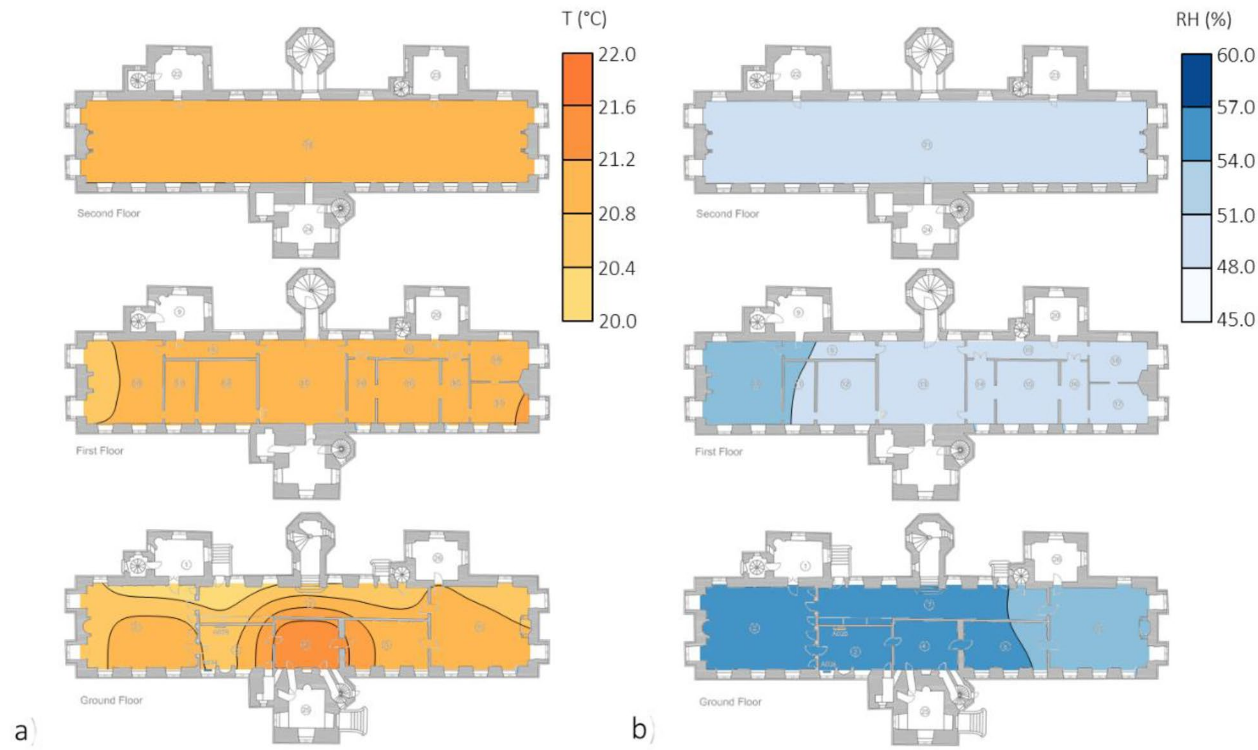

Fig. 8 The Danish Royal Collection—Rosenborg (Copenhagen, Denmark): **a** Microclimate map of air temperature (at 0.4 °C intervals); **b** Microclimate map of relative humidity (at 3.0% intervals). Microclimate field campaign was performed in May 2022

collections under different museum scenarios (MS). The term "museum scenario" refers to contexts associated with the availability of collected microclimate data over a sufficiently long period (i.e., at least one calendar year or multiple years) and/or with the possibility to conduct microclimate measurements campaigns. The proposed procedures make it possible to design where to deploy sensors both as a first guess (or initial) deployment and for its optimisation/improvement (in case of sensors already installed). Since the deployment configuration depends on the number of available sensors, we have identified two possible circumstances.

The *artwork-related deployment* (i.e., there are as many sensors as the number of artworks), even hypothetical, is advisable when the artwork is often moved from one museum to another one. Each artwork has its own climate fingerprint that can be monitored even during transport and temporary exhibitions. This way, the host institution will be able to set up the exhibition room reproducing climate conditions comparable with its climate fingerprint.

The *artwork-envelope-related deployment* (i.e., the number of available sensors is less than the number of artworks) is usually the case of permanent collections and is further subdivided into basic (MSI and MSII) and advanced (MSIII and MSIV) procedures. Advanced procedures are preferable over basic procedures when several time series of microclimate data have been collected for at least one calendar year in several sampling points. Every time microclimate measurements campaigns can be performed, the protocol for MSII and MSIV are preferable over those for MSI and MSIII, respectively.

Following the approach proposed by this paper, an interdisciplinary evaluation would be possible on the deployment of sensors, combining the expertise of all the experts involved in the microclimate monitoring (manager, conservator and conservation scientist). The procedures were effectively applied during the demonstration phase to museums involved in EU H2020 project CollectionCare (Grant Agreement No 814624) which house permanent collections.

We expect that the application of these procedures to temporary exhibitions might ease the fulfilment of microclimate requirements contained in loan agreements thus encouraging the movement of artworks between hosting institutions.

Finally, we hope that this guidance would hopefully become useful to less experienced collection managers or conservation professionals embarking on installing or

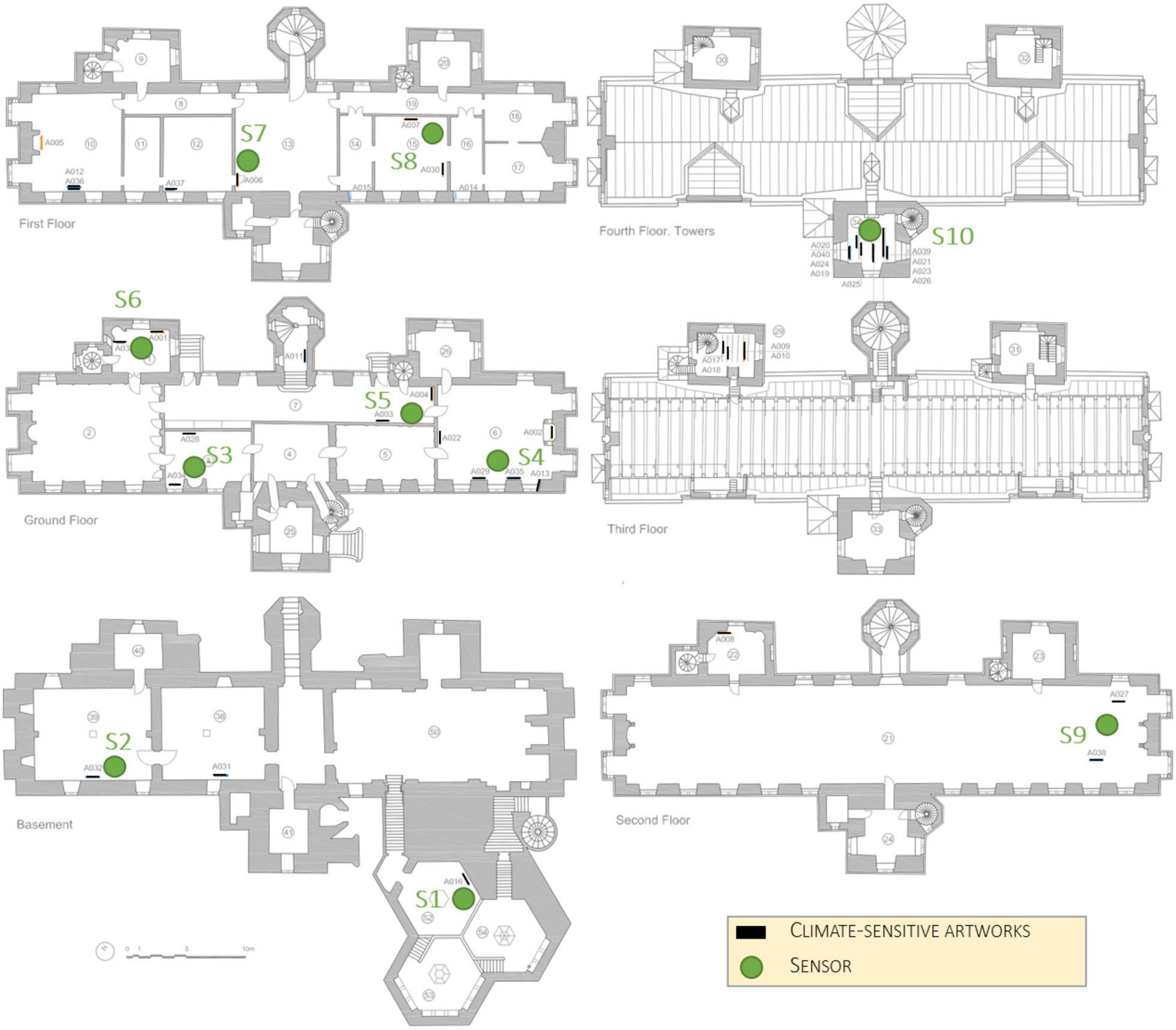

Fig. 9 Artwork-envelope-related deployment – Museum Scenario IV: The Danish Royal Collection—Rosenborg (Copenhagen, Denmark). Green circle indicates sensor, black solid rectangle artwork. The alphanumeric code identifies the artwork

modifying microclimate monitoring in spaces housing collections.

Appendix

The survey

A survey was conceived as a useful tool to obtain the background information on the conservation space needed to assign it to the Museum Scenario. The survey is organized into two main sections: (i) general information on the museum, its building, and collections; (ii) information on the microclimate measurements and the microclimate system. The survey was drawn up in Microsoft Excel. Most items and the related answers are shown as drop-down menus or closed questions (i.e., there are only two possible responses, yes/no). Drop-down menus have the main advantages of conserving space and to providing users with a given number of options. Some open-ended questions are highlighted by a grey background. If the respondent does not select any answer, this is interpreted as not available information (N/A).

Abbrevations

5Ws1H: Five Ws and One H method; DFA_AAM: Alava Arms Museum of Diputación Foral de Álava (Álava, Spain); DFA_AFAM: Alava Fine Arts Museum of Diputación Foral de Álava (Álava, Spain); IEEE: National Historical Museum. Historical and Ethnological Society of Greece (Athens, Greece); IVC: Institut

Valencià de Cultura (Valencia, Spain); KMK: Musical Instruments Museum, Royal Museums of Art and History (Brussels, Belgium); MS: Museum Scenario; N/A: Not available; OALM: Ethnographic Open-Air Museum of Latvia (Riga, Latvia); Q#: Question number; RDC: The Danish Royal Collection. Rosenborg (Copenhagen, Denmark); RH: Relative humidity; S#: Sensor number; T: Temperature; UPV: Museum of Informatics of the School of Informatics (University of Valencia, Spain); URO1: Museo delle Origini (Sapienza University of Rome, Italy).

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Author contributions
AMS FF and EV: Conceptualisation, methodology, data curation, formal analysis, supervision, writing—original draft; APV: plan design; AB AG CC FF. and FJGD: data collection; FJGD: data curation; CCB GF EF and FJGD: writing – review and editing. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

Author details
[1]Department of Physics, Sapienza University of Rome, P.le Aldo Moro 5, 00185 Rome, Italy. [2]Itaca Institute, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain. [3]Present Address: Centro de Investigación PEGASO, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain. [4]Royal Danish Collection, Øster Voldgade 4A, 1350 Copenhagen K, Denmark. [5]Department of Fundamental and Applied Sciences for Engineering, Sapienza University of Rome, Via A. Scarpa 16, 00161 Rome, Italy. [6]Department of Biology and Biotechnologies "Charles Darwin", Sapienza University of Rome, Viale dell'Università 32, 00185 Rome, Italy. [7]Department of Science of Antiquities, Sapienza University of Rome, P.le Aldo Moro 5, 00185 Rome, Italy. [8]Department of Environmental Biology, Sapienza University of Rome, P.le Aldo Moro 5, 00185 Rome, Italy. [9]Department of Applied Physics (U.D. Industrial Engineering), Universitat Politècnica de València, 46022 Valencia, Spain.

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