The regulations and reality of indoor environmental standards for objects and visitors in museums

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Abstract

The management of indoor microclimates is an important function of museum operations, a topic that has recently received growing attention. The way in which museum microclimates are specified is still not well documented universally, particularly in developing countries where a significant part of the global 'movable' heritage is situated. Most of the current contributions come from scholars covering climate control practices in developed nations. The bibliography related to museum environmental and climate management in other regions is comparatively limited. Heritage institutions have varying levels of resources, funding mechanisms, management protocols and expertise. In the absence of shared best practices, great variability in the environmental management practice exists across different institutions and countries. This paper brings together 96 studies that were selected and critically evaluated to review publications in the field over the last two decades and trace the variations in climate control practice across regions. The findings of the review confirmed the gaps in research in the field and identified the relevance to the implementation of regulatory frameworks particularly in regions where little or no research of museums' indoor environments is taking place. The paper also shows that the fragmentation of tools and methods to assess the indoor environment in museums has contributed to variations in practices across the sector. Moreover, the paper provides evidence of the struggle to comply with the strict, and in cases exaggerated requirements, that aim at satisfying a varying range of conflicting criteria to provide indoor comfort to visitors while continuing to protect artefacts

Keywords: Museums; Indoor environment; Environmental monitoring; Objects conservation; Comfort; Energy efficiency; Standards

1. Introduction

Museums are repositories for cultural heritage and are responsible for the care of collections for the benefit of present and future generations. Key to this stewardship role is the management of indoor conditions to prevent deterioration of vulnerable objects. Preventive control measures are required to keep the indoor microclimate within conservation limits by maintaining environmental conditions within certain parameters and by minimising environmental fluctuations. Visitors and staff also demand excellent thermal comfort, access to natural light and good air quality to enable them to access these collections. Over the past 40 years a range of standards has been published which set out the ideal environmental parameters for the storage and display of museum collections. Environmental requirements often require a degree of compromise and full compliance with standards may not be achievable. Different climatic regions face localised environmental challenges, and less industrialised countries may lack access to advanced and specialist technological solutions. Economic and environmental imperatives to reduce the carbon footprint and cut energy costs must be considered. As increasingly large fractions of our energy are generated from renewable sources, capacity and intermittency are becoming significant issues [1]. Reducing energy in museums can contribute to energy reduction while less prescriptive standards will allow museum buildings to act more reactively to energy supply fluctuations, given appropriate incentives.

Many of these museum standards are based on an understanding of museum climatology and the mechanisms for the degradation of artefacts which have limited global reach, often developed by western scholars. Managing environmental demands will become ever more challenging as the impact of climate change leads to more frequent extreme weather conditions. Where environmental control and management systems in museums fail to respond to adverse and unstable climatic conditions vulnerable artefacts will inevitably deteriorate and internal conditions will be detrimental to the wellbeing of staff and visitors. Published literature on the management of museum microclimates is indicative of the challenges faced by museums in addressing competing environmental goals for indoor conditions and how practical solutions might be identified.

This paper examines issues and trends for the management of competing environmental demands in museums through a literature review of specialist academic journal papers published over the last two decades. It seeks to establish the current state of research in the field and the practical application of this knowledge and understanding to the management of museum microclimates across global regions. The paper begins by summarising the historical background and context for current standards and guidance for the management of museum environments. The next section sets out the methodological process for the conduct of the review and the organisation of the specialist literature into four broad categories: empirical or in situ studies, experimental studies, studies or reviews of processes for the optimisation of microclimates and overview papers of practices within particular contexts. An analytical summary of the literature is provided, followed by the findings from the analysis which are organised into five sub-headings reflecting the identified trends. Finally, a discussion of the implications of the findings is presented, highlighting the issues which are directly and indirectly expressed through this body of literature. The gaps in current knowledge and understanding are identified in order to direct future research. The potential of new technologies to provide solutions for enhanced environmental management as museums face advancing climate change and increased frequency of extreme weather events is explored.

2. Historical Background and Context for Environmental Management in Museums

The scientific understanding of the link between environmental conditions and the degradation of museum objects which underpins current museum environment standards was recognised by the late 19th century. Factors such as temperature, humidity, light, dust and air pollutants were understood as having a deleterious impact on collections [2-4]. Observations suggested that there were optimum conditions for the preservation of certain types of historic artefacts. From the early years of the 20th century to the 1960s research was conducted on the introduction of heating, ventilation and air-conditioning systems in museum buildings and the monitoring of the effects, primarily on works of art. Advances in technology made tighter control of internal conditions using mechanical methods and monitoring more possible. This research emanated from Europe, UK and North America [2-6]. In the UK, the necessity to evacuate collections from London museums to temporary storage during WWI and WWII and the observations of the impact of the temporary conditions on artefacts was a significant impetus for scientific research. The International Institute for the Conservation of Museum Objects (IIC) was established in 1950, and the journal '*Studies in Conservation*' in 1952 to disseminate research in the field.

In the late 1950s the establishment of environmental standards was pursued by the International Council of Museums (ICOM) and the International Centre for the Preservation and Restoration of Cultural Property (ICCROM), underpinned by scientific research and consultation with museums. This work resulted in a report by Harold Plenderleith and Paul Philippot in 1960 [7] which set out a European standard range for RH of 50-60%. This range was further refined by ICOM in 1974 to RH 54% +/- 4% for the purposes of loan agreements between institutions. Guidance and standards continued to be developed through the 1960s, 70s and 80s as knowledge and understanding of the effects of environmental parameters on different materials grew. Garry Thomson's seminal publication, *The Museum Environment*, first published in 1978 [8-9], discussed the impact of variable RH, temperature, light and air pollution, based on a limited but growing body of research still issuing largely from UK, Europe and North America and developed around more sensitive and vulnerable materials and artefact types. Thomson's approach was pragmatic, and he acknowledged that different building types and different climatic regions required different solutions. Nevertheless, the recommended environmental parameters were taken up as prescriptive. As Hatchfield [5, p.42] notes, '*Conditions of 50% ±5° relative humidity (RH) and 70°F ±2° (called "50/70" in museum parlance) became a sort of shorthand used by curators, conservators, registrars and engineers. The values were written into building specifications and loan agreements almost as a guarantee of high quality in construction, handling, storage and display*.'

The late 20th century saw a reaction against the imposition of rigid international environmental parameters for the preservation of museum collections and an acknowledgement that a range of variables must be considered to optimise internal conditions. Research by the Smithsonian Institute in the U.S. and the Canadian Conservation Institute (CCI) in the late 1980s and 1990s led to revised climate specifications, and in 1999 specifications for museums, galleries, archives and libraries were added to the *Handbook of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers* (ASHRAE). This introduced standards which were more realistic, and which recognised the building context as a significant factor in the management of internal environmental conditions [10,2].The ASHRAE climate classes stipulated in the handbook provide enough opportunities to find climate specifications suitable for many museums. However, Ankersmit *et al*. argue that translating these guidelines to practical specifications, namely the numbers to a control algorithm for the HVAC system, is not a straightforward task but requires some '*critical thinking to find a solution that fits a specific institution*' [11,p.55]. An alternative table for temperature and relative humidity specifications was suggested by the authors.

The new millennium brought calls for wider debate about environmental standards amongst museum professionals and further research to build an evidence base. '*For decades, museums adhered to certain prescribed "ideal" conditions of relative humidity and temperature in an attempt to protect the objects in their care. But uncertainty about the efficacy of these guidelines for all types of materials—along with concerns about the environment and the economy—have now motivated many in the museum profession to consider new standards for the storage, loan and exhibition of museum holdings*' [5, p.40]. Concerns about the impact of climate change on the care of collections came to the fore, providing a focus of discussion at the first IIC 'Dialogues for a New Century' in 2008. The need to minimise energy consumption for the care of collections and to address visitor comfort were acknowledged as essential considerations for the management of museum environments. In the UK the National Museum Directors' Conference of 2009 drafted guidance for reducing museums' carbon footprint and minimising excessive energy use, setting wider ranges for T and RH. '*Environmental standards should become more intelligent and better tailored to clearly identified needs. Blanket conditions should no longer apply. Instead, conditions should be determined by the requirements of individual objects or groups of objects and the climate in the part of the world in which the museum is located*' [12, p.1].

The past decade has seen a bewildering range of new environmental guidelines and standards, not all of which are specific to museum environments but which are nonetheless relevant to the management of internal conditions in museum buildings. The extent to which museums adhere to these standards and guidelines in practice whilst balancing competing environmental demands is a key consideration for this review paper.

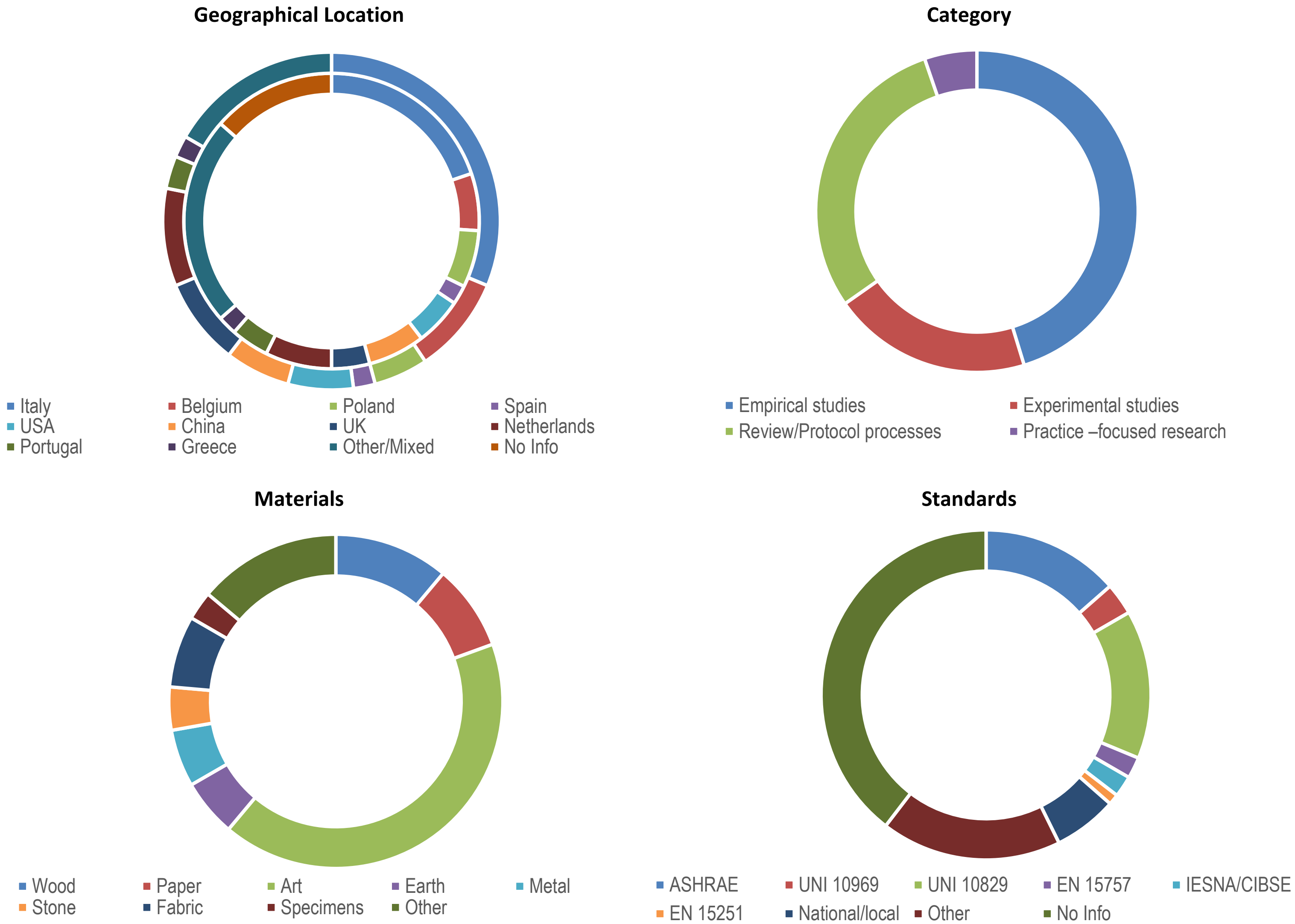
3. Method: Sample selection, review and inspection process

Several phases of literature search and selection were undertaken to identify relevant publications in the field covering the period between 2000 and 2019. The literature was chosen following a systematic search of recent museum microclimate-related papers on *Google* and *ScienceDirect* databases. Target searches were conducted using a combination of the following keywords: ‘museum microclimate’, ‘environmental monitoring’, ‘preventive conservation’, ‘microclimatic control’, ‘management and operation’, ‘live monitoring’ and ‘visitor comfort’. More than 40 papers published in key conservation, museum and built environment-related journals were initially identified as the most relevant to the subject of the review. References that accompany each selected journal publication were then carefully inspected to identify additional studies resulting in a comprehensive list of over 110 papers. Another phase of evaluation was conducted afterward to re-assess the relevance of the added papers. The final selection process was limited to articles that focused on the environmental management of museums, galleries and/or storage spaces, hence studies that looked at other heritage institutions and historic building types such as old churches, old libraries and listed houses were excluded. Only papers published in peer-reviewed archival journals were included in the analysis resulting in a sample of 96 papers.

The first stage of the review included extracting the following data: first author, paper category, publication year, focus of the study and scope, geographical location, standards used in the evaluation (e.g. Italian Standard UNI10829, ASHRAE's museum climate classes, EN 15757), methodology, environmental variables recorded and key findings. The three main fields/aspects often associated with the management of museum environments and collections care, namely ‘artefact preservation’, ‘visitor comfort’ and ‘energy saving’ were also identified as part of the inspection and mapping process (see attached appendix). Previous literature review papers and key studies were also inspected [e.g. 13-16]. Uncertainties regarding the content of any study, the methodological procedures employed, or the issues covered were addressed through the discussion. The selected literature varied in their research scope and the adopted methodologies. Studies, in general, might be classified as broad in nature with emphasis on protocols, articles that are mainly concerned with compliance with standards, research that attempts to contextualise the guidelines with a particular geographical focus, and those experimental in scope with a technical focus reporting empirical data and/or simulation of case studies. For ease of review, the surveyed literature was classified based on focus into **four broad categories**: empirical/ field studies, experimental studies, protocol processes for/(review of) indoor climate optimization and overview papers offering an insight into the climate control practice in a certain context. Table 1 summarises the scope of the examined studies, the methods adopted, issues covered, and the region of research. The studies are also listed in the Appendix and, where referenced in the following sections, highlighted with the relevant number. Figure 1 is a graphical representation showing the general trends across the sample as well as highlighting the spread of the literature. More detailed graphical representation of the frequency within each category is illustrated in Figures 2 to 5.

Table 1: Summary of papers with trends/categories identified across the sample

Typology/ Class	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Paper Category	Empirical (Field / PoE) studies	Review / Protocol processes	Experimental studies	Practice – focused research								
	38	28	24	5								
Geography:	Italy	Belgium	Netherlands	UK	China	USA	Poland	Portugal	Spain	Greece	Other Or Mixed	No Info
First Author's Institute	30	9	9	8	6	6	5	3	2	2	16	/
Region of research	21	7	7	4	6	5	6	4	2	2	21	11
Materials / Collection Types	Art: artworks paintings drawings	Paper: books manuscripts maps photos	Wood: Wooden objects furniture	Metal	Fabric: tapestries	Earth: terracotta tiles sculpture	Stone	Specimens	Other: flora/ fauna ethnography instruments			
	32	6	8	8	5	4	3	3	11			
Standards referred to	ASHRAE	UNI 10829	EN 15757	National/ local	IESNA / CIBSE	EN 15251	UNI 10969	Other	No Info			
	28	18	6	6	3	4	3	24	39			



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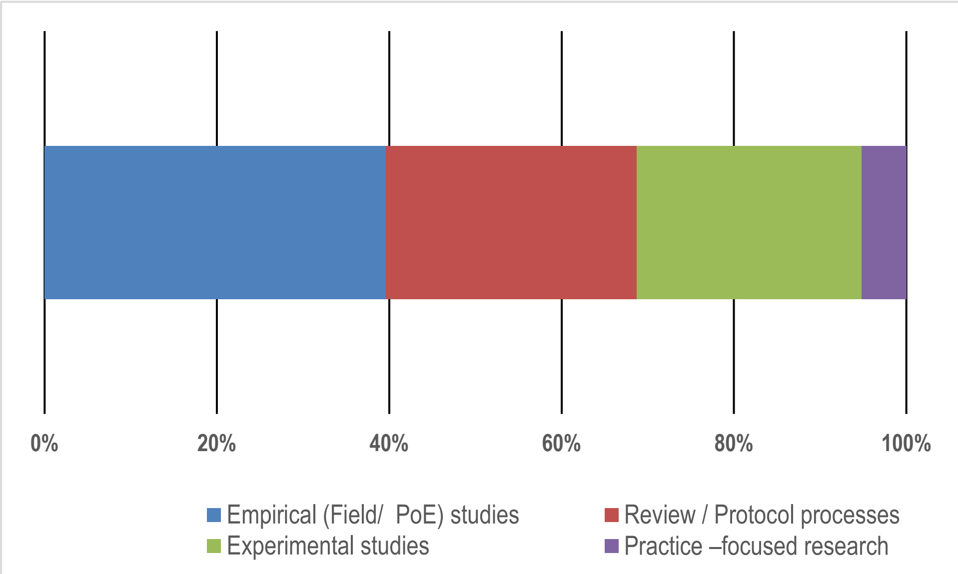


[Insert figure 2 near here]

The majority of the surveyed articles fall under the first category 'empirical' (N=38) (Figures 1,2), mostly evaluating the indoor environmental quality of a single case or a small number of museums in terms of conservation requirements, and in a few cases in relation to comfort and energy efficiency considerations. As detailed in the appendix this group of studies [17-54] provided in situ environmental and survey data presenting the findings of assessing the quality of the indoor environment of selected (often local) case studies recorded over a certain timeframe. Nearly one-third of the sample (N=28) were review or methodology papers proposing procedures for the microclimate assessment of museum environments [11, 13-15, 55-78] and one-quarter (N=25) were experimental in the approach adopted [79-103]. A modest number of the experimental studies focused on climate optimization through testing various classes of indoor conditions and control strategies for reducing energy use while addressing conservation and comfort requirements. Other experimental studies explored the deployment of remote sensing systems for environmental monitoring. Few studies presented 'multi-objective' operational protocols or 'multi-objective' assessments of museum environments merging the three different fields stated above (conservation, comfort, and energy efficiency) (see appendix). Only a handful of practice-focused papers (N=5) were identified across the sample [16,104-107].

4. Museum environments and climate management

The findings of the analysis of the literature review of museum environments and indoor climate management were organised under five sub-headings to reflect the trends in research in this area (Monitoring, Modelling, and Compliance) and to identify the gaps in literature (Geographical focus and Contextualising). These sub-headings are discussed below under the following sections:

- *In situ monitoring campaigns*
- *Simulation modelling, climate and energy projections*

- *Compliance with standards and reference to guidelines*
- *Geographical focus*
- *Contextualising the guidelines*

4.1 *In situ monitoring campaigns*

Various methodological approaches and a range of instrumentation were utilised across the sample to quantify the museum environment, in terms of collections safety and comfort requirements. The most common data gathering approach employed was in situ environmental monitoring using standalone logging devices and/or spot measurements [e.g.16,20,24,27,31-36,39,41-42,57-58,63-64,67-68,71,73,93]. Additionally, wireless sensing devices offering instant records of the state of the indoor climate are also gradually becoming common measuring instruments in museum environments [41,84,97,101,103].Several newly formulated or adapted metrics such as the 'performance index' (PI) [63-64,32], 'simultaneous performance index' (SPI) [67] together with thermal comfort assessment indices (e.g. predicted percentage of dissatisfied 'PPD' [66]), risk assessment, and damage functions (e.g. equivalent lifetime multiplier 'eLM' [63,66]) are increasingly used in several publications. As key performance indicators, they were often used to evaluate the quality of the indoor climate and the effectiveness of the control systems including the efficiency of heating, ventilation and air conditioning systems (HVAC) in keeping the hygrothermal parameters within the imposed comfort and conservation limits. Climate risk- assessment methods applied by scholars were classified as 'general' and 'specific'[89, p.453]. Whereas the former method of assessment , also referred to as 'global assessment' [64], '*consists of calculating the percentage of time that the indoor climate fits*' within certain limits/or at the desired values, '*the specific climate risk assessment accounts for how the objects react to the indoor climate*' [89, p.453]. Most of the empirical findings reported concern the general assessment of the microclimatic conditions, less about assessing the degradation phenomena of artefacts. Air temperature and relative humidity were the most investigated indoor environmental quality parameters, followed by indoor air quality (carbon dioxide concentrations, and dust), resonating previous observations. '*Up to now the distributed measurement system[s] installed in museums and archaeological sites are devoted to monitor[ing] temperature, humidity, light conditions, [and] CO2*' [29, p.1006]. Scholarly interest in air temperature and relative humidity is mostly attributed to the high energy cost often caused by the use of mechanical applications to eliminate sources of excess relative humidity and uncomfortable indoor temperature. Part of the emerging interest in the assessment of damage to artefacts by pollutants and indoor air quality is related to the growing concern over the effects of global warming threats (the synergy between climate change and air pollution) and the reality of urban air pollution in many regions, cities and heritage sites [27]. In several cases maintaining acceptable humidity rates is proved to be more demanding than controlling the temperature value. In the study on Serbian heritage institutions [105, p.116], concerns over controlling '*the level of relative humidity and [the] request for recommendations for acquiring climate control equipment (such as humidifiers, dehumidifiers and air-conditioning units)*' were the most raised issues by museums curators. High relative humidity rates were also an issue raised by other museums including those situated in tropical and subtropical regions where elevated relative humidity values are characteristic of the local climate. In the Oscar Niemeyer Museum case in Brazil, for instance, the mean humidity values obtained were relatively higher than the values noticed in other international museums ranging between (59% and 68%) [27]. One or two papers reported 'acceptable' values of temperature and relative humidity (T: 18–24ºC, RH: 40–55%) based on a short-term monitoring campaign. In the absence of a systematic monitoring practice and recorded data, it is difficult to use snapshot measurements to comment on the safety of the exhibition environment and the microclimate of the cases. With reference to the monitoring practice in Poland, Ferdyn-Grygierek [32, p.125] pointed out the importance of systematic environmental monitoring stating that '*reading of control parameters once a day (as it is the case in most Polish museums), does not allow to assess dangerous hourly and daily fluctuations in these parameters and could cause errors in the control of heating and cooling systems*'. The core focus across the sample was on the analysis of 'macro-environments (galleries/rooms)', with a smaller number of papers focusing on the analysis of 'micro-environments' including showcases [92] and microclimate frames [68]. Another area that seems to be lacking in the literature is acoustic comfort and vibration damage to artefacts.

There is an obvious variation in the methodological and analytical approaches adopted by scholars interested in assessing the quality of the thermal and visual environments and those focusing on indoor pollutants and their deleterious effects on artefact degradation. Indoor particulate matter (or total suspended particles) deposition studies are relatively limited, with most of the reviewed papers were mainly carried out by a handful of European researchers [e.g. 17,21,30,34,38,44,46]. The evaluation of the extent of surface blackening or soiling by suspended particulates together with the examination of the deposition rate and concentration of airborne particles require the use of various laboratory methods which are often expensive, demanding not only the cooperation of outside entities and collaboration between various areas of expertise and branches of knowledge, but also the use of specialised testing laboratory equipment (e.g. optical reflection microscopy, spectrophotometry) and analytical procedures (e.g. image processing techniques). The extract from Proietti *et al*'s study [91, p.65] briefly captures the complexity of implementing this type of assessment stating that '*most of the [pollutants deposition] studies [require] the use of expensive instrumentation and chemical–physical analysis*'. Consequently, their study proposes the use of 'simpler' dust detection and analysis methods that are based on the use of 'less expensive instrumentation' and computer processing and analysis. They introduce a novel dust analysis approach that is based on image capturing and pattern recognition. Although the image capturing device employed is affordable (a simple webcam and its built-in sensor as a deposition substrate), the subsequent stages of data pre-processing and analysis are still complex requiring a high level of expertise, presenting scholars with a different obstacle. In addition, novel experimental applications often demand further testing and resources before rolling out as new procedures. The combination of these factors may explain the paucity of research into indoor pollution assessment in museum environments in certain regions, echoing previous research findings [16, 27].

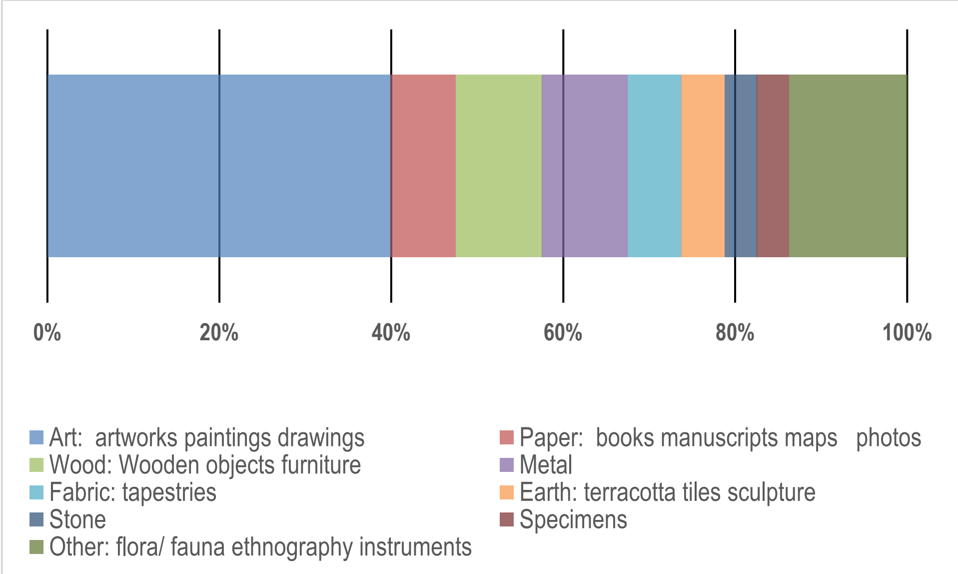
Statistical and mathematical modelling are also increasingly becoming a normal component/characteristic across recent publications, most probably due to the increasing capacity of logging devices and the large volume of data recorded. Since long term monitoring campaigns generally result in a large volume of fine data, various data visualisation and data mapping techniques were introduced by researchers to assist with data inspection and analysis. Silva *et al.* [63], for example, suggested a five-category colour-coded classification of the risk of indoor microclimate to museum collections with five rated as an ideal climate and one as high risk to artefacts. García-Diego *et al.* [68] investigated the choice of sampling frequency in microclimate field surveys in museum buildings. Their research concludes that hourly sampling is effective in obtaining highly reliable results, and in some instances daily means calculated from the sampling of every hour can lead to the same conclusions as those of high frequency. Such outcome could be useful in improving data logging design and in handling the resulting datasheets.

4.2 *Simulation modelling, climate and energy projections*

Building simulations and climate projections are not widely represented in the sample. Lankester and Brimblecombe [80] utilise this methodology to evaluate the potential impact of future climate on historic interiors and historic collections on open display within them, with a focus on the south of England. They note that the success of the methodology depends on the availability of high-resolution local climatic data in order to accurately assess risks and environmental threats. Huijbregts *et al*. [56] propose a method for predicting damage risks to museum objects in historic buildings as a result of climate change using case studies in the Netherlands and Belgium. Their method combines weather data from future outdoor climate scenarios with indoor climatic modelling. Their research confirms the need for further data in order to model future climate scenarios based on different locations.

Bøhm and Ryhl-Svendsen [81] focus on modelling of the building envelope to investigate the thermal conditions of a museum store in temperate climates. They use a Finite Element Model (FEM) to simulate the effect of the building envelope, focusing on the wall thickness and its interaction with the ground to understand the impact on the indoor thermal conditions of the store. This tool can be useful for improving museum design, taking into account issues of thermal massing and wall insulation.

Where specific collection types are referred to in papers the primary focus is almost invariably on art objects (Figure 3), which are viewed as being particularly sensitive to environmental conditions in museums and at risk of damage from poor environmental management. Art objects such as paintings and furniture are vulnerable to physical and mechanical degradation. They are often complex objects composed of different materials which may respond differentially to environmental parameters. Extending the conventionally accepted environmental limits can potentially pose threats to such sensitive objects. Reference to research into damage potential for different materials and objects is limited in the sample papers, and some highlight the need for further research in this area in order to better understand the nature of the risks and to respond with appropriate environmental management. Allegretti *et al.* [79] propose a hygromechanical monitoring method for wooden panel paintings as a tool for potentially revising environmental parameters for specific objects based on an understanding of the object's sensitivity to short- and long-term variations. This would lead to more informed decision-making as opposed to adopting a standardised approach.



[Insert figure 3 near here]

Museums are under pressure to improve their energy efficiency without compromising on the care of their collections. Whilst the need to reduce energy consumption and carbon emissions are understood, limited papers focus specifically on achieving energy savings in museum environments [25,87-90]. Ascione *et al.* [87] examine strategies for reducing the energy requirements for HVAC systems in a simulated modern museum exhibition hall using Italian climatic data. The authors of the paper argue that significant savings can be made if ASHRAE's climate variations are relaxed for less sensitive objects. Similar results were obtained by Kramer *et al.* [89] which perform computer simulations to investigate various setpoints on the energy consumption of an exhibition area housed in a renovated historic museum in the Netherlands. They reported a 77% reduction in energy use as compared to a strictly conditioned indoor climate while improving thermal comfort and collection preservation. The authors of the paper also note the necessity for considering adaptive comfort guidelines since temperature setpoints are dominantly determined by thermal comfort requirements. This is an important recommendation given the limited research on visitor comfort as the findings of this literature review has revealed (see paragraph below). In a more recent study, Kramer *et al.* [90] further explored the energy impact of five levels of museum climate control (setpoint strategies) for four building models simulated using weather data of twenty locations throughout Europe. For some locations, imposing more stringent limits on RH was found to result in lower energy requirements than adopting less stringent targets due to air-conditioning efficiency differences between humidification and dehumidification. This observation highlights the need for more research on this aspect.

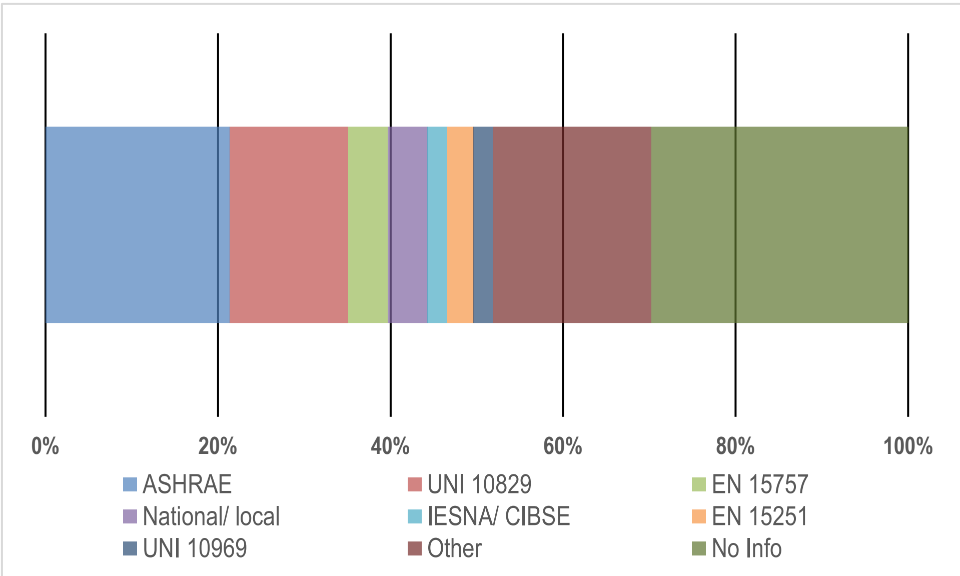
The impact of staff and visitors on museum environments is acknowledged as a contributory environmental factor in the degradation of museum objects, but there is little specific research which is focussed on this area in the sample papers examined. Pollutants brought in by visitors are discussed by Hu *et al.* [22] in relation to Emperor Qin's Terra-cotta Museum, where soiling and physical weathering hazards due to visitor activities in the Exhibition Hall are identified.

There is a consensus among scholars on the lack of research on human thermal comfort in museum buildings. This remark is further confirmed by the small number of studies that focus specifically on visitor comfort [20,33,36]. The frequent conflict between the environmental demands relating to the conservation of objects and visitor comfort is equally widely acknowledged along with the need to establish a practical compromise in meeting recommended technical standards. La Gennusa *et al.* [60] look for common ranges for the preservation of art objects and the thermal comfort of visitors, proposing a revision to the standards and advocating a simultaneousness index. In their discussion of the environmental management challenges for converting the historic White Tower at Thessaloniki, Greece, into a contemporary city museum, Papadopoulos *et al.* [96] propose an approach using measurement and simulation to evaluate the building's thermal behaviour. Indoor air quality and measurements of CO2 concentrations were compared to the acceptable levels proposed by Greek Technical Guidelines on IAQ and by the respective ASHRAE standard. The resulting data, they argue, can be used to design methods for passive cooling, ventilation and dehumidification in order to manage internal environments for the care of collections and for visitors, as well as taking account of the significance of the historic building. Yau *et al.* [20] are concerned with the challenge of maintaining thermal comfort for visitors to museums in tropical regions, where cooling might be needed throughout the year and 24 hours a day. Their study of the thermal environment and occupants' comfort at the National Museum in Malaysia found that conditions did not satisfactorily meet the ASHRAE standard. The data collected informed an energy-saving approach to the design of heating, ventilating and air-conditioning (HVAC) systems, taking into account visitors' own thermal adaptation adjustments. Mishra *et al.* [36] examine the evolution of thermal perception of visitors reporting the results of a field survey that was organised at the Hermitage Amsterdam museum. The findings suggest that '*people did not reach their normal level of discernment*' regarding the quality of the thermal environment immediately upon entering the building, but retained a connection with outdoor temperature for nearly 20 minutes. Based on this evidence they argue that adjusting the setpoint temperature in a manner so as to encourage adaptive thermal responses among visitors could offer opportunities for '*flexible and less energy intensive indoor conditioning options in transitional spaces*' [36, p.48].

4.3 *Compliance with standards and reference to guidelines*

The review provided evidence on museums' wide efforts as well as on the struggle to meet the strict environmental targets that aim at satisfying a varying range of conflicting criteria. Evaluating the indoor environmental quality of a Polish museum, Ferdyn- Grygiere [25] stated that maintaining the internal summer temperature at the 'desired' level of less than 24ºC can only be delivered with the provision of air conditioning during the summer period. Recorded temperature values varied on average from 17 to 28º C and relative humidity from 20% in winter to over 70% in summer despite full air conditioning. Elevated indoor temperatures and summer overheating detected during a monitoring campaign in the National History Museum of Florence were described as 'hazardous' for the preservation of the kind of objects exhibited (wax specimens) [35]. Unsatisfactory indoor air quality with high gaseous pollutants was found in two museums in Cyprus [34]. Variable temperature and humidity values deviating from requirements were also recorded in a Portuguese museum as a result of the ineffectiveness of the control system in keeping the predefined limits [63]. Unstable indoor conditions and gaseous pollutants exceeding international recommendations (ASHRAE guidelines) were also a concern in several museums in Southern China [106]. As elaborated by several authors and illustrated in the summary appendix many of these collections are exhibited in historical buildings that were originally built to serve different functions to their current use/life, not purposely built as museums and often are not equipped with full mechanical installations. On the contrary, a fewer number of field studies reported good to satisfactory microclimate quality in inspected cases, such as in the case of the main exhibition hall of Vleeshuis museum in Antwerp, Belgium [67].

Across the empirical/experimental papers, the indoor climate quality was frequently evaluated based on the degree of compliance with conventional international 'stringent' guidelines. The target values most used were those stipulated in the ASHRAE Manual, which was the most cited reference in the sample, and the Italian Standard UNI 10829 (Figure 4). A few papers make reference to other national or regional standards. For example, in their investigation into indoor air quality at the Capodimonte Museum in Naples, Italy, Chianese *et al*. [18] refer to legal limits for gaseous pollutants and particulate matter (PM) stipulated in national standards for museums by the Ministry of Heritage and Cultural Activities (MiBAC, 2001). In a South Korean context, Lee *et al.* [83] utilise recommended standards for pollutants established for indoor air quality for public facilities by the Korean Ministry of Environment (KMOE) as well as indoor air quality standards set for public records management facilities required by the Ministry of Public Administration and Security (KMOPAS). Environmental standards for cultural heritage collections are not available in many countries [68], thus the reliance on international standards to compensate for the lack of national standards. Only a handful of papers adopted wider target values based on empirical data and contextual considerations of the climatic adaptation of artefacts 'acclimatization', past environmental history, and change in the operation practice [e.g. 105-106]. A brief description of these emerging practices and the shift towards contextualising the microclimate specifications is given below (Section 4.5).

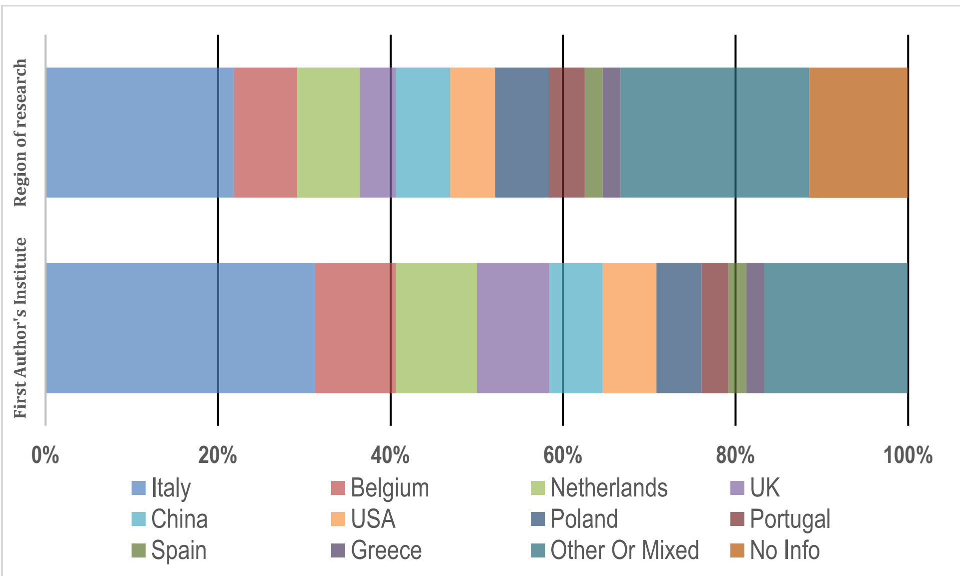


[Insert figure 4 near here]

As it may be expected, the use and reference to the guidelines varied across the sample. In some studies, recommendations for preventive conservation and comfort guidelines were only stated as part of the introductory section and background information, while in others the analysis of the data and the degree of compliance were clearly explained and thoroughly interpreted [e.g. 63, 88]. The primary safety or preventive conservation criteria used were that temperature and relative humidity were kept or fell below specific prescribed target values, depending on material responses and the sensitivity category. Pursuing the safety requirements, further considerations included limiting the daily and seasonal fluctuations of temperature and relative humidity that are generally quantified by dividing the minimum to maximum values.

4.4 *Geographical focus*

Whereas most empirical studies had named their geographical focus, procedure and review papers are generic in nature, often written to serve different locations and purposes. Yet, the ancillary information that accompanies each journal publication such as the first author's affiliation data allows reliable identification of the region of publication. Both types of information, the geographical focus and the first author's institutional data were used to discern the geographical pattern of museum climate management research, as a 'proxy' indicator of the interest in the topic across the various regions. The findings of this aspect of the analysis confirm the popularity of the topic among western scholars with nearly three-quarters of the articles published in the last two decades led by authors from European countries (Figure 5). This finding is very much in agreement with the outcomes of previous review papers. Environmental monitoring practice including occupancy and post occupancy evaluation is on the whole more common in western countries than in other regions and cultural obstacles seem to influence the utilisation of this data collection approach. Some regions are poorly represented, and papers highlight a lack of domestic research into museum standards and insufficient environmental and climatic data. Agbota *et al*. [16] focus on pollution monitoring for cultural heritage preservation in developing and emerging economies, with particular reference to Africa, Asia and Latin America. In addition to noting the lack of regional air pollution data, their questionnaire survey demonstrated that lack of awareness of risk and lack of technical expertise as well as cost implications all presented obstacles. Technical issues such as problems with power supply and internet connectivity also impede progress with monitoring and implementing museum standards. Mundo-Hernández *et al*. [26] presented the results of an 'indicative' post occupancy evaluation of a converted art gallery in Mexico that was carried out through a short user survey and walkthrough investigation. The authors stated the difficulty of assessing the interior environmental quality of the building due to administration and permission issues. '*Unfortunately, physical measurements of light, temperature, air quality, and acoustics were not collected because of the gallery's administration policies*' [26, p.333].



[Insert figure 5 near here]

4.5 *Contextualising the guidelines*

International standards for indoor environmental conditions in museums have been in use globally for several decades (section 2). However, in recent years, the high running cost of museums combined with the lack of funding has contributed to the debate over the implementation of the current strict regulations and the shift towards the use of less demanding targets. Revised carefully crafted or customised targets are currently being considered as part of heritage institutions wide efforts to manage resources efficiently. Yet, the findings of this literature review suggested that journal papers that may offer an insight into such applications are rather limited. Of the reviewed papers, only two or three studies have provided an overview of such emerging practices and applications of the use of contextualised targets for a certain region [105-106,11]. Živkovic and Dzikic [105] have elaborated on the efforts recently undertaken in Serbia to revise, establish and contextualise museums' environmental specifications. The manuscript refers to several cases where the process used to specify their environmental requirements suggests a change of approach from 'prescriptive' to 'evidence-led guidelines'. Since 2005, the Central Institute for Conservation in Belgrade has been liaising with heritage institutions in Serbia, on determining the necessary environmental requirements for collections and proposing adequate control solutions. The strategy adopted favours cost-effective solutions that do not impose excessive investments in museum buildings but mainly focuses on eliminating sources of extreme indoor conditions considering minimal risks to collections. Environmental requirements for a single case or a specific collection are determined based on a systematic data gathering process including surveys of facilities/collections and in-house monitoring followed by an evaluation of the climate risk to collections. Considering objects acclimatization and the history of conservation conditions, in some cases, recommendations were made not to change the existing climate conditions when they are observed as stable both for collections and buildings, even if unmaintained at a certain level. This may sound controversial, but recent research evidence in the field indicates that objects are far more tolerant than it has been considered until recently. Over time, Silva *et al.* [63, p.21] state, '*it became evident that the use of stringent targets may not be scientifically justifiable, since new researchers showed higher resistances of some materials to ampler ranges than those considered so far*'. Kramer *et al.* [88, p.287] further note '*no evidence has been found that less strict indoor climates result in collections damage*'. Lack of resources and investments in the preservation of cultural heritage due to the global economic situation in Serbia, were cited as the main driver that has initiated the need for such a shift. Given the increasing financial challenges facing most museum curators worldwide, contextualising the specifications of museum environments based on the choice of 'proper' rather than the most 'optimal conditions' might become the norm or the 'new normal' in the future.

Ankersmit *et al.* [11] presented an overview of the climate specifications in museums in the Netherlands where in the last two decades many museums have been renovated and previously developed specifications have been revisited. A review of the current requirements of several museums indicates that the re-established specifications are very similar, '*have not become more stringent or significantly more relaxed over the years*' [11, p.52]. The authors of the paper further stated that in one case, they were able in consultation with other stockholders and based on the susceptibility of the collection units and contents to design indoor climate requirements that consider collection care as well as energy efficiency demands. The final set of requirements for the galleries regarded as suitable for the collection with very sensitive objectives in show cases were 16ºC <T<25ºC, 35%<RH<65%, a range that is context-driven rather than standardised, fitting the institution-specific needs.

On the other side of the globe, an impressive number of new museums have emerged in China since the late 1970s hosting thousands of exhibitions, attracting millions of visitors, but also causing many accumulating objects to be left in unsuitable environments, resulting in irreversible damage. In a review of the recent efforts undertaken in China to regulate environmental management practice in museums, Feng [106] has added another dimension to the debate over the standardization of targets, elaborating on the high restoration cost of damaged artefacts. A nationwide survey conducted by the State Administration of Cultural Heritage in 2002 and 2005 revealed some disturbing facts with nearly half of the 35 million museum objects showing signs of serious degradation. Almost 23 million had suffered varying degrees of degradation, which amounted to nearly 17% of all national museum objects. This alarming situation and the ever-increasing demand for artefact restoration have increased the awareness of the necessity to control museums' environmental conditions as a key preventive conservation strategy. However, museums in China are widely distributed across the regions with artefacts exposed to various climatic conditions. Whereas the south is humid, the north is very dry with a relative humidity of 20-30%. As objects have already adapted to these low humidity values, it was argued that chasing the 50% RH uniform mark could cause more damage, demanding more funds and facilities. Several other studies stressed the importance of understanding the past climate, object adaption to the local climate, history of collections and signs of degradation before specifications are made.

5. Discussion

Temperature, relative humidity, visual light, ultraviolet radiation, air pollution and dust are well recognised as the main environmental agents for artefact deterioration. When exceeding certain thresholds or fluctuation limits/magnitudes hazardous environmental parameters could induce mechanical, chemical or biological degradation in environmentally sensitive objects dependent on materiality, age, and type. Temperature and relative humidity, as discussed in section 4.1, are the mostly recorded parameters reported by the empirical papers and the most cited across the whole sample, followed by air pollution, dust and visible light. As much as monitoring temperature and relative humidity is critical to enhance the safety and the quality of the indoor microclimate, museums need to collect data more diligently and collectively to inform more coherent evidence-based mitigation measures or intervention solutions by implementing more holistic multiple-agent monitoring campaigns. For many years, visible and ultraviolet radiation was considered as the primary agent of damage for vulnerable objects. Recent research into the environmental management of historic tapestries indicates that the 'synergistic' cumulative effects of other parameters could be equally damaging, stating '*a synergistic temperature, relative humidity and pollution degradation pathways was almost as damaging as UV radiation*' [108, p.587]. The emergence of such evidence reiterates the need for more comprehensive monitoring campaigns and management regimes rather than concentrating on monitoring certain parameters. As stated earlier (section 4.1), there is an obvious division between the focus of the monitoring campaigns /research programme and a separation between thermal and visual environment-related studies and pollution-focused studies. The advent of relatively cheap/affordable wireless sensing devices are extending the capacity and the effectiveness of in situ live monitoring by enabling fine logging of multiple environmental variables simultaneously. Conducting such types of holistic monitoring campaigns could be more expensive than target monitoring. However, in the long term, some of the upfront cost might be compensated by the reduction of artefact restoration costs and the need for repair, as per the case in China.

An interesting application of the use of monitoring to inform effective conservation environmental risk-mitigation measures (and conservation priorities) in listed heritage settings can be seen at Hampton Court Palace in Surrey (UK), one of the National Trust's most prestigious historic properties, housing an 'invaluable' collection of tapestries. Following a lengthy but gradually implemented environmental monitoring campaign a range of evidence-based conservation solutions (solutions/interventions for conservation in situ) were executed allowing the visitor to experience the tapestries in their original location on open display (without negatively affecting the physical integrity of the surroundings of the historic interior) [108]. Where collections are largely housed in traditional historic buildings (section 4.3, appendix 1), context-driven, holistic, multiple-agent environmental survey/monitoring could assist in finding not only less intrusive measures but also the most effective energy reduction options. Advances in glazing materials and UV filtering films, lighting and dimming technology and smart shading systems could help in controlling the amount of visual and UV radiation hence contributing to the quality of the ambient environment both thermally and visually.

Section 4.4 highlights the gaps in research and the relevance to the implementation of regulatory frameworks particularly in regions where little or no research of museum indoor environments is taking place. Given the lack of localised standards for museum indoor environments in many parts of the World, countries have only demanding international standards [88] to comply with. The review shows that increasing demands due to climate change as well as scarcity of resources make compliance with current international standards not only increasingly difficult but also in many cases unreasonable, such was the case in Serbia and South China [105, 106]. The applicability of common standards to heritage buildings that were not originally built as museums is also questionable [67]. There is therefore a need to widen and contextualise research in museum indoor environments. More relevant and localised standards are needed to reflect more precise requirements for adequate indoor environments for both users and exhibits.

Localised internal and external climatic conditions have implications for object preservation and for users of museum buildings. Several studies have focused on spatial distribution and users' experience of objects and displays within museums [109-111]. Few studies, however, have focused on the relationship between the users and their surrounding indoor environment. Emphasis is given to artefact conservation, which is considered a priority in these types of buildings [112]. Hu *et al*. [22], for example, investigated the occupants' effect on the surrounding indoor environment which leads to the deterioration of the artefacts. Although thermal comfort has proven to be crucial to users' comfort and satisfaction within the indoor environment, its application to museum environmental management is still quite limited [20, 36] and is generally ruled by the suitable conditions for the objects [33]. The reviewed studies demonstrated a clear need for an integrated approach that considers the artefact preservation and the occupants' thermal comfort as well as energy efficiency. This multi-objective approach has recently provided the focus for a study by Schito *et al*. [112]. The contextual nature of thermal studies also requires taking into consideration the users' comfort levels within different climate classifications.

While there is a considerable challenge to managing the conflicting requirements of the museum environment, emerging standards such as EN 16893 [113] place the conservator at the centre of defining environmental requirements for museums. To make such decisions, informed choices must be made based on clear science and a good understanding of the different materials and structures that make up their collections. A good example of artefact-centred rather than specification-centred recommendations is the work on painted wood by Bratasz [55] resulting in a recommended range and rates of change in relative humidity for painted wooden artefacts based on micro-level optical and acoustic monitoring of moisture penetration and dimensional change. This and other work have been taken further by Kramer *et al* [89] and developed into a scoring system by Silva *et al* [63]. Such integrated systems are still in their infancy and require close monitoring to be effective. Wireless data loggers are becoming available at low cost which, coupled with reductions in computing cost, allow conservators to observe their collection's environment with increasing precision. Improvements in readability of the data to allow conservators to interpret the output are needed and a wider selection of targeted materials science is central to better conservation outcomes while reducing energy inputs and improving visitor and staff comfort.

6. Conclusions

The management of indoor environments is an important function of museum operations in any part of the World. This in-depth literature review shows that studies in this field have neither examined all aspects of the indoor environment nor evenly covered different parts of the World. Such gaps in the literature have led to limited sharing of best practices across different institutions and different countries with implications on various levels for compliance with regulatory frameworks.

The paper examines the bibliography that falls into this field of research. The surveyed literature was classified under four broad categories. The first category refers to the types of empirical/ field studies, and the other categories include experimental studies, protocol processes for indoor climate optimization and overview papers offering an insight into climate control practice in a certain context. Most of the papers in this category (40%) focused on assessing existing indoor environments in selected cases. The papers illustrate the struggle to comply with the strict, and in cases exaggerated, requirements that aim at satisfying a varying range of conflicting criteria to provide indoor comfort to visitors while continuing to protect artefacts. The bibliography has rarely shown an integrated practical approach to either examine the reasons for non-compliance or to discuss further possible improvement to practices. The complexity of the management of museum environments suggests a need for more research to develop tools and practices that allow for management of multiple agents.

The paper also shows the fragmentation of tools and methods to assess the indoor environment in museums. In situ monitoring studies were mainly related to indoor climatic conditions while focus on air pollutants was very limited and separately examined. The survey also shows that a more recent trend in publications is the increasing use of statistical and mathematical modelling. The reviewed articles have mostly reported the findings of just one year of monitoring, with the risk that this could be an exceptional year of climatic conditions and thus might not be enough to make an informed decision about the safety of the environment to objects or to understand past climate history over longer periods. Archival data accumulated from extended monitoring is key to shed some light on object acclimatisation, suggesting that the move towards more contextualized climate specifications requires long term monitoring. In other words, data collected from extended monitoring could facilitate the adoption of contextualized climate specifications, an aspect that could positively contribute to museums' efforts in reducing their energy use.

With regards to the impact of indoor climate on exhibits, most of the papers (60%) examined the impact on paintings, drawings/texts and wooden artefacts. The paper confirmed the lack of research on human thermal comfort, integrated energy studies, and the impact of staff and visitors on indoor climate.

The paper also highlighted the limited coverage of case studies in different parts of the World. More than 60% of the papers surveyed are produced in Europe and 70% of studies are by European institutions. Research of the cultural aspects of comfort or the impact of local climatic conditions on the preservation of artefacts was very limited. Studies in China have shown the importance of further understanding how objects acclimatise within a particular context rather than apply blanket standards across all parts of the World.

Recent publications in museum studies provide hints of possible future directions. There is, for example, increasing research into the role of Artificial Intelligence (AI) in improving the visitor experience and enhancing museum operations [114]. Climatic analytics tools could rely on AI to make decisions and optimise museum indoor environments. The evolving cultural roles and design of museums will also affect the management of their indoor environments. Ambient environment plays a key role in visitors' experience [37]. Increasing use of museums as social, conference, and celebratory hiring spaces would necessitate a shift in museum design and related management of indoor environments. Research in this area will be particularly important for museums in the post COVID-19 pandemic era with more emphasis on the management of air quality and possibly limiting freedom of movement of visitors within galleries and other spaces [115]. The balance of the trade-off in ensuring human comfort in museums versus protecting artefacts is therefore an evolving yet imperative research topic. Research would need to examine in depth the role of advanced technologies in monitoring, analysing, and visualising indoor environmental data. Sharing best practices as well as challenges, in different parts of the World, would no doubt provide better insights to update more contextualised and more tailored standards across different regions.

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References

[1] International Energy Agency. Electricity Security 2021: Challenges and opportunities ahead for electricity security, Paris: International Energy Agency. https://www.iea.org/reports/electricity-security-2021[assessed 10 August 2021]

[2] Michalski S. Climate Guidelines for Heritage Collections: Where we are in 2014 and How we Got Here. In: Stauderman S, Tompksins WG, editors. Summit on the Museum Preservation Environment, Proceedings of the Smithsonian Institution, Washington D.C.: Smithsonian Institution Scholarly Press; 2014, p.7-32. https://repository.si.edu/bitstream/handle/10088/34611/13.03.EnvironPreservationSummit.Final.pdf?sequence=1&isAllowed=y [accessed 23 August 2019]

[3] Staniforth S. Historical perspectives on preventive conservation. Readings in Conservation 6. Los Angeles: Getty Conservation Institute; 2013.

[4] Lambert S. The Early History of Preventive Conservation in Great Britain and the United States (1850–1950). CeROArt; 2014. https://journals.openedition.org/ceroart/3765 [assessed 15 September 2019]

[5] Hatchfield P. Crack Warp Shrink Fake: A New Look at Conservation Standards. Museum 2011: 40-51. http://www.conservation wiki.com/w/images/b/bd/Crack_Warp_Shrink_Flake_2011.pdf. [accessed 23 August 2019]

[6] American Institute for Conservation. Environmental Guidelines. http://www.conservation-wiki.com/wiki/Environmental_Guidelines;2019 [accessed 23 August 2019]

[7] Plenderleith H, Philippot P. Climatology and conservation in museums. Museum 1960; 13:4. https://unesdoc.unesco.org/ark:/48223/pf0000127409. [accessed 23 August 2019]

[8] Thomson G, The Museum Environment. London: Butterworth/Heinemann;1978.

[9] Thomson G, The Museum Environment. London: Butterworth & co;1986.

[10] Michalski S. The ideal climate, risk management, the ASHRAE chapter, proofed fluctuations, and toward a full risk analysis model. Contribution to the Experts' Roundtable on Sustainable Climate Management Strategies. http://getty.art.museum/conservation/science/climate/paper_michalski.pdf;2007 [accessed 23 August 2019].

[11] Ankersmit B, Stappers M H L, Kramer R. Guideline in Jeopardy: Observations on the Application of the ASHRAE Chapter on Climate Control in Museums. Studies in Conservation 2018; 63:1-7.

[12] National Museum Directors' Conference NMDC Guiding Principles for Reducing Museums' Carbon Footprint. https://www.nationalmuseums.org.uk/media/documents/what_we_do_documents/guiding_principles_reducing_carbon_footprint.pdf;2009 [accessed 23 August 2019]

[13] Lucchi E. Review of preventive conservation in museum buildings. Journal of Cultural Heritage 2018; 29:180–193.

[14] Sharif-Askari H, Abu-Hijleh B. Review of museums' indoor environment conditions studies and guidelines and their impact on the museums' artifacts and energy consumption. Building and Environment 2018; 143:186-195.

[15] Bickersteth J. Environmental conditions for safeguarding collections: What should our set points be? Studies in Conservation 2014; 59 (4): 218-224.

[16] Agbota H, Young C, StrličM. Pollution monitoring at heritage sites in developing and emerging economies. Studies in Conservation 2013; 58:129-144.

[17] Krupińska B, Worobiec A, Rotondo GG, Novaković V, Kontozova V, Ro C-U, Van Grieken R, De Wael K. Assessment of the air quality (NO2, SO2, O3 and particulate matter) in the plantin-moretus museum/print room in antwerp, Belgium, in different seasons of the year. Microchemical Journal 2012; 102: 49–53.

[18] Chianese E, Riccio A, Duro I, Trifuoggi M, Iovino P, Capasso S, Barone G. Measurements for indoor air quality assessment at the Capodimonte museum in Naples (Italy). International Journal of Environmental Research 2012; 6 (2): 509-518.

[19] Cao J-J, Chow J, Watson J, Lee S, Rong B, Dong J-G, Ho K-F. Chemical composition of indoor and outdoor atmospheric particles at Emperor Qin's Terra-cotta museum, Xi'an, China. Aerosol and Air Quality Research 2011; 11 (1): 70–79.
[20] Yau Y H, Chew BT, Saifullah A Z A. A Field Study on Thermal Comfort of Occupants and Acceptable Neutral Temperature at the National Museum in Malaysia. Indoor and Built Environment 2013; 22(2): 433-444.
[21] Worobiec A, Samek L, Krata A, Van Meela K, Krupinska B, Stefaniak E A, Karaszkiewicz P, Van Grieken R. Transport and deposition of airborne pollutants in exhibition areas located in historical buildings e study in Wawel Castle Museum in Cracow, Poland. Journal of Cultural Heritage 2010; 11 (3) 354-359.
[22] Hu T, Lee S, Cao J, Chow J C, Watson J G, Ho K, Ho W, Rong B, An Z. Characterization of winter airborne particles at Emperor Qin's Terra-cotta museum, China. Science of the Total Environment 2009; 407(20) 5319-5327.
[23] Papadopoulos A M, Avgelis A, Anastaselos D. Low energy cooling of the White Tower, functioning as a contemporary museum. Energy and Buildings 2008; 40 (8) 1377-1386.
[24] Hu T, Jia W, Cao J, Huang R, Li H, Liu S, MaT, Zhu Y. Indoor air quality at five site museums of Yangtze River civilization. Atmospheric Environment 2015; 123:449-454.
[25] Ferdyn-Grygierek J. Indoor environment quality in the museum building and its effect on heating and cooling demand. Energy and Buildings 2014; 85:32–44.
[26] Mundo-Hernández J, Valerdi-Nochebuena M C, Sosa-Oliver J. Post-occupancy evaluation of a restored industrial building: A contemporary art and design gallery in Mexico. Frontiers of Architectural Research 2015; 4: 330–340.
[27] Godoi R H M, Carneiro B H B, Paralovo S L, Campos V P, Tavares T M, Evangelista H, Van Grieken R, Godoi A F L. Indoor air quality of a museum in a subtropical climate: The Oscar Niemeyer museum in Curitiba, Brazil. Science of the Total Environment 2013; 452–453: 314–320.
[28] Abdul-Wahab S A, Salem N, Ali S. Evaluation of indoor air quality in a museum (Bait Al Zubair) and residential homes. Indoor and Built Environment 2015; 24(2): 244–255.
[29] Lamonaca F, Pizzuti G, Arcuri N, Palermo A M, Morello R. Monitoring of environmental parameters and pollution by fungal spores in the National Gallery of Cosenza: A case of study. Measurement 2014; 47:1001-1007.
[30] Anaf W, Bencs L, Van Grieken R, Janssens K, De Wael K. Indoor particulate matter in four Belgian heritage sites: Case studies on the deposition of dark-colored and hygroscopic particles. Science of The Total Environment 2015; (506–507): 361-368.
[31] Anaf W, Horemans B, Madeira T I, Carvalho M L, De Wael K, Van Grieken R. Effects of a constructional intervention on airborne and deposited particulate matter in the Portuguese National Tile Museum, Lisbon. Environ Sci Pollut Res 2013; 20:1849–1857.
[32] Ferdyn-Grygierek J. Monitoring of indoor air parameters in large museum exhibition halls with and without air-conditioning systems. Building and Environment 2016; 107: 113-126.
[33] Martinez-Molina A, Boarin P, Tort-Ausina I, Vivancos J L. Assessing visitors' thermal comfort in historic museum buildings: Results from a Post-Occupancy Evaluation on a case study. Building and Environment 2018;132: 291–302.
[34] Zorpas A A, Skouroupatis A. Indoor air quality evaluation of two museums in a subtropical climate conditions. Sustainable Cities and Society 2016; 20: 52–60.
[35] Sciurpi F, Carletti C, Cellai G, Pierangioli L. Environmental monitoring and microclimatic control strategies in "La Specola" museum of Florence. Energy and Buildings 2015; 95:190–201.
[36] Mishra A K, Kramer R P, Loomans M G L C, Schellen H L. Development of thermal discernment among visitors: Results from a field study in the Hermitage Amsterdam. Building and Environment 2016; 105: 40-49.
[37] Jeong J-H, Lee K-H. The physical environment in museums and its effects on visitors' satisfaction. Building and Environment 2006; 41:963–969.

[38] Worobiec A, Samek L, Karaszkiewicz P, Kontozova-Deutsch V, Stefaniak E A, Van Meel K, Krata A, Bencs L, Van Grieken R. A seasonal study of atmospheric conditions influenced by the intensive tourist flow in the Royal Museum of Wawel Castle in Cracow, Poland. Microchemical Journal 2008; 90: 99–106.
[39] Schieweck A, Lohrengel B, Siwinski N, Genning C, Salthammer T. Organic and inorganic pollutants in storage rooms of the Lower Saxony State Museum Hanover, Germany, Atmospheric Environment 2005; 39: 6098–6108.
[40] Gysels K, Delalieux F, Deutsch F, Van Grieken R, Camuffo D, Bernardi A, Sturaro G, Busse H-J, Wieser M. Indoor environment and conservation in the Royal Museum of Fine Arts, Antwerp, Belgium. Journal of Cultural Heritage 2004; 5: 221–230.
[41] Corbellini S, Di Francia E, Grassini S, Iannucci L, Lombardo L, Parvis M. Cloud based sensor network for environmental monitoring. Measurement 2018; 118: 354-361.
[42] Marchetti A, Pilehvar S, 't Hart L, Pernia D L, Voet O, Anaf W, Nuyts G, Otten E, Demeyer S, Schalm O, De Wael K. Indoor environmental quality index for conservation environments: The importance of including particulate matter. Building and Environment 2017; 126:132-146.
[43] Kramer R, Schellen L, Schellen H. Adaptive temperature limits for air-conditioned museums in temperate climates. Building Research & Information 2018; 46(6): 686-697.
[44] Cartechini L, Castellini S, Moroni B, Palmieri M, Scardazza F, Sebastiani B, Selvaggi R, Vagnini M, Delogu G L, Brunetti B G, Cappelletti D. Acute episodes of black carbon and aerosol contamination in a museum environment: Results of integrated real-time and off-line measurements. Atmospheric Environment 2015; 116:130-137.
[45] Pencarelli T, Cerquetti M, Splendiani S. The sustainable management of museums: an Italian perspective. Tourism and Hospitality Management 2016; 22 (1): 29-46.
[46] Krupińska B, Van Grieken R, De Wael K. Air quality monitoring in a museum for preventive conservation: Results of a three-year study in the Plantin-Moretus Museum in Antwerp, Belgium. Microchemical Journal 2013; 110: 350-360.
[47] del Hoyo-Meléndez J M, Mecklenburg M F, Domenech-Carbo M T. An evaluation of daylight distribution as an initial preventive conservation measure at two Smithsonian Institution Museums, Washington, DC, USA. Journal of Cultural Heritage 2011; 12(1): 54-64.
[48] Reddy M K, Suneela M, Sumathi M, Reddy R C. Indoor Air Quality at Salarjung Museum, Hyderabad, India. Environ Monit Assess 2005; 105: 359–367.
[49] Camuffo D, Van Grieken R, Busse H-J, Sturaro G, Valentino A, Bernardi A, Blades N, Shooter D, Gysels K, Deutsch F, Wieser M, Kim O, Ulrych U. Environmental monitoring in four European museums. Atmospheric Environment 2001; 35: S127-S140.
[50] Camuffo D, Bernardi A, Sturaro G, Valentino A. The microclimate inside the Pollaiolo and Botticelli rooms in the Uffizi Gallery, Florence. Journal of Cultural Heritage 2002; 3 (2): 155-161.
[51] Strada M, Carbonari A, Peron F, Porciani L, Romagnoni P. The microclimate analysis of tezone '105' of the Venetian Arsenale. Journal of Cultural Heritage 2002; 3(1): 89-92.
[52] Salmon L G, Cass G R, Bruckman K, Haber J. Ozone exposure inside museums in the historic central district of Krakow, Poland. Atmospheric Environment (2000);34 (22): 3823-3832.
[53] Yoon Y H, Brimblecombe P. Contribution of Dust at Floor Level to Particle Deposit Within the Sainsbury Centre for Visual Arts. Studies in Conservation 2000; 45(2): 127-137.
[54] Muething G, Waller R, Graham F. Risk Assessment of Collections in Exhibitions at the Canadian Museum of Nature. Journal of the American Institute for Conservation 2005; 44(3): 233-243.
[55] Bratasz Ł. Allowable microclimatic variations for painted wood. Studies in Conservation 2013; 58 (2): 65-79.
[56] Huijbregts Z, Kramer R P, Martens M H J, van Schijndel A W M, Schellen H L. A proposed method to assess the damage risk of future climate change to museum objects in historic buildings. Building and Environment 2012; 55: 43-56.

[57] Corgnati S P, Filippi M. 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). Journal of Cultural Heritage 2010; 11 (3): 345-349.
[58] Franzitta V, Ferrante P, La Gennusa M, Rizzo G, Scaccianoce G. Off-line methods for determining air quality in museums. Conservation Science in Cultural Heritage 2010); 10 (1):159-184.
[59] Bacci M, Cucci C, Mencaglia A, Azelio M, Grazia A. Innovative sensors for environmental monitoring in museums. Sensors 2008; 8 (3):1984-2005.
[60] La Gennusa M, Lascari G, Rizzo G, Scaccianoce G. Conflicting needs of the thermal indoor environment of museums: in search of a practical compromise. Journal of Cultural Heritage 2008; 9 (2):125-134.
[61] Lucchi E. Multidisciplinary risk-based analysis for supporting the decision making process on conservation, energy efficiency, and human comfort in museum buildings. Journal of Cultural Heritage 2016; 22:1079–1089.
[62] D’agostino V, d’Ambrosio Alfano F R, Palella B I, Riccio G. The museum environment: A protocol for evaluation of microclimatic conditions. Energy and Buildings 2015; 95:124–129.
[63] Silva H E, Henriques F M A, Henriques T A S, Coelho G. A sequential process to assess and optimize the indoor climate in museums. Building and Environment 2016; 104: 21-34.
[64] Corgnati S P, Fabi V, Filippi M. A methodology for microclimatic quality evaluation in museums: Application to a temporary exhibit. Building and Environment 2009; 44:1253–1260.
[65] Lucchi E. Simplified assessment method for environmental and energy quality in museum buildings. Energy and Buildings 2016; 117: 216–229.
[66] Schito E, Conti P, Testi D. Multi-objective optimization of microclimate in museums for concurrent reduction of energy needs, visitors’ discomfort and artwork preservation risks. Applied Energy 2018; 224:147–159.
[67] Litti G, Audenaert A, Fabbri K. Indoor Microclimate Quality (IMQ) certification in heritage and museum buildings: The case study of Vleeshuis museum in Antwerp Giovanni. Building and Environment 2017; 124: 478-491.
[68] García-Diego F-J, Verticchio E, Beltrán P, Siani A M. Assessment of the Minimum Sampling Frequency to Avoid Measurement Redundancy in Microclimate Field Surveys in Museum Buildings. Sensors 2016;16 (8): 1291.
[69] Bradley S. Preventive Conservation Research and Practice at the British Museum. Journal of the American Institute for Conservation 2005; 44 (3):159-173.
[70] Weintraub S. The Museum Environment: Transforming the Solution into a Problem, Collections: A Journal for Museum and Archives Professionals 2006; 2(3): 195–218.
[71] Gennusa M L, Rizzo G, Scaccianoce G, Nicoletti F. Control of indoor environments in heritage buildings: experimental measurements in an old Italian museum and proposal of a methodology. Journal of Cultural Heritage 2005; 6: 147–155.
[72] Litti G, Audenaert A. An integrated approach for indoor microclimate diagnosis of heritage and museum buildings: The main exhibition hall of Vleeshuis museum in Antwerp. Energy and Buildings 2018;162: 91-108.
[73] Pisello A L, Castaldo V L, Piselli C, Cotana F. Coupling artworks preservation constraints with visitors’ environmental satisfaction: Results from an indoor microclimate assessment procedure in a historical museum building in central Italy. Indoor and Built Environment 2018; 27(6): 846–869.
[74] Schito E, Testi D, Grassi W A. Proposal for New Microclimate Indexes for the Evaluation of Indoor Air Quality in Museums. Buildings 2016; 6 (4): 41.
[75] Angelini E, Civita F, Corbellini S, Fulginiti D, Giovagnoli A, Grassini S, Parvis M. Innovative monitoring campaign of the environmental conditions of the Stibbert museum in Florence. Appl. Phys 2016; A 122: 123.
[76] Atkinson J K. Environmental conditions for the safeguarding of collections: A background to the current debate on the control of relative humidity and temperature. Studies in Conservation 2014; 59 (4): 205-212.

[77] Raphael T. Preventive Conservation and the Exhibition Process: Development of Exhibit Guidelines and Standards for Conservation. Journal of the American Institute for Conservation 2005; 44(3): 245-257.
[78] Austin M, Firnhaber N, Goldberg L, Hansen G, Magee C. The Legacy of Anthropology Collections Care at the National Museum of Natural History. Journal of the American Institute for Conservation 2005; 44 (3):185-202.
[79] Allegretti O, De Vincenzi M, Uzielli L, Dionisi-Vici P. Long-term hygromechanical monitoring of wooden objects of art (WOA): A tool for preventive conservation. Journal of Cultural Heritage 2013; 14 (3): e161–e164.
[80] Lankester P, Brimblecombe P. The impact of future climate on historic interiors. Science of the Total Environment 2012; (417-418): 48–254.
[81] Bøhm B, Ryhl-Svendsen M. Analysis of the thermal conditions in an unheated museum store in a temperate climate. On the thermal interaction of earth and store. Energy and Buildings 2011; 43 (12): 3337-3342.
[82] Al-Sallal K A, Bin Dalmouk M M. Indigenous buildings' use as museums: evaluation of day-lit spaces with the Dreesheh double panel window. Sustainable Cities and Society 2011; 1 (2): 116-124.
[83] Lee C M, Kim Y S, Nagajyothi P C, Thammalangsy S, Goung S J N. Cultural heritage: a potential pollution source in museum. Environmental Science & Pollution Research 2011; 18: 43–755.
[84] Peralta LM R, Brito L M P L, Gouveia B A T, Sousa D J G, Alves C S. Automatic monitoring and control of museums' environment based on Wireless Sensor Networks. Electronic Journal of Structural Engineering Special Issue: Wireless Sensor Networks and Practical Applications (2010); 12-34.
[85] Ascione F, Minichiello F. Microclimatic control in the museum environment: air diffusion performance. International Journal of Refrigeration 2010; 33(4): 806-814.
[86] Van Schijndel A W M, Schellen H L, Timmermans W J. Simulation of the climate system performance of a museum in case of failure events. Energy and Buildings 2010; 42 (10): 1790-1796.
[87] Ascione F, Bellia L, Capozzoli A, Minichiello F. Energy saving strategies in air conditioning for museums. Applied Thermal Engineering 2009; 29 (4) 676-686.
[88] Kramer R P, Schellen H L, van Schijndel AW M. Impact of ASHRAE's museum climate classes on energy consumption and indoor climate fluctuations: Full-scale measurements in museum Hermitage Amsterdam. Energy and Buildings 2016; 130: 286–294.
[89] Kramer R P, Maas M P E, Martens M H J, van Schijndel AWM, Schellen H L. Energy conservation in museums using different setpoint strategies: A case study for a state-of-the-art museum using building simulations. Applied Energy 2015; 158: 446–458.
[90] Kramer R, van Schijndel J, Schellen H. Dynamic setpoint control for museum indoor climate conditioning integrating collection and comfort requirements: Development and energy impact for Europe. Building and Environment 2017; 118:14-31.
[91] Proietti A, Panella M, Leccese F, Svezia E. Dust detection and analysis in museum environment based on pattern recognition. Measurement 2015; 66: 62–72.
[92] Romano F, Colombo L PM, Gaudenzi M, Joppolo C M, Romano L P. Passive control of microclimate in museum display cases: A lumped parameter model and experimental tests. Journal of Cultural Heritage 2015;16: 413–418.
[93] Pisello A L, Castaldo V L, Pignatta G, Cotana F. Integrated numerical and experimental methodology for thermal-energy analysis and optimization of heritage museum buildings, Building Serv. Eng. Res. Technol. 2016; 37(3): 334–354.
[94] Bellia L, Capozzoli A, Mazzei P, Minichiello F. A comparison of HVAC systems for artwork conservation. International Journal of Refrigeration 2007; 30:1439-1451.
[95] Van Schijndel A W M, Schellen H L, Wijffelaars J L, van Zundert K. Application of an integrated indoor climate, HVAC and showcase model for the indoor climate performance of a museum. Energy and Buildings 2008; 40: 647–653.

[96] Papadopoulos A M, Avgelis, A.; Santamouris, M. (2003) Energy study of a medieval tower, restored as a museum. Energy and Buildings; 35: 951–961
[97] Klein L J, Bermudez S A, Schrott A G, Tsukada M, Dionisi-Vici P, Kargere L, Marianno F, Hamann H F, López V, Leona M. Wireless Sensor Platform for Cultural Heritage Monitoring and Modeling System. Sensors 2017;17: 1998.
[98] Luo X, Gu Z, Yu C W, Li K, Xiao B. Preservation of in situ artefacts by local heating in earthen pit in archaeology museum in cold winter. Building and Environment 2016; 99: 29-43.
[99] Ferdyn-Grygierek J, Baranowski A. Internal environment in the museum building—Assessment and improvement of air exchange and its impact on energy demand for heating. Energy and Buildings 2015; 92: 45-54.
[100] Ge J, Luo X, Hu J, Chen S. Life cycle energy analysis of museum buildings: A case study of museums in Hangzhou. Energy and Buildings 2015; 109:127–134.
[101] Agbota H, Mitchell JE, Odlyha M, Strlič M. Remote Assessment of Cultural Heritage Environments with Wireless Sensor Array Networks. Sensors 2014; 14:8779-8793.
[102] Arafat A, Na'es M, Kantarelou V, Haddad N, Giakoumaki A, Argyropoulos V, Anglos D, Karydas A G. Combined in situ micro-XRF, LIBS and SEM-EDS analysis of base metal and corrosion products for Islamic copper alloyed artefacts from Umm Qais museum, Jordan. Journal of Cultural Heritage 2013; 14 (3): 261-269.
[103] Peralta L M R, de Brito L M P L. An Integrating Platform for Environmental Monitoring in Museums Based on Wireless Sensor Networks. International Journal on Advances in Networks and Services 2010; 3 (1 & 2):114-124.
[104] Garside D, Curran K, Korenberg C, MacDonald L, Teunissen K, Robson S. How is museum lighting selected? An insight into current practice in UK museums. Journal of the Institute of Conservation 2017; 40 (1):3-14.
[105] Živković V, Dˇziki´ V. Return to basics—Environmental management for museum collections and historic houses. Energy and Buildings 2015; 95:116–123.
[106] Feng N. Overview of preventive conservation and the museum environment in China. Studies in Conservation 2016; 61 (1):18-22.
[107] Nunberg S, Eckelman M J, Hatchfield P. Life Cycle Assessments of Loans and Exhibitions: Three Case Studies at the Museum Fine Arts, Boston. Journal of the American Institute for Conservation 2016; 55 (1): 2-11.
[108] Frame K, Vlachou -Mogire C, Hallett K, Takami M. Balancing Significance and Maintaining 'Sense of Place' in the Sustainable Display of Tudor Tapestries in the Great Hall, Hampton Court Palace. Studies in Conservation 2018; 63 (1): 87-93.
[109] Falk JH, Dierking LD. Learning from Museums: Visitor Experiences and the Making of Meaning, California: Rowman & Littlefield Publishers; 2000.
[110] Rojas M d C, Camarero M del C. Experience and satisfaction of visitors to museums and cultural exhibitions. International Review on Public and Non Profit Marketing 2006; 3(1): 49–65.
[111] Packer J, Bond N. Museums as restorative environments. Curator: The Museum Journal 2010; 53(4): 421–436.
[112] Schito E, Conti P, Uranucci L, Testi D. Multi-objective optimization of HVAC control in museum environment for artwork preservation, visitors' thermal comfort and energy efficiency. Building and Environment2020; 180:107018.
[113] CEN. BS EN 16893:2018. Conservation of Cultural Heritage – Specifications for location, construction and modification of buildings or rooms intended for the storage or use of heritage collections. London: British Standards Institution; 2018.

[114] Villaespesa E, French A. AI, Visitor Experience, and Museum Operations: A Closer Look at the Possible, Humanizing the Digital: Unproceedings from the MCN 2018 Conference, independently published; 2019.
[115] Navigating the New Normal, Mijksenaar White Paper on Museums and COVID-19. Amsterdam; 2020, https://www.mijksenaar.com/navigating-the-new-normal-museums-after-covid-19/ [assessed 10 August 2021]