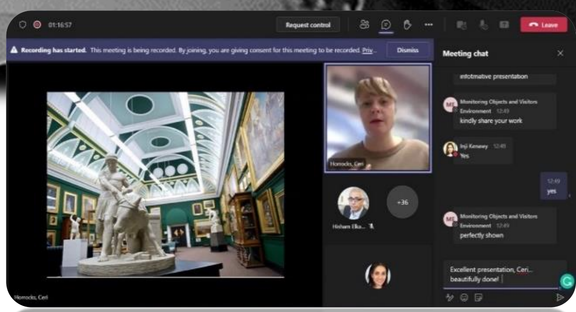
Monitoring Object and Visitor Environments

MOVE_FINAL REPORT
2022



Final project report submitted to the Arts and Humanities Research Council (AHRC), United Kingdom by the University of Salford_ (Grant number AH/R007810/1)

MOVE 2022

Monitoring Object and Visitor Environments

FINAL REPORT -Draft v5

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Project summary

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. Conflicting environmental requirements often require a degree of compromise and managing these environmental demands will become ever more challenging for museums 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 the need to accurately monitor microclimatic variations over time is fundamental to good museum practice.

The safe preservation of cultural heritage is an essential mission of Egyptian museums where some of the world's most ancient and valuable artefacts are conserved (Ingo et al, 2015). The lack of environmental control programmes in the region is generally attributed to resource limitations and skills shortages, which often result in compromised indoor environmental quality leading to the accelerated deterioration of vulnerable objects. These risks can be mitigated with adequate knowledge of the indoor environmental parameters required for collections care and with robust and accurate monitoring programmes. New user-friendly methods of monitoring using cutting-edge technology are needed if Egyptian museums are to take action in response to changing external conditions and reduce the threat of damage to artefacts from extreme weather patterns.

The **MOVE** (***Monitoring Object and Visitor Environments***) project proposes to develop a visual live environmental dashboard of digital data that is aimed at assisting museum curators in achieving stable and controlled indoor conditions to address seasonal variations and unpredictable weather patterns. The project contributes a new application for the use of real-time environmental data as a means of supporting actions to reduce risks to artefacts and improve comfort in visitor areas. A key principle of the digital platform is its ease of use. The Salford Museum and Art Gallery in the Greater Manchester Area in the UK provided the basis for prototyping the dashboard. Internal environmental parameters recorded at the site has been used to assess the performance of the case study against relevant conservation requirements, and comfort standards, and to develop a user-friendly prototype sensor management live dashboard that can be replicated in other museums across Egypt. The proposed dashboard provides accurate measurements of a range of criteria including exposure and illumination in light, pollution levels, relative humidity, internal operative and air temperature, and external temperature. In-situ detailed live monitoring of this environmental data could inform decision-makers and staff on curation, exhibition design and safe storage environments while optimising consumption of resources.

Project description

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 have been published which set out the ideal environmental parameters for the storage and display of museum collections. In reality conflicting 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. 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.

The safe preservation of cultural heritage is an essential mission of Egyptian museums, where some of the world's most ancient and valuable artefacts are conserved. Yet, the lack of environmental control programmes, which is generally attributed to resource limitations and skills shortages often results in comprised indoor environmental quality which could accelerate the deterioration process. These risks can be mitigated with adequate knowledge of indoor environmental parameters and their contribution to the process of deterioration. New methods of instant monitoring using advanced technology are therefore needed if Egyptian museums are to take action in order to reduce the risk of damage to artefacts.

The MOVE project proposes to develop a visual digital live environmental dashboard that aimed at assisting museum curators in achieving stable indoor conditions during different seasons and weather pattens. The project adds new application for the use of real-time data as a means of supporting actions to reduce risks to artefacts and improve comfort in visitor areas. In line with the scope and objects, an extended in situ environmental monitoring campaign was designed and conducted at the Salford Museum and Art Gallery over the second and third year of the project. The internal environmental data recorded at the museum has been used to

- Firstly, assess the performance of the case study against conservation requirements and comfort standards
- Secondly, to build up a user-friendly prototype sensor management live dashboard that can be replicated in other museums across UK and Egypt to facilitate the management of their environments.

MOVE was originally divided into several interrelated work packages. The project's theoretical framework was split into two major thematic areas: Conversation and Comfort. Under WP1, a comprehensive review of relevant publications on museum design and preventive conservation measures in relation to visitors' experience, collections display, and storage and energy use was carried out and revisited throughout the project to develop the theoretical research framework. In addition to the discussion with the Conservation Manager at the V&A where one of the first environmental monitoring dashboards has been developed for heritage conservation during the first engagement event (in 2018) and the visit to the highly controlled display environment at the Mary Rose Museum, the project team also reviewed other national and international approaches to museum management and environmental control to establish the state of the art in the field.
MOVE 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. The literature review 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 findings of the literature review are recently published in the journal of RSER (see appendix) and explained briefly below.

As for WP2 and WP5 (see above), and the dashboard development (WP3), a range of data processing methods was employed by the research team to carry out the different phases of evaluation. The project end event hosted by the project partner in Cairo last December (2021) was the part of WP6.

COVID-19 impact

The temporary closures of cultural venues and the lockdown measures introduced by the UK government in March 2020 affected the museums sector across the country. This unprecedented situation has resulted in an experimental setting that had never been experienced previously with empty galleries and artefacts exposed to free-running environmental conditions. On the one hand, assessing the quality of the microclimate in such exceptional circumstances offers a unique insight into the performance of these buildings in other unpredicted situations such as in the case of air conditioning system failure or events of summer heatwaves. On the other hand, the restrictions on households' mixing and number of visitors limited the possibility of meaningful comfort survey of museums visitors.

Egypt security clearance impact

MOVE is a collaboration between the University of Salford (UoS), University of Portsmouth (UoP) and Ain Shams University (Egypt) with the Salford Museum and Art Gallery (SMAG-UK) and a partner museum in Egypt. While the sensor installation and monitoring at the Salford Museum have been conducted as originally planned, equipment installation was problematic in Egypt. The installation of sensors requires a security clearance and approval from certain committees. The initial approval obtained by the team in Egypt was deemed by the Conversation Centre at the Grand Egyptian Museum (GEM-CC) as insufficient to proceed and the second request for clearance submitted by the team to install the sensors in the Islamic Museum was never received. The situation has unfortunately prevented the opportunity for recording live empirical data, and hence the design of the digital dashboard has been based on the climate data recorded in the Salford Museum.

Research Team

Prof Hisham Elkadi (UoS)is the MOVE project lead. Co-I Dr Sura Al-Maiyah (UoS) and Dr, D. Brett Martinson (Up) contributed to this report and its sections. Initial technical reports provided by Ethan Bellmer and papers presented at the MOVE international conference by Dr Karen Fielder (Up) and Dr Inji Kenawy (UoS.) are used in compiling the report. The journal paper published by the Egyptian team concerning the environmental control procedures in museums in Egypt is also included in the appendices.

1. Background Information & Focus of Research

1.2 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 a 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 the MOVE project and the focus of the literature review section (originally WP1) discussed below.

1.3 Research Questions

- What is the ability of museums in meeting the standards and whether there is evidence of deterioration associated with environmental management?
- What is the impact of the change in the daily operation of the case study due to exceptional circumstances (Lockdown, control system failure) on the quality of the

indoor microclimate and the safety of the collection?

- What are the technical requirements for delivering an integrated environmental management dashboard of digital data appropriate for the management of relevant environmental parameters in museums?

2. Methodology: Literature Review & Data Acquisition

2.1 Literature Review

Several phases of literature search and selection were undertaken as part of the theoretical review (WP1) 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 table 2). 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 table 2 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 the RSER attached (see appendix, Figures 2 to 5).

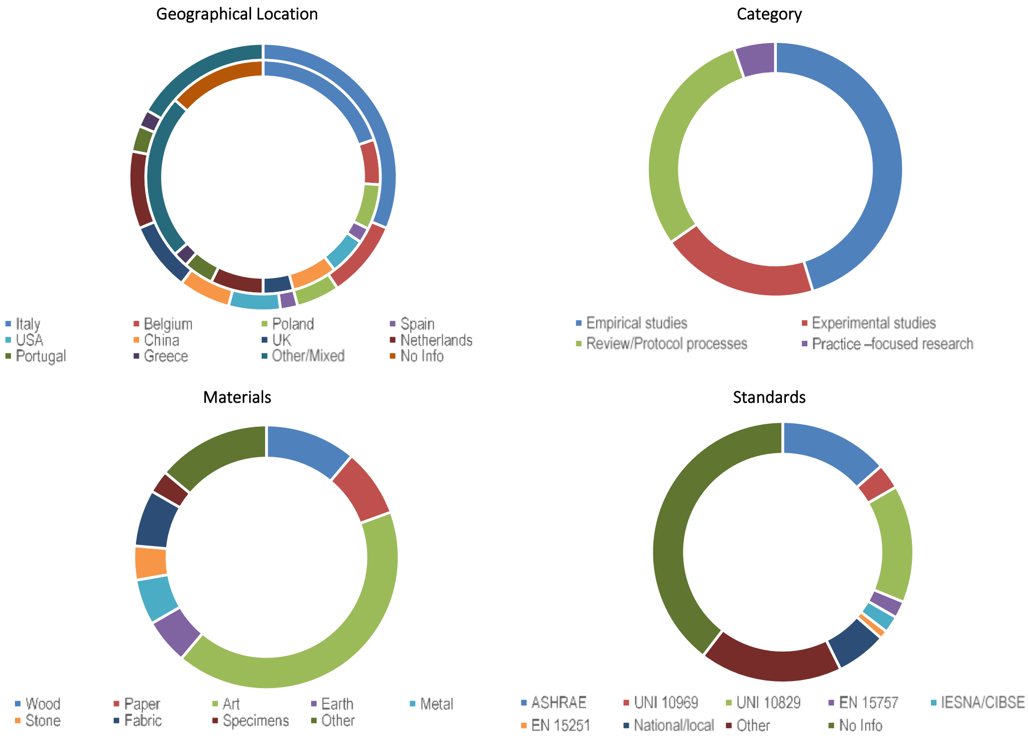


Figure 1. Classification of the reviewed papers by
Geography: (Author's Institute-Outer ring, Region of research), Paper type, Collection typology, Standards

The majority of the surveyed articles fall under the first category 'empirical' (N=38) (Figures 1), 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 table 2 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 table 2). Only a handful of practice-focused papers (N=5) were identified across the sample [16,104-107].

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

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

Table 2: Summary content of the review sample

Ref No	First author	Paper Category	Country of first author	Region of research	Museum type: Historic, Modern, Converted etc.	Collection type	Standards/ Guidelines referred to	Focus: Technical environmental monitoring and management	Specific environmental factors	Artefact preservation	Visitor comfort	Energy saving	Methodology for research
11	Ankersmit	Review	Netherlands	Netherlands			ASHRAE	Critique of the ASHREA's chapter on climate control		√	√	√	Literature, consultation with stakeholders
13	Lucchi	Review	Italy	International			Various, Inc. Italian and European, MGC, EN 15757 European Committee CEN/TC 346, ASHRAE, CIBSE UNI 10829, UNI 10586	Preventive conservation in museum buildings	Light, T, RH, air pollution	√	√	√	Review
14	Sharif-Askari	Review	United Arab Emirates	International			Various, ASHRAE, PAS (UK) HCC (Australia), AICCM, IESNA (light)	Indoor environment quality of museums; studies & guidelines	T, RH, light (Lux, UV), pollution, air quality	√	√	√	Review
15	Bickersteth	Review	UK	International			Various, Inc. PAS 198, Thomson, ASHRAE	Environmental conditions in museums					Review
16	Agbota	Practice – focused	UK	Africa, Asia, Latin America	Heritage sites			State of air pollution monitoring practice	Air pollution	√			Questionnaire, review, spot measurements
17	Krupińska	Empirical	Belgium	Belgium	Historic building	Books & manuscripts		Assessment of air quality	Air pollution; NO_2, SO NO_2, O_3, PM	√			Sampling, analysis (energy dispersive X-ray fluorescence (EDXRF) & electron probe micro-analyser (EPMA))
18	Chianese	Empirical	Italy	Italy	Capodimonte Museum	Works of art	National limits	Indoor air quality assessment	Gaseous pollutants, PM	√			Monitoring campaigns, sampling
19	Cao	Empirical	China	China	Terracotta Museum	Terracotta		Assessment of atmospheric particles	T, RH, air pollution	√			Sampling
20	Yau	Empirical	Malaysia	Malaysia	National Museum		ASHRAE, Literature	Thermal Comfort of Occupants	T, RH, air velocity		√	√	Questionnaire, measurements
21	Worobiec	Empirical	Poland	Poland	Wawel Castle Museum	Works of art		Investigation of transport & deposition of pollutants	Air pollution; gases, PM	√			Sampling, analysis (EDXRF & EPMA)
22	Hu	Empirical	China	China	Terracotta Museum	Terracotta		Contribution of visitors to airborne particles	Air pollution	√			Sampling, analysis (morphological & elemental using SEM-EDX)
23	Papadopoulos	Empirical / Experimental	Greece	Greece	City Museum - Historic	More about the building & visitors than collections	Greek Technical Guideline on IAQ ASHRAE	Environmental management interventions to convert a historic building to a museum	T, RH, CO, CO_2		√		Monitoring, simulation
24	Hu	Empirical	China	China	Site museums		ASHREA 2011	Assessment of indoor air quality	T, RH, gaseous pollutants, dust	√			Spot measurements, sampling & analysis
25	Ferdyn-Grygierek	Empirical Experimental	Poland	Poland	Historic building		UNI 10829	Temperature setpoints, heating & cooling demands	T, RH, CO_2	√	√	√	Measurements, simulation, validation & analysis
26	Mundo-Hernández	Evaluation	Mexico	Mexico	Converted historical building			Indicative post occupancy evaluation			√		Historical research, analysis of the conversion, survey & walkthrough
27	Godoi	Empirical	Brazil	Brazil	Oscar Niemeyer museum		The US National Bureau of Standards	Indoor air quality and levels of pollutants	SO_2, NO_2, O_3, acetic & formic acids, volatile organic pollutants, PM, T, RH	√			Sampling, measurements & analysis
28	Abdul-Wahab	Empirical	Sultanate of Oman	Sultanate of Oman	(House of Al Zubair museum - Historic	Maps, furniture, prints and photographs	Purafil, Inc. Technical Bulletin-600A	Assessment of indoor air quality	T, RH, PM, CO_2, SO_2, NO_2, O_3, volatile organic compounds	√			Sampling, analysis
29	Lamonaca	Empirical	Italy	Italy	National Gallery of Cosenza-Historic	Paintings	Italian Standard UNI10829	Approach for evaluating indoor pollution by airborne fungal spores	T, RH, air pollution (fungal spores)	√			Measurements, Sampling, Lab identification of microorganisms
30	Anaf	Empirical	Belgium	Belgium	MuZEE, MAS /Museum Aan de Stroom & Rubens House	Works of art		Surfaces blackening and deposition of inorganic aerosol components	Particulate matter (PM)	√			Sampling, analysis of blackening, optical reflection microscopy & Spectrophotometry
31	Anaf	Empirical	Belgium	Portugal	Portuguese National Tile Museum - Historic	Collection of tiles		Assessment of the effects of a constructional intervention on particles disposition	Air pollution (PM), T, RH, climate data	√			Active and passive sampling, loggers, chemical analysis, X-ray fluorescence spectrometry microscopy & image processing
32	Ferdyn-Grygierek	Empirical	Poland	Poland	Purpose-built city museum - Historic	Various Inc. flora/ fauna, ethnography exhibits & paintings	UNI 10829 For ventilation; ASHRAE 62.1; CEN CR 1752	Assessment of microclimatic conditions	T, RH, CO_2	√			Monitoring(sensors), analysis
33	Martinez-Molina	Empirical	Spain	Spain	Valencia History Museum		ASHRAE 55	Visitors' thermal comfort in a historic building	T, RH, air speed, climate data		√		Post occupancy evaluation measurements, questionnaire
34	Zorpas	Empirical	Cyprus	Cyprus	Archaeological museum & Byzantine museum		ASHRAE 2003, 2011	Indoor air quality evaluation	T, RH, PM, CO, CO_2, SO_2, NO_x, O_3, volatile organic pollutants	√			Sampling, measurements, analysis
35	Sciurpi	Empirical	Italy	Italy	La Specola museum -Historic	Zoological collections Inc. specimens, anatomical waxes	Italian UNI 10829, European UNI EN 15757	Environmental monitoring & solar gain control solutions	T, RH		√	√	Measurements (loggers), simulation & analysis

36	**Mishra**	**Empirical**	**Netherlands**	**Netherlands**	**Museum Hermitage Amsterdam**		**ASHRAE 55**	**Feld study on visitors' thermal comfort**	**Air T, RH, globe T, air velocity, climate data**		√	√	**Survey, measurements (loggers, BMS) & analysis**
37	Jeong	Empirical/ survey	Korea	South Korea	Various: History, Science & Art museums			Museums' physical environment & visitors' satisfaction	Perceived variables Inc. (thermal, noise & illumination)		√		Questionnaire, analysis
38	Worobiec	Empirical	Belgium	Cracow, Poland	Royal museum of Wawel Castle	Artworks and Flemish tapestries		Assessment of tourist flow on air quality & microclimate	T, RH, climatic data, air quality (TSP)	√			Particular matter sampling, monitoring (loggers), analysis (electron probe microanalysis & EDXRF spectrometer)
39	Schieweck	Empirical	Germany	Germany	Lower Saxony State Museum Hanover	Works of arts Inc: wooden sculptures, paintings, metals, fossils & ethnography	German guideline VDI 4300-8	Measurements of indoor pollutants in storage rooms	T, RH, organic and inorganic air pollutants	√		√	Measurements (loggers), active sampling, chemical analysis, dust sampling & analysis
40	Gysels	Empirical	Belgium	Belgium	KMSK, Royal museum of fine arts - Historic			Investigation of indoor particulate and gaseous pollution, microbiology & microclimate	T, RH, specific RH, pollutants SO2, NO2, climate data	√			Aerosol sampling /analysis, energy dispersive X-ray fluorescence spectrometry (EDXRF), pollutants sampling, measurements & microbiology
41	Corbellini	Empirical / application	Italy					Cloud-based system for environmental monitoring	T, RH				Sensors in showcases, wireless receiver routing data to the system
42	Marchetti	Empirical / method	Belgium	Belgium	Royal Military Museum part of the War Heritage Institute	Mixed Inc. paintings, textiles, leather, metal, stone, ceramics, weapons, instruments	ASHRAE Thomson	Indoor microclimate assessment including PM concentration monitoring	T, RH, Vis and UV light, CO2, PM	√			Monitoring (sensors), PM sampling (Harvard impactors), chemical analysis (XRF and IC) & IEQ-index calculation
43	Kramer	Empirical	Netherlands	Netherlands	Hermitage Amsterdam museum - Renovated		ASHRAE EN-ISO 7730	Comfort & operative temperature limits in a strictly conditioned environment	Air T, radiant T, RH, air speed		√	√	Survey, monitoring
44	Cartechini	Empirical	Italy	Italy	Galleria Nazionale dell'Umbria - Historic	Paintings		Black carbon and aerosol contamination events in museum environment	Air quality (PM), T, RH	√			Real-time sampling, filter sampling and off-line analyses (EM-EDX microanalysis & GCeMS)
45	Pencarelli	Survey	Italy	Italy	61 regional museums			Sustainability in museum management					Review, survey
46	Krupińska	Empirical	Belgium	Belgium	Plantin-Moretus Museum/print room	Various, Incl. manuscripts, book collections incunabula, old drawings, wooden objects, zinc plates & typographical materials		Assessment of air quality	Pollutant gases (NO2, SO2, O3), PM, black carbon	√			Sampling, monitoring (composition and mass concentration of PM) & laboratory analysis (EDXRF spectroscopy)
47	del Hoyo-Meléndez	Empirical	USA/Spain	USA	The Donald W. Reynolds Center for American Art and Portraiture	Artworks	Limits by IESNA, Canadian Conservation Institute (CCI), Commission Internationale del'Eclairage(CIE),Thomson	Light levels assessment and evaluation of distribution in exhibition areas	Visible light levels, UV radiation	√			Monitoring (meters & loggers), simulation & validation
48	Reddy	Empirical	India	India	Salarjung Museum	Artworks Inc. paintings ivory, glass, porcelains archival materials (books, manuscripts)	National Ambient Air Quality Standards (NAAQS), American National Standards Institute	Indoor air quality assessment	Suspended particulate matter (SPM), SO2, NOx, H2S, NH3, HCHO, O3, T, RH				Monitoring (indoor and outdoor air quality), sampling
49	Camuffo	Empirical	Italy	Italy, Austria, Belgium & UK	Correr Museum, Kunsthistorisches Museum, Royal Museum of Fine Arts, Sainsbury Centre for Visual Arts -3 Historic	Various Inc. artworks made of plants such as canvas		Assessment of variation in microclimate, gaseous and particulate air pollution & biological contamination	T, RH, SH (specific humidity), NO2, SO2, H2S	√			Monitoring, suspended particles, gaseous pollution & microbiological measurements
50	Camuffo	Empirical	Italy	Italy	The Uffizi Gallery, Florence	Paintings		Assessment of variation in microclimate	T, RH, SH	√			Monitoring
51	Strada	Empirical	Italy	Italy	tezone 105 of the Venetian Arsenale		Thomson	Analysis of microclimate	T, RH, ST (surface temperature)				Monitoring
52	Salmon	Empirical	USA	Poland	Wawel Castle, Matejko Museum, Collegium Maius, the Cloth Hall & the new National Museum	Various; Tapestries, tents, banners, carpets, paintings, furniture, jewels, equipment & university professors' belongings	ASHRAE	Analysis of ozone concentration and the effectiveness of the existing ozone removal system in one site	Ozone concentration	√			Measuring ozone concentrations in outdoor air & indoors
53	Yoon	Empirical	UK	UK	Sainsbury Centre for visual arts	Art collection		Analysis of dust (amount, size, source)					Analysis of dust, Sampling

54	**Muething**	**Empirical / Risk Assessment**	**Canada**	**Canada**	**Victoria Memorial Museum Building-Historic**	**Specimens (live plants, animals in aquariums & terrariums)**			**Light, UV radiations, T, RH**	√			**Risk assessment using the Cultural Property Risk Analysis Model (CPRAM), interviews**
55	Bratasz	Review	Poland			Painted wood	Various, UNI 10969, EN 15757, ASHRAE	Inc. techniques for modelling historic climate of acclimatisation	T, RH	√		√	Review
56	Huijbregts	Procedure	Netherlands	Netherlands Belgium	Historic buildings	Panel paintings, Wooden furniture	ASHRAE	Damage risk assessment of climate change	Climate change, T, RH	√			Predictive climate scenarios, indoor climate simulations, Measurements
57	Corgnati	Procedure	Italy	Italy	Historic building	Works of art	UNI 10829, EN 15251	Assessment of thermo-hygrometric quality	T, RH	√			Monitoring (sensors & loggers), analysis
58	Franzitta	Procedure	Italy	Italy	Regional Gallery of Sicily& the Diocesan Museum		Literature Inc. US dept. of Commerce, UNI 10586	Monitoring methods	Air pollution	√			Monitoring, sampling
59	Bacci	Review	Italy	Europe		Works of art		'Impact sensors' to monitor synergistic environmental effects, esp. optical fibre technology	Whole environment (cooperative effects)	√			Review of EC projects
60	La Gennusa	Procedure	Italy	Italy		Works of art (broadly interpreted)	Various (Inc UNI 11120, UNI 11131, UNI 10969, UNI 10829, Ministerial Decree, ANSI/ASHRAE)	Thermal indoor environment of museums	T, RH	√	√		Analysis of standards
61	Lucchi	Protocol	Italy	International			UNI 10969, UNI 10829 UNI 10586, CEN 16163, EN 15757	Multidisciplinary risk-based analysis to support micro-climate management		√	√	√	Review
62	D'agostino	Protocol	Italy	International			Italian Standards UNI 10829	Evaluation of microclimatic conditions, & quantification of factors responsible for degradation	T, RH, air quality, light	√	√		Review
63	Silva	Procedure	Portugal	Portugal	Historic building	Panel paintings Wooden furniture Sculptures	Targets specified by the museum. For comfort, ISO 7330, ASHRAE	Indoor microclimate classification & optimization	T, RH	√	√	√	Measurements, climate evaluation, risk-assessment & statistical optimization
64	Corgnati	Procedure	Italy	Italy		Temporary exhibit (paintings)	Italian Standard UNI10829, European EN 15251	Statistical methodology for microclimatic quality assessment	T, RH	√	√		Monitoring (loggers), analysis
65	Lucchi	Protocol	Italy	Europe (eight countries)	Various, Historic & Purpose-built	Various mainly artworks		Inspection method for microclimate & energy assessment	T, RH, light, UV, IR radiation, dust, air pollution, sound	√	√	√	Review, walkthrough energy audit & interviews
66	Schito	Procedure	Italy	Italy		Panel paintings	Italian Technical Standard UNI 10829	Multi-objective methodology for microclimate optimisation	T, RH, climatic data	√	√	√	Dynamic simulations (testing various setpoints), measurements, validation, & analysis
67	Litti	Procedure	Belgium	Belgium	Vleeshuis museum - Historic	Musical instruments	EN ISO 7726, UNI 10829 ISO 7730, EN 15251 EN 15757, EN 16242	Multi- objective indoor microclimate quality certification model	T, RH, Light, CO2, radiant/operative T, air velocity	√	√		Measurements (loggers), analysis
68	García-Diego	Procedure	Spain	Spain	Pio V Museum of Fine Arts of Valencia	Portraits	UNI 10829 EN 15757 ASHRAE 2011	Minimum sampling frequency in microclimate monitoring	T, RH (Room + microclimatic frame)	√			Different sampling intervals, measurements (sensors)& analysis
69	Bradley	Review	UK	London, UK	British museum	Various		Development of preventive conservation practice	Factors covered (T, RH & pollutant gases)	√			British Museum research
70	Weintraub	Review	New York					Knowledge and Implementation of environmental specs in museums	Light, T, RH, pollution	√	√		Review
71	La Gennusa	Procedure/ Experimental	Italy	Italy	Regional Gallery; Palazzo Abatellis of Palermo	Artworks Inc: Paintings & pottery	Italian standard UNI 10829, ISA-S71.04	Experimental campaign and an approach for indoor environmental control	T, RH, air quality	√			Monitoring (loggers, reactive coupons) & Tests
72	Litti	Procedure	Belgium	Belgium	The Vleeshuis museum in Antwerp	Musical instruments	National &European: CTI, UNI 10829, CEN, EN 15757, For thermography EN 13187	Integrated methodology for microclimate assessment of heritage buildings/ museums	Dry bulb T, Dew T, RH, light, CO2, air velocity	√	√	√	Monitoring, Infrared thermography, building documentation & analysis
73	Pisello	Procedure	Italy	Italy	Palazzo della Penna - Historic	Artworks	EN 15757, UNI 10829, UNI 10969, EN ISO 7730, EN 15251, (for light CEN/TS 16163) ASHRAE, Italian (D.M. 2001, UNI 10969)	Integrated microclimate analysis for artworks preservation and occupants' conditions optimization	T, RH, CO2, illuminance, surface T electricity consumption, climate data	√	√		Monitoring (weather station, sensors, data gathering gateway), analysis
74	Schito	Procedure	Italy	Italy	Palazzo Blu, a museum in Pisa	Artworks (drawings)	UNI 10829	Indexes for the evaluation of microclimate suitability	T, RH, light	√			Application of the procedure proposed, monitoring (sensors)
75	Angelini	Procedure/ Empirical	Italy	Italy	Stibbert Museum in Florence - Historic	Metallic artefacts (iron & copper) in historic showcases		Indoor microclimate & atmosphere aggressivity in museum environments	T, RH	√			Monitoring and sampling (sensors & copper reference samples), imaging, colorimetric & FESEM techniques
76	Atkinson	Review	UK	International		Various Inc. ASHRAE, EN 15757, PAS 198		Background to the current debate on the strict microclimate control		√			Review

77	**Raphael**	**Review / Procedure**	**USA**	**USA**				**Museum exhibitions; development of guidelines and standards for conservation**	**T, RH, light, pollutants, dust**	√			**Review of guidelines and standards developed by the National Park Service**
78	Austin	Review	USA	USA		Anthropology collection		Overview of collections care history at the National Museum of Natural History	T, RH, light, dust	√			Review & analysis of archival records
79	Allegretti	Experimental	Italy	Italy		Wooden art objects	ASHRAE	Hygromechanical monitoring for evaluating objects behaviour	T, RH	√			Simulation, analysis
80	Lankester	Experimental	UK	UK	Historic interiors			Assessment of future climate	T, RH, climate change	√			Simulation, high resolution climate prediction
81	Bøhm	Experimental	Denmark	Denmark	Unheated museum store			Thermal properties of the building envelope on indoor temperature	T				Simulation (Finite element model), validation
82	Al-Sallal	Experimental / Empirical	UAE	UAE	Traditional building		IESNA, CIBSE Code for Lighting	Daylighting performance and control recommendations	Illuminance, luminance	√		√	Simulation, measurements
83	Lee	Examination of data	South Korea	South Korea			KMOE, KMOPAS (Korean government dept.)	Identification of hazardous environmental factors	T, RH, air pollution	√			Review, meta-analysis
84	Peralta	Experimental	Portugal	Portugal	Art museum			Wireless networks (WISE-MUSE project)	T, RH	√			Deployment of the monitoring system
85	Ascione	Experimental	Italy	Italy	Notional exhibition room		ASHRAE	HVAC system design - air diffusion equipment(s) performance	T, RH, air speed			√	Modelling (Energy simulation & CFD airflow program)
86	Van Schijndel	Experimental	Netherlands	Netherlands	Dutch Naval Depot – High tech		ASHRAE	HVAC system design - assessment of performance in case of failures	T, RH predicted				Modelling, validation
87	Ascione	Experimental	Italy	Italy		Works of art	ASHRAE	HVAC system design	T, RH			√	Simulation, operating costs & payback calculations
88	Kramer	Experimental	Netherlands	Netherlands	Museum Hermitage Amsterdam (renovated)	Mixed (weapons, uniforms, wooden &marble sculptures, furniture, letters & paintings)	ASHRAE	Assessment of ASHRAE's climate classes on energy use and microclimate fluctuations	T, RH, BMS data	√	√	√	Measurements of the Air Handling Unit system Energy use calculations, full-scale testing & analysis
89	Kramer	Experimental	Netherlands	Netherlands	Museum Hermitage Amsterdam	Books, panel paintings, furniture, wooden sculptures		Assessment of energy saving potential & setpoint strategies	T, RH, CO2	√	√	√	Measurements, energy consumption simulation, validation & analysis
90	Kramer	Experimental	Netherlands	Europe (twenty locations)	Models representing historical & purpose-built		ASHRAE	Algorithm for dynamic T and RH setpoint calculations & assessment of energy use of climate classes	T, RH	√	√	√	Environmental and energy simulation, validation & analysis
91	Proietti	Experimental / method	Italy	International				Dust detection based on pattern recognition by machine learning	Air pollution (dust)	√			Image capturing/pre-processing, analysis by machine learning algorithm
92	Romano	Experimental	Italy	International				Simulation tool for showcase design optimization, operation & performance assessment	Showcase T, RH	√	.		Simulation, validation, re-configurable showcase & climatic test chamber
93	Pisello	Experimental	Italy	Italy	Historic building	Bronze statue	Italian D.M. UNI 10829	Multi-objective methodology for microclimate & energy efficiency optimisation	T, RH	√	√	√	Measurements (loggers), simulation, validation, & analysis
94	Bellia	Experimental	Italy	Italy	Notional modern museum	Artworks		HVAC systems design- operating costs and thermal-hygrometric performance	T, RH (predicated)	√		√	Dynamic simulation modelling
95	Schijndel	Experimental	Netherlands	Netherlands	Famous museum in the Netherlands	Wallpaper fragments	LCM Foundation	Performance based design of a HVAC system & control strategy	T, RH	√			Review, measurements, heat air and moisture (HAM) modelling, validation & simulation
96	Papadopoulos	Experimental	Greece	Greece	Museum of Byzantine history - Converted medieval tower		Requirements set by the 10th Ephorate of Byzantine Antiquities – ASHRAE, Greek regulation	Energy behaviour study and HVAC system design				√	K-value measurements, analysis & alternative options
97	Klein	Experimental / Empirical	USA	USA	The Cloisters, New York Metropolitan Museum of Art	Metal objects		Wireless sensing platform for cultural heritage monitoring	T, RH, air quality	√			Monitoring, wireless sensors, Interpolation &CFD simulation
98	Luo	Experimental	China	China	Experimental facility with funerary pit	In situ/unearthed artefacts	Thomson	HVAC systems design Environmental control systems for artefacts preservation in archaeology museums	T, RH, air velocity& T of the supply/return water for the radiant system	√	√	√	Laboratory building simulating exhibition hall, environmental control testing & monitoring
99	Ferdyn-Grygierek	Experimental	Poland	Poland	Historic building	Mixed Inc. Flora, Fauna & Ethnography exhibition	ASHRAE	Impact of ventilation systems on energy consumption	Air flow (simulated), T			√	Simulations (computer programs CONTAM and ESP-r), validation & calibration
100	Ge	Experimental	China	China				Life cycle energy assessment of museums				√	Energy consumption per unit area and CO² emissions calculations, simulation (PKPM)

101	**Agbota**	**Experimental**	**UK**	**UK, Benin**	**Apsley House in London & Royal Palaces of Abomey in Benin - Historic**	**Paintings, porcelain plates, vases, silver-gilt pieces. thrones, weapons, jewels, textiles & bas-reliefs**		**Dosimetric remote sensing system based on piezoelectric quartz crystal technology for environmental monitoring**	**T, RH, pollution (O3, NO2 and SD2)**	√			**System development and deployment, monitoring & Laboratory validation**
102	Arafat	Experimental /Empirical	Jordan	Jordan	Objects from Umm Qais museum	Metallic (Islamic copper alloyed artefacts)		Preservation state of metallic artefacts from an archaeological site/ museum		√			In situ analyses (portable Micro X-Ray Fluorescence (-XRF) and Laser-Induced Breakdown Spectroscopy (LIBS) spectrometers), Scanning Electron Microscopy - Energy Dispersive X-Ray (SEM-EDS analysis &monitoring
103	Peralta	Experimental	Portugal	Portugal	Museum Fortaleza São Tiago-Historic			Wireless sensor nodes (WSN) as an environmental monitoring application in museums	T, RH, light				Deployment of the Wireless Sensor Network
104	Garside	Practice – focused research	UK	UK	Various, Majority national museums		CIE Technical Collection, CIE 157 (on damage by radiation), IES 2015 (on colour rendering)	Current practice of selecting lighting in UK museums	Lighting	√	√		Interviews with museum professionals
105	Živković	Practice – focused	Serbia	Serbia	Historic buildings		ASHRAE PAS 198	Environmental management practice based on the state of conservation	T, RH, light, UV, pollution	√		√	Surveys of buildings & collections, interviews & measurements
106	Feng	Practice – focused	China	China			State Administration of Cultural Heritage “rec.” For light, GB/T 23863 For IAQ, GB/T 18883	Overview of Preventive conservation and microclimate control	T, RH, light, pollution	√			Review
107	Nunberg	Practice – focused	USA	USA	Museum Fine Arts, Boston			Life cycle assessments of loans and exhibitions				√	LCA software Platform & EPA's Tool for Impact assessment

2.2 Literature Review Findings

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). Only a summary of the key findings identified under these five sub-headings '*In situ monitoring campaigns; Simulation modelling, climate and energy projections; Compliance with standards and reference to guidelines; Geographical focus; and Contextualising the guidelines' is given in this section. However,* for a detailed explanation and exploration of the findings of each section, the reader can refer to the journal paper included in the appendix of this report entitled '*The regulations and reality of indoor environmental standards for objects and visitors in museums*' published in December 2021 as one of MOVE's key outcomes, *Renewable and sustainable energy reviews* (Journal).

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, are found to be 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 elaborated in the paper (i.e. section 4.1), there is an obvious division between the focus of the monitoring campaigns /research programme and 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, 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.

The review also 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, refer to section 4.5 in the paper]. 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.

2.3 Data acquisition & Digital platform

Information and illustrations on sensor installation, data processing procedures and data protocol for sensors installed at Salford Museum are published on the Researchfish platform. Summary of the methods utilized for analysing the environmental data collected over the last two years are given below. The link to the digital platform which is currently under development will be made live in due course.

3. Process and Analysis of Data

Artefact metrics are based on Silva & Henriques (2015) and Silva et al (2016) which are largely derived from the work of Martens (2012) with some updated source material for underlying data. Martens provides a summary of the data sources for modelling of the differing artefacts he considers which is reproduced in Figure LL. These methods are described in greater detail below including any consideration of newer data or changes to methodology.

	Biological degradation: Mould Growth	Chemical degradation: Lifetime Multiplier	Mechanical degradation: Base material	Mechanical degradation: Pictorial layer
Book	Sedlbauer's method	Lifetime Multiplier: E_A = 100kJ/mol		
Panel painting	Sedlbauer's method	Lifetime Multiplier: E_A = 70kJ/mol	Yield point: Mecklenburg	Gesso on wood: Bratasz
Furniture	Sedlbauer's method	Lifetime Multiplier: E_A = 70kJ/mol	Wood & lacquer: Bratasz	
Wooden sculpture	Sedlbauer's method	Lifetime Multiplier: E_A = 70kJ/mol	Yield point: Jakiela	

Figure LL: Artefacts and degradation mechanisms considered in Martens (2012)

"Surface" and "full" response

A number of deterioration processes are defined by differences in temperature and/or humidity across the cross-section of an artefact. As moisture or heat take time to penetrate into an object, there will be differential expansion and contraction within it. To calculate the surface and full response, Martens (2012) developed a simplification of a first order function when the time-step is small compared to the response time of the form:

$$RH_{response,i} = \frac{RH_{response,i-1} + \frac{RH_i}{n/3}}{1 + \frac{1}{n/3}} \qquad (1)$$

Where $RH_{response,i}$ is the relative humidity experienced by the artefact at the timestep, $RH_{response,i-1}$ is the relative humidity experienced by the artefact at the previous time-step, RH_i is the relative humidity of the air at the time-step i (the data logger reading), and n is the number of time-steps in the response time for the artefact (i.e. the number of logged readings in the response time). Martens also tabulates a number of response times based on the half responses from the ASHRAE handbook (ASHRAE, 2015) and other sources. The time-step for the Salford Museum loggers is 15 minutes, so a number in the response time is easily calculated.

Table XX: Response times calculated by Martens (2012)

Object	Relevant response	Response time	Reference (used by Martens)	Time steps in response time
Paper	Full response of single sheet	"Minutes"	(S. W. Michalski, 1993)	<1
Panel painting	Surface response just under oil paint	4.3 days	(ASHRAE, 2015)	413
	Full response of entire panel	26 days	(ASHRAE, 2015)	2,496
Lacquer box	Full response of entire lacquer box	40 days	(Bratasz et al., 2008)	3,840
Wooden sculpture	Surface response	10 hours	(ASHRAE, 2015)	40
	Sub-surface response causing maximum stresses	15 days	(Vici et al., 2006)	1,440

Note: Martens used a 2011 edition of ASHRAE, but the relevant data is unchanged in the 2015 edition

Mould growth and RH

Silva & Henriques (2015)and Martens (2012)use the Isohyet method of Sedlbauer (2001)which is widely cited in various places in the literature including the Standards (BSI, 2012, 2017; CEN, 2018; ISO, 2018) and further written-up (though with less detail) in Sedlbauer (2002). The suggested equation for the "envelope curve" of $RH = a\cosh\left(T - T_{opt}\right) + b$ (where *RH* is relative humidity, *T* is the temperature , T_{opt} is the optimal temperature for fungoid growth, while *a* & *b* are constants) doesn't fit the curves terribly well, but a good fit has been found using a quadratic corresponding to $RH = 0.03T^2 - 1.78T + 98$, which is somewhat in-keeping with the other Isohyet models described in Vereecken & Roels (2012) e.g. $RH = 0.033T^2 - 1.5T + 96$ for *Aspergillus versicolor* (Hens, 1999).

Chemical degradation

Silva & Henriques (2015) and Martens (2012) use the Lifetime Multiplier (LM) developed using the Arrhenius equation by Michalski (2002) which comperes the potential for chemical degradation to a "standard" environment of 20 °C & 50% RH. Martens developed the following formula from Michalski's work:

$$LM_x = \left(\frac{50\%}{RH_x}\right)^{1.3} e^{\frac{E_A}{R}\left(\frac{1}{T_x} - \frac{1}{293}\right)} \qquad (2)$$

Where LM_x is the lifetime multiplier for the time-step, RH_x is the relative humidity experienced by the object at the time-step (%), E_A is the activation energy (J/mol), *R* is the gas constant (8.314 J/mol K), T_x is the temperature at the time-step (K), while the constant of 293 is 20 °C in K. The method used by both incorporates a running mean of the last 30 days for RH and 24 hours for temperature as specified in the methodology for calculating Time-Weighted Preservation Index (TWPI) (Nishimura, 2011; Reilly et al., 1995). LM has been graphed as a time series for 2 values of E_A, 70,000 J/mol which is used for varnish yellowing and 100,000 J/mol which is appropriate for the degradation of cellulose materials such as paper.

As chemical degradation is cumulative, the overall LM experienced by an artefact is a useful measure. It can be achieved finding the reciprocal of the mean of the reciprocal of each value of LM which is in keeping with the calculation of the Image Permanence Institute's TWPI (Reilly et al., 1995).

Mechanical damage due to changes in humidity

Silva & Henriques (2015), in common with Martens (2012) used the method developed by Mecklenburg et al (1998) which was developed for constrained materials (i.e. materials where the wood is held fast in a frame of some kind). This was taken further with consideration of the moisture gradient between surface and deeper parts of the material acting against each other by Martens.

In this case, the same graph was used, but the axes changed to "surface response" and "full response" and the regions changed from "plastic behavior" to "damage possible" and "failure" to "damage likely" based on the assumption that elastic behavior. Interestingly, Silva & Henriques, while using the surface and full response concept keep graph labelling used by Mecklenburg et al. Regions are based on experimental data and have been reproduced point-by-point.

For sculptures, Silva & Henriques (2015) used a chart of a similar form to that of Mecklenburg et al (1998) developed by Martens (2012) based on simulations of a 130 mm limewood cylinder by Jakieła et al (2008). The chart is based on a step-change, though a less-stringent set of rules has also been incorporated into the original research based on a gradual change over 24-hours which is likely more realistic. Both regions have been incorporated.

It should be noted that, while Martens and subsequently Silva & Henriques and Silva et al have considered the mechanical damage graphs as representations of different *artefact* types, the underlying research actually refers to *material* types rather than forms. Bratasz (2013) even goes so far as to superimpose the graphs of Japanese cypress, lime wood & cottonwood (which underly the graphs for painted wood, sculpture and furniture in Martens' work) on common axes. A better (though possibly conservative) approach is, therefore, to consider the 3 woods as defining a "safe" region as shown in Figure MM. Form may be accounted for by considering different response times of larger and smaller objects in determining the value of the "final level of RH" using Equation 1.

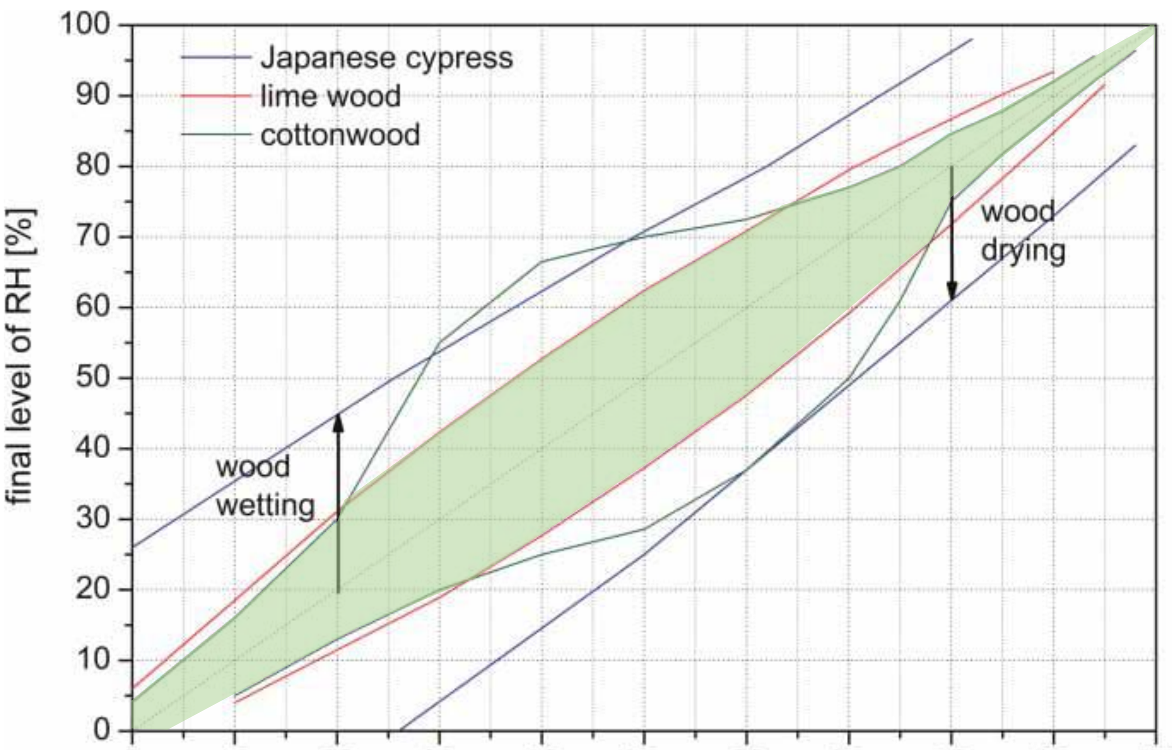


Figure MM: Japanese cypress, lime wood & cottonwood mechanical damage graphs on common axes (Bratasz, 2013) with proposed "safe" region in green.

4. Findings & Results

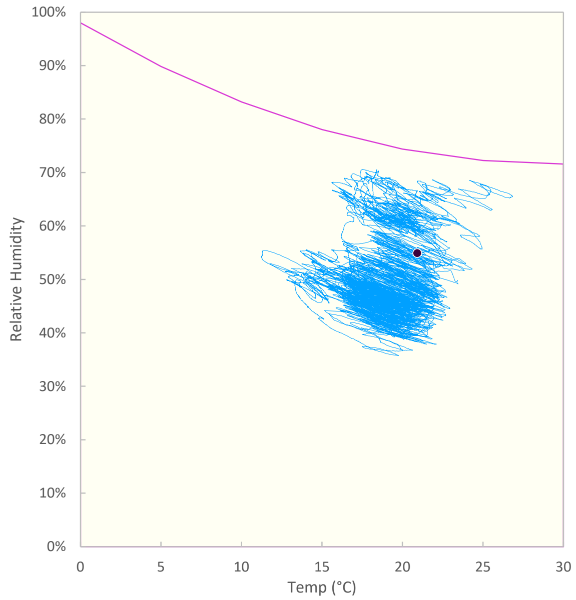


Figure XXa: Trace of relative humidity and air temperature from the Victoria Gallery. Area above the red line has potential for mould growth

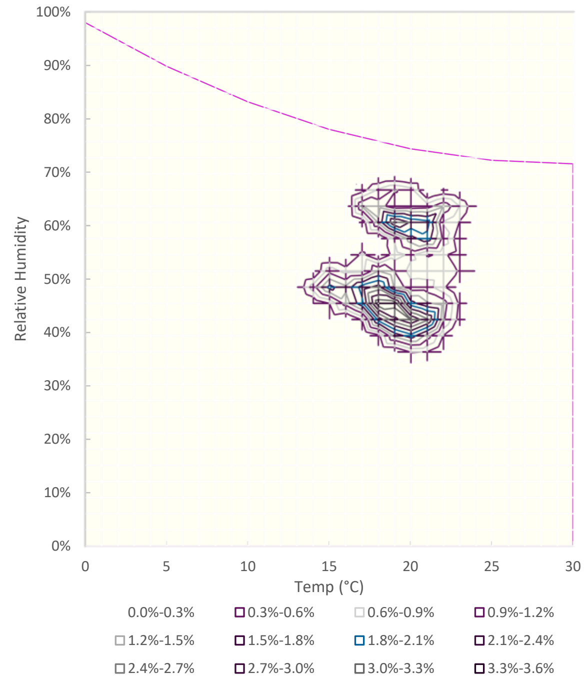


Figure XXb: Frequency contours of relative humidity and air temperature from the Victoria Gallery

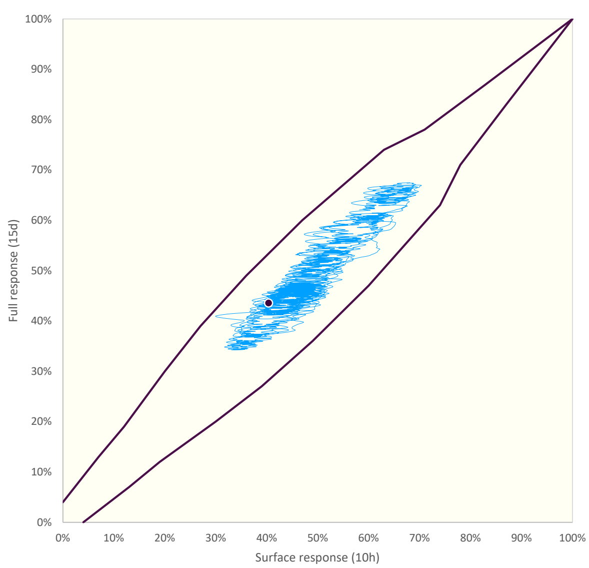


Figure YYa: Trace of exponential moving average relative humidity from the Victoria Gallery at 10 hours and at 15 days, representing humidity at the surface penetration into small sculptures. The area inside the lozenge-shaped region is safe from mechanical damage

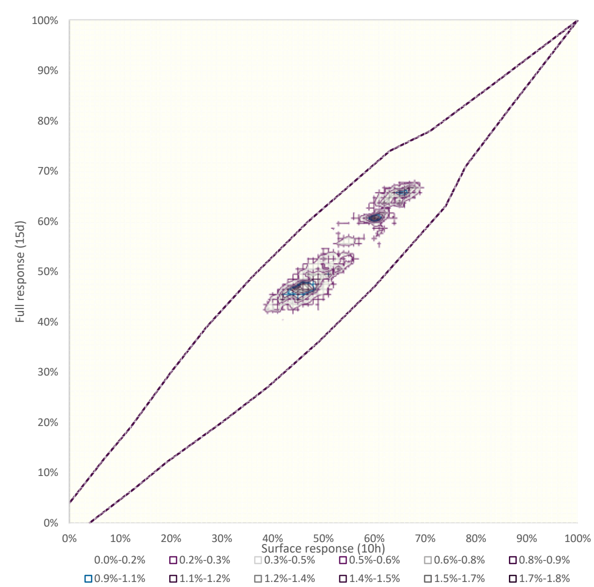


Figure YYb: Frequency contours of exponential moving average relative humidity from the Victoria Gallery at 10 hours and at 15 days,

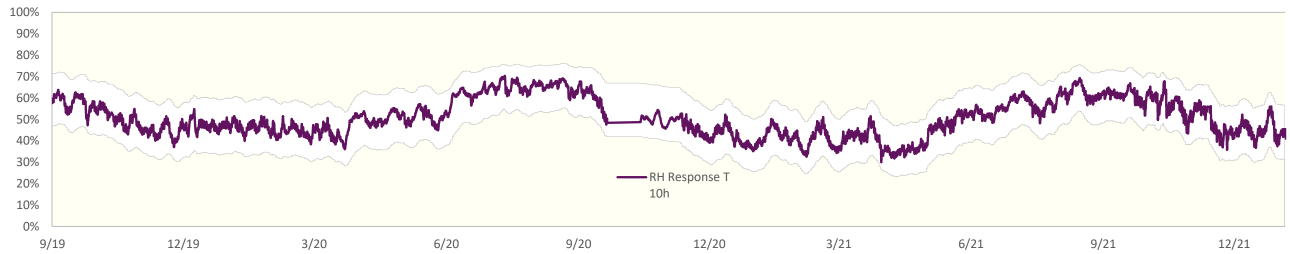


Figure YYc: The data from FigYYa presented as a time series. The line represents the surface while the central region represents the safe zone where mechanical damage is unlikely.

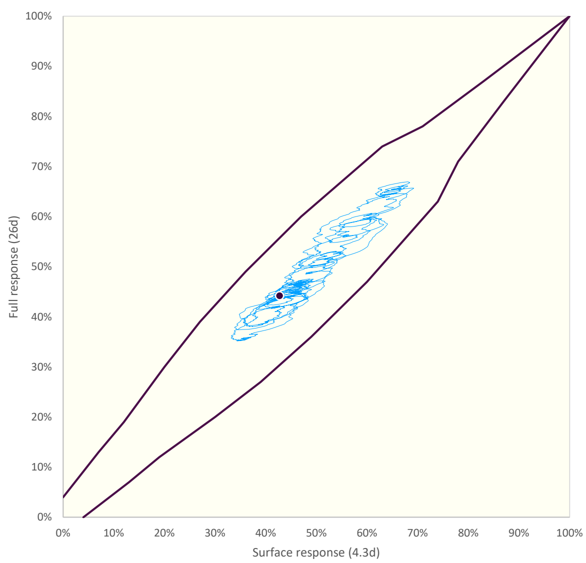


Figure ZZa: Trace of exponential moving average relative humidity from the Victoria Gallery at 4.3 days and at 26 days, representing humidity at the surface penetration into panel paintings. The area inside the lozenge-shaped region is safe from mechanical damage

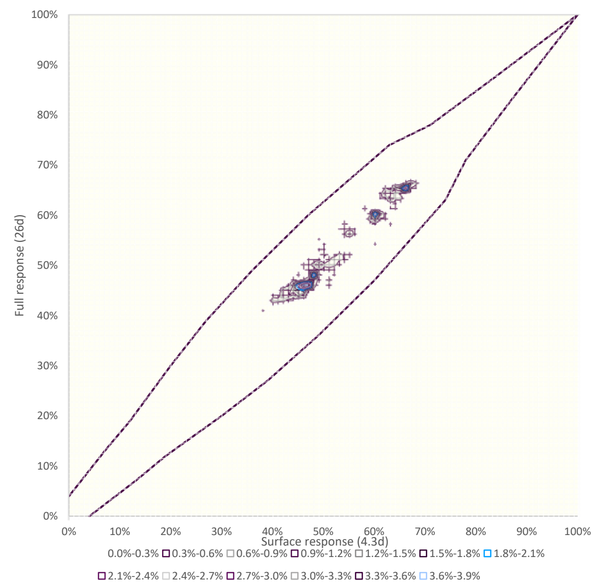


Figure ZZb: Frequency contours of exponential moving average relative humidity from the Victoria Gallery at 4.3 days and at 26 days,

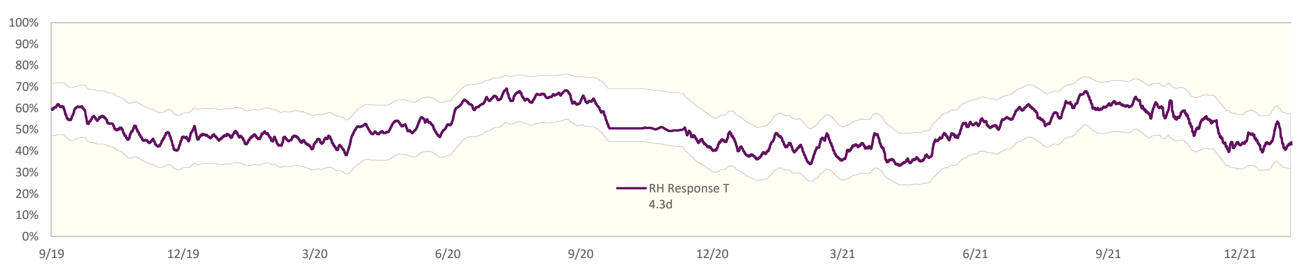


Figure ZZc: The data from FigZZa presented as a time series. The line represents the surface while the central region represents the safe zone where mechanical damage is unlikely.

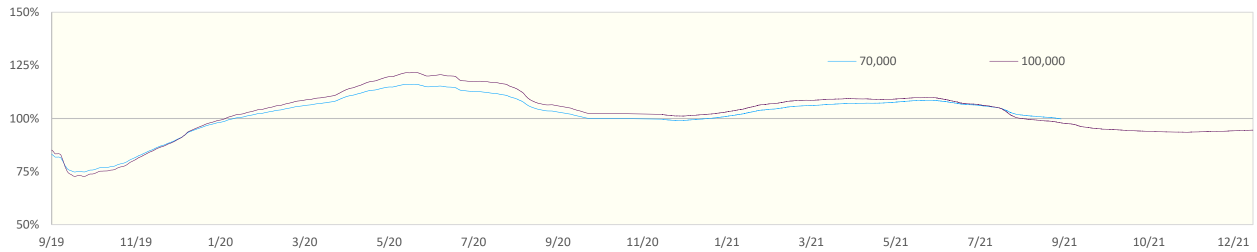


Figure AA: Cumulative lifetime multiplier for artefacts in the Victoria gallery.

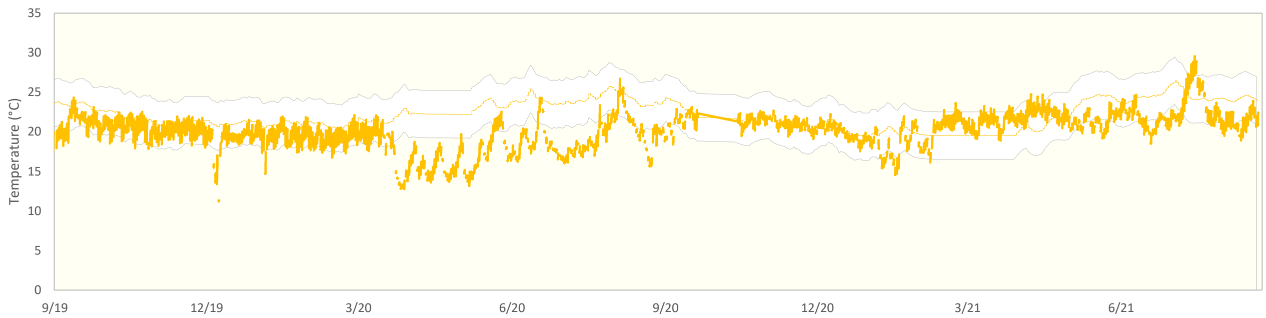


Figure BB: Air temperature in the Victoria Gallery with the region of adaptive comfort derived from a Type II building in EN BS 15251.

The analysis of the environmental data and the performance of the museum against benchmarks and regulations including the shift in performance due to the disruption caused by the pandemic are currently being used in drafting the second major journal publication of the project.

Completed publications and information of the main dissemination event of the project (MOVE international conference) are included in the appendices.

Appendices

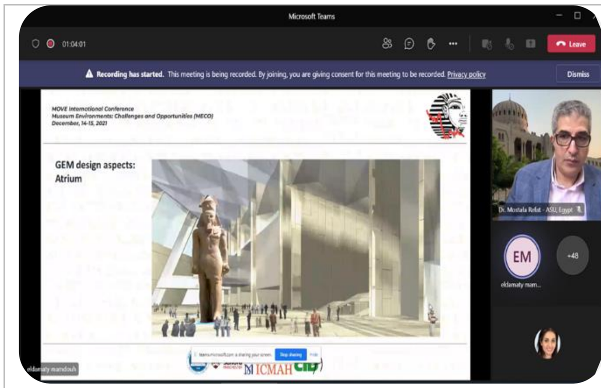
- **Conference**
- **Published Papers**

An International Conference on Museum Environments: Challenges and Opportunities

14-15 December 2021

Cairo-Egypt

The final international conference, which was MOVE's end event, and the apex of the dissemination plan of the project, was materialised through the collaborative efforts between the Egyptian and UK consortium. Hosted by Ain Shams University in Egypt, while planned in collaboration with the UK team, this two-day virtual conference on **Museum Environments: Challenges and Opportunities** brought together a diverse audience of stakeholders in academia, research, museums, and cultural organisations. The decision taken by the host institution and the conference scientific committee on conducting the conference as a virtual hybrid event was a result of the uncertainty and the travel restrictions caused by the global health crisis. Over 100 participants attended the conference which was split into four sessions over two days offering a platform for over15 international contributions and six keynote speeches sharing their knowledge, research, and experience in the field of museology and management of museum environments. Planning the event over two days and the interactive nature of the TEAMS online platform allowed added opportunities for global networks and exchange of knowledge alongside the conference proceedings/ papers presented by the participants. The conference programme (see below) was successfully concluded with a technical workshop elaborating by the leading institution (UoS) on the environmental monitoring campaign, the data recording procedures adopted by the team for the partner museum (SMAG, and a keynote speech by the operational manager of the museum. Conference invitation, conference programme, and other related information are given below.


Microsoft Teams
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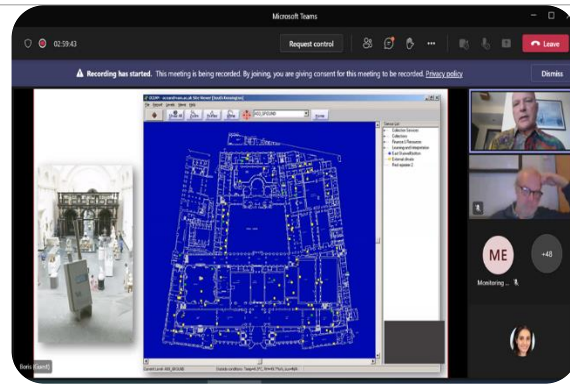
GEM design aspects:
Atrium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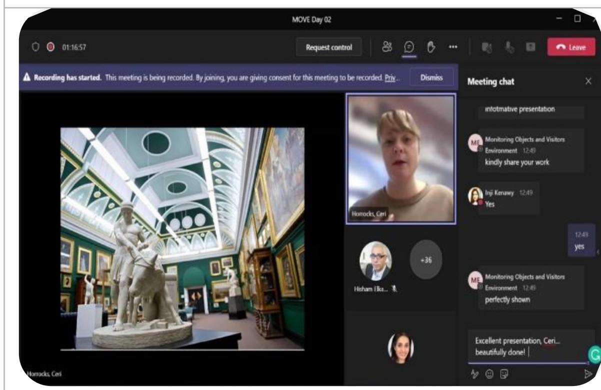
MOVE Day 02
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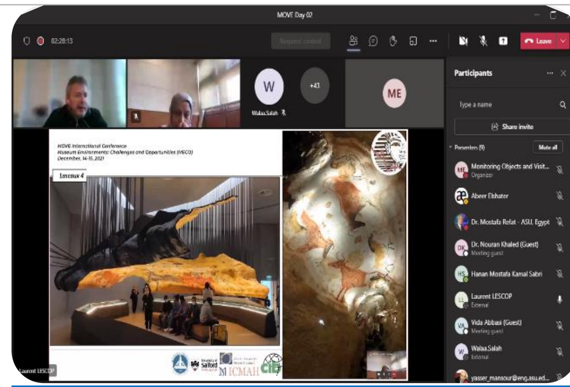
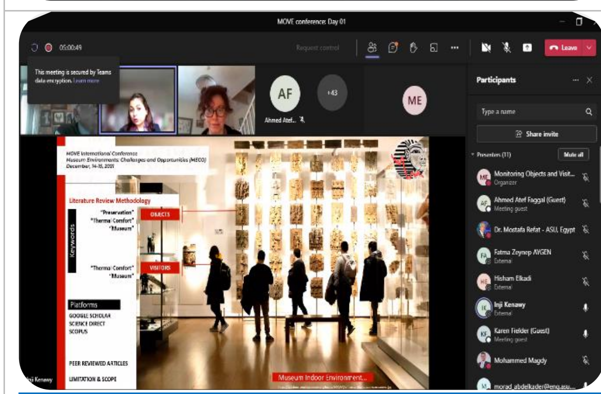
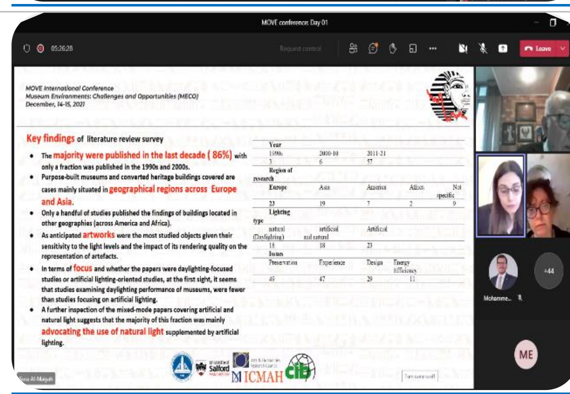
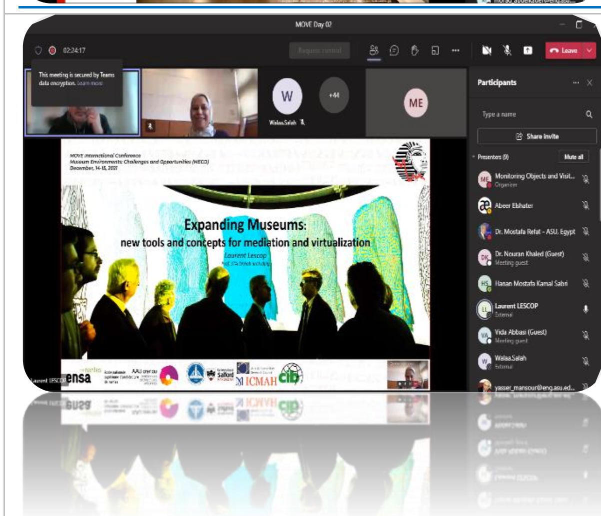
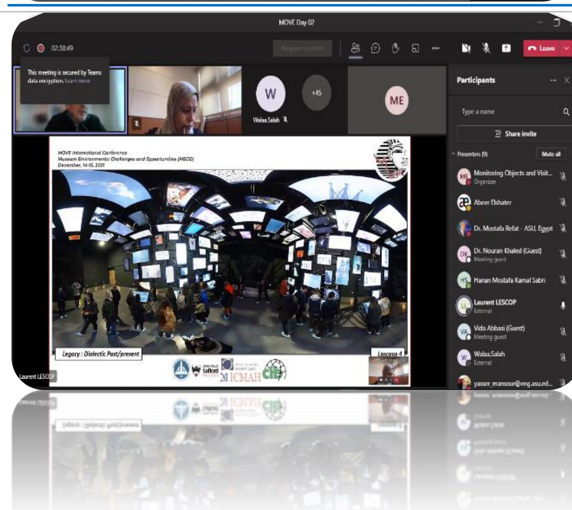
Meeting chat
Excellent presentation, Ceri... beautifully done!

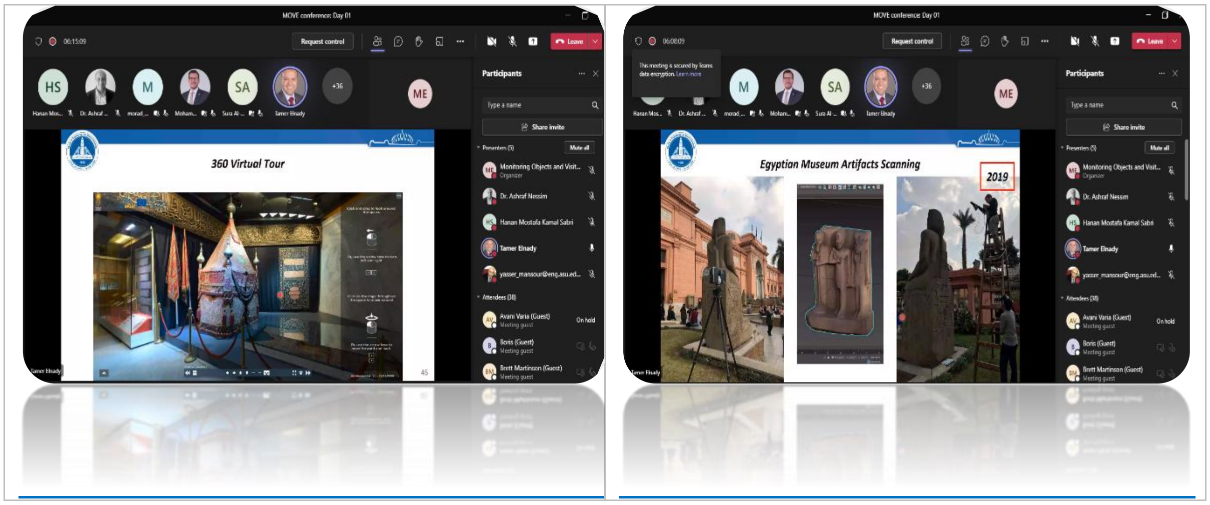

MOVE Day 02
Participants


MOVE conference: Day 01
Participants
Literature Review Methodology
Museum Indoor Environment


MOVE conference: Day 01
Key findings of literature review survey


MOVE Day 02
Participants
Expanding Museums:
new tools and concepts for mediation and virtualization


MOVE Day 02
Participants
Legacy : Dialectic Past/present



Screenshots of MOVE end event _14-15th December 2021

Conference Invitation

Museums are repositories for our cultural heritage and are responsible for the care of precious collections for the benefit of present and future generations. The key to this stewardship role is the management of indoor conditions to prevent deterioration of valuable objects. Preventive control measures are required to keep the indoor climate within conservation limits by maintaining environmental conditions within certain parameters and by minimizing 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. Conflicting environmental requirements often require a degree of comprise and managing these environmental demands will be become ever more challenging for museums as the impact of climate change leads to more frequent extreme weather conditions. The safe preservation of cultural heritage is an essential mission of museums around the globe regardless of geographical boundaries or borders. However, the variation in the levels of resources, funding mechanisms, and management protocols often results in great variability in the environmental management practice and procedures adopted by the different institutions where valuable lessons learned can be shared and used. The 1st international conference on ***Museum Environments: Challenges and Opportunities*** *will provide a platform for museum curators, academics, conservation architects and heritage collection managers to present and share the latest research results, knowledge and experience in the field of museums' microclimate management and operation. The conference aims at presenting and sharing best practices in museology and mobile heritage conservation including the challenges associated with meeting conflicting environmental requirements, demanding international standards and the use of technology in assessing museum performance, digital twinning, and monitoring indoor conditions.*

As the prime location of one of the world's oldest civilizations and the home to some of the most priceless heritage wonders, Cairo has been an attractive node for hosting prestigious international forums enabling the interactive exchange of state-of-the-art knowledge on the management and conservation of cultural heritage. The conference will be organized by the Faculty of Engineering, Ain Shams University, Egypt and the Smart Urban Futures research group at the University of Salford in the United Kingdom together with other collaborating higher education and heritage institutions from Egypt and the United Kingdom.

Scholars and practitioners are invited to share their knowledge, ideas, experiences, projects as well as to expand their professional networks and explore opportunities for future research collaboration with *heritage organizations and academic institutions around the world. The conference is committed to showcasing, sharing and disseminating the latest research findings in the field.*

***Organizers**:*

The Conference is jointly organized by:

- *Faculty of Engineering, Ain Shams University, Cairo*
- *Smart Urban Futures Research Group (SURF) at the University of Salford, Greater Manchester*

***Location**:*

The conference is planned to be a Hybrid Event at the Faculty of Engineering, Ain Shams University, Cairo. It is a socially distanced full-scale conference but due to the current restrictions on travel and the ongoing uncertainty caused by the COVID -19 pandemic, the organizing committee will be also offering online participation to the event with a virtual video presentation option and electronic conference proceedings.

Proceedings:

The conference proceedings are planned to be published on ICOM-ICMAH's publication webpage

http://icmah.mini.icom.museum/

Language:

The official language of the Conference is English.

[Call of Abstracts]

Conference Themes

The organizing committee of the conference invites abstract submissions for full papers and online virtual participation under each of the four following themes:

The architecture of museums

- *Architecture of museums*
- *Museums and cultural heritage*
- *Ergonomics of museums' indoor environment*
- *Museums in digital World*

Environmental control for objects and visitors

- *(Day) Lighting design for museums*
- *Energy savings and HVAC systems*
- *Monitoring for environmental control*
- *Restoration and maintenance of exhibits*

The social role of museums

- *Museums for sustainable and local development*
- *Museums for urban regeneration*

The art of display and innovative solutions

- *Virtual and mixed reality in museum exhibitions*
- *Interactive displays*

Chapter 2 *Scientific Committee*

Professors, in Alphabetic Order

- *Abdel kader, Morad-Ain Shams university-Egypt*
- *Atef, Ahmed-Ain Shams University-Egypt*
- *Aygen, Zeynep-Maymar University-Turkey*
- *Azzab, N.-Uni of the Bahamas-The Bahamas*
- *De La Rosa, Lea-Univ Santo Thomas-The Philippines*
- *Elshater, Abeer-Ain Shams University-Egypt*
- *Farouk, Ghada-Ain Shams university-Egypt*
- *Hastak, Makarand-EPCOM -Purdue University-USA*
- *Horrocks, Ceri-Salford Museum & Art Gallery-United Kingdom*
- *Kamel, Shaimaa-Ain Shams university-Egypt*
- *Khouri, Samia-Former Director of Jordan Museums- Jordan*
- *Kulatunga, Udaya-Univ of Morotawa-Sri Lanka*
- *Leao, Simone-Uni New South Wales-Australia*
- *Lombardi, Patrizia-Univ of Torino-Italy*
- *London, Kerry-Torrents University-Australia*
- *Missingham, Gregory-Melbourne University-Australia*
- *Ng, Veronica-Taylor University-Malaysia*
- *Nguyen, Thao-Hanoi Univ of G&M-Vietnam*
- *Pretzel, Boris-Victoria and Albert Museum-United Kingdom*
- *Sabry, Hanan-Ain Shams university-Egypt*
- *Saridar, Sawsan -Lebanese University-Lebanon*
- *Shafik, Zeinab-Cairo university-Egypt*
- *Weddikara, Chitra-BCAT-Sri Lanka*

Chapter 3

Chapter 4 Organizing Committee

Conference Chair

Prof. Dr. Omar El Husseiny *Dean of Faculty of Engineering, Ain Shams University*

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- *Professor Hanan Sabry* *hanan_sabry@eng.asu.edu.eg*
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University of Portsmouth, UK

- *Dr Brett Martinson* *brett.martinson@port.ac.uk*
- *Dr Karen Fielder* *karen.fielder@port.ac.uk*

Day 1

Tuesday 14 December 2021

Day 1

Opening Session: Chairman Speech

Professor Dr. Omar Elhusseiny **Dean of Faculty of Engineering – Ain Shams University**	09:45 – 9:50 am

Keynote Speaker - Session_01

Session Moderator **Professor Dr. Mostafa Refat**

- **Keynote Speech**

Professor Dr. Mamdouh Mohamed Eldamaty **Title: *"The Grand Egyptian Museum and the Future of the Cairo Museum Collection"***	10:00 – 10:45 am

Break 10:45 – 11:00 am

The Social Role of Museums and The Art of Displays – Session 02

Session Moderators **Professor Dr. Ghada Farouk and Associate Prof. Dr. Ashraf Nessim**

- **Papers Presentations**

Paper 19.	**Regina Faden**, "*Building a Sustainable Tourism Infrastructure In a Geographic Cul-de-Sac*".	11:00 – 12:00 pm
Paper 28.	**Mark Watson, Avani Varia and Sanmitra Chitte**, "*Experience economy and Museum Development in India*".	
Paper 14.	**Ibrahim Mohamed Ali**, "*Innovative display and storage methods for glass negative collections*".	
Paper 12.	**David Thickett, Paul Lankester, Melissa King and Antanas Melinis**, "*Simple, Accessible Modelling for Showcase Performance*".	
Paper 13	**Dalia Hafiz**, "*Successful Museums: A comparative analysis framework to Enhance the Museum's Visitors' Experience*".	

Break 12:00 – 12:30 pm

Keynote Speaker - Session 03

Session Moderator **Dr Brett Martinson**

- **Keynote Speech**

12:30 – 1:15 pm

Title: ***"From Theory to Impact: A Brief History of Measuring, Monitoring, and Interpreting Museum Environments and Their Impacts on Collections."***

Break 1:15 –1:30 pm

Environmental Control for Objects and Visitors – Session 04

Session Moderators	**Professor Dr. Morad Abd El Kader and Professor Dr. Ahmed Atef**	
• **Papers Presentations**		1:30 – 2:30 pm
Paper 03.	**Hisham Elkadi**, "*Museums' D-Light*".	
Paper 06.	**Zeynep Aygen**, "*Visitor Comfort versus Conservation Principles: Converting Historic Buildings to Museums: Case Study Turkey*".	
Paper 18	**Inji Kenawy and Karen Fielder**, "*Objects' preservation and visitors' thermal comfort within museums*".	
Paper 21	**Mohamed El Adl,** "*Indoor Air pollutants in Museums: Identification and Impact on Artefacts*".	
Paper 25	**Sura Al-Maiyah and Karen Fielder,** "*The Complexity of Daylighting Design Practice in Museum Environments*"	

Break 2:30 –3:00 pm

Virtual Museums – Session 05

Session Moderator	**Professor Dr. Hanan Sabry**	
• **Keynote Speech**	**Professor Dr. Tamer Elnady** **Title***: "Online Virtual Museums: Capture and Display"*	3:00 – 3:45 pm
• **Discussion**		3:45 – 4:00 pm

End of Day 1

Day 2

Wednesday 15 December 2021

Day 2

Keynote Speaker - Session_01		
Session Moderator	**Professor Dr. Mostafa Refat**	
• **Keynote Speech**		
	Professor Dr. Yasser Mansour **Title: "*Museum Design & Cultural Message: A Catalyst for Change*"**	10:00 – 10:45 am
Break	**10:45 – 11:00 am**	
The Architecture of Museums – Session 02		
Session Moderators	**Professor Dr Hanan Sabry and Professor Dr. Abeer Elshater**	
• **Papers Presentations**		11:00 – 12:00 pm
Paper 09	**Nouran Khaled**, "*The Interpretation of Museums Microclimate - The Emergence of New Museum Architecture After the Pandemic*".	
Paper 11.	**Vida Abbasi**, "*The introduction of a mobile application using gamification for increasing demand and revenue management in museums focusing on small and mid-sized venues: The case study of Milanese Museums*".	
Paper 07.	**Walaa Ismaeel**, "*Adaptive Re-use of cultural heritage buildings to museums; case study Sabil Mohamed Ali*".	
Paper 15.	**Sara Biscaya**, "*Museum Architecture Post Covid19 and the role of Digital Transformation*".	
Paper 26.	**Laurent Lescop**, "*Expanding Museums: new tools and concepts for mediation and virtualization*".	
Break	**12:00 – 12:30 pm**	
Workshop: Monitoring of Museum Environments – Session 03		
Session Moderator	**Dr. Nouran Khaled**	
• **Keynote Speech**		
	Dr. Abd El Razek El Nagar **Title: "*Monitoring of Indoor and Outdoor Museum Environments for Diagnosis of Object Degradation: Case Studies from the Egyptian and British Museums*"**	12:30 – 1:15 pm
• **Discussion/ Questionnaire**		1:15 – 1:30 pm
Break	**1:30 –2:00 pm**	

Session Moderator	**Professor Dr. Hisham Elkadi**

• **Keynote Speech** **Mrs Ceri Horrocks** **Title:** ***"Building Back Better – How Our Museum Has Weathered the Storm."***	2:00 – 2:45 pm

Break 2:45 –3:00 pm

Technical Session – Session_05

Session Moderator	**Professor Dr. Hisham Elkadi**

• **Keynote Speech** **Mr. Ethan Bellmer** **Title:** ***"Dashboard for Monitoring Object and Visitor Environments "MOVE" in Salford Museum and Art Gallery."***	3:00 – 3:45 pm

Conference Conclusion	**3:45 –4:00 pm**

Museums' D-Light

The role of daylight in shaping futures of museums

Hisham Elkadi H.Elkadi@salford.ac.uk
University of Salford, United Kingdom

Abstract: Museums have played a major role in documenting human history. Both display of exhibits and the sphere that contains them have dramatically changed in the last two decades. Many factors have led to such transformation. These factors ranged from environmental consideration of monitoring indoor spaces, technology of display and interaction, to shift in visitors' expectations. The use of daylight becomes a key ingredient in the design of new museums. Far from being the environmental nemesis of sensitive exhibits, daylight becomes a tool to design and manage display of exhibits and improve visitors' experience. Looking at the history of this transformation in the use of daylight, this paper examines the role of daylight in the design and environmental management of contemporary museums. The paper provides a critical historical review of the use of daylight in museums. The paper discusses how recent research in daylight has enabled the use of daylight in the display of sensitive artifacts. Examples are given of contemporary design and best practices of museums in different parts of the World. The paper critically examines the current glazing technologies to control indoor daylight and provides research trends to improve indoor museum environments for both exhibits protection and visitors experience.

Keywords: Museums, Architecture, Design, Daylight, Energy

Chapter 5 1 Introduction

Our physical environment has dramatically evolved over the last two decades. The Earth's atmosphere and surface are continuously changing. The global ramifications of life's birth progressively merged these forces. The only way to understand about the beginnings of life and, perhaps, its future is to go back in time (Allegre & Schneider, 2005). In almost all religions, from Manichaeism to Buddhism through to the Abrahamic religions, light represents purity, knowledge, and truth. Darkness, on the other hand, portrays evil, ignorance, and sinfulness. The angels, the celestial beings, are either made of, or glow of, light; they are luminous beings created by God.

In the beginning of time God created the heavens and the earth. Now the earth was without shape and empty, and darkness was over the surface of the watery deep, but the Spirit of God was moving over the surface of the water. God said, "Let there be light." And there was light! God saw that the light was good, so God separated the light from the darkness. (Genesis 1, 2). Light in one of Verse no. 35 in the Quran also describes light in the most mystical and esoteric way. The remarkable beauty and imagery of Light presented in this verse has captured the imagination and inspired philosophers for centuries. It reads:

Allah (God) is the Light of the heavens and the earth.
The example of His light is like a niche within which is a lamp,
The lamp is within glass, the glass as if it were a pearly [white] star,
Lit from [the oil of] a blessed olive tree,
Neither of the east nor of the west,
Whose oil would almost glow even if untouched by fire.
Light upon light.
Allah guides to His light whom He wills.
And Allah presents examples for the
people,

and Allah is Knowing of all things.

Al Ghazâli (1058-1111), a Sufi Muslim philosopher, interpreted this verse and separation of light and darkness as the separation of human souls from the Deity. Seventy thousand veils of shades of lights need to be crossed for a naked human soul to stand face to face with the naked Deity. The human soul begins at the bottom (darkness) and works up the light ladder, layer by layer to the very top. Architecture, in many ways, is the embodiment of such interpretation. In architecture, light influences human perception. Architecture is therefore a product of the play of light, shades and shadows to create a meaningful place. It allows us to perceive the many aspects of objects of our surroundings such as size, geometry, form, texture, and color. Whether we prefer total isolation in full darkness or absolute freedom in glorious light, we can manipulate our place and our feelings with light, shade and shadows to articulate our feelings and control our movements.

The articulation of light to reveal the beauty of objects cannot be as crucial in any structure as it is in museums where artefacts need to be presented to convey certain meanings and to exploit our senses and emotions. Museums are important architecture typology for the preservation of our culture and heritage. By displaying the tangible and intangible relics of our planet, these institutions convey the narrative of our history and pass it on to each new generation. The importance of museums, their design and their abilities to signify historic messages, to humanity is critical for the development of our future through studying the works of our forefathers.

Fig. 1 Library of Alexandria, 323 BC

The term museum originated from the Latin word mouseion, which has a wide range of meanings. It was once thought to be a temple dedicated to the muses, a group of nine goddesses who were in charge of epic, music, love, poetry, oratory, history, tragedy, comedy, dance, and astronomy. In 1995, the International Council of Museums (ICOM) defined museum as a "non-profit, permanent institution in the service of society and its development, open to the public, which acquires, conserves, researches, communicate and exhibits the tangible and intangible heritage of humanity and its environment for the purpose of education, study and enjoyment". Museums exhibit the cultural identity of the owners of the artifacts that is stored in its establishment.

In earliest times there was no distinction between a record room (or archive) and a library. Around the 3rd millennium BC, a temple with number of rooms filled with clay tablets were found near the Babylonian town of Nippur. Similar collections of Assyrian clay tablets of the 2nd millennium BC were found at Tell el-Amarna in Egypt. An early example was in 2nd millennium BCE, in Larsa in Mesopotamia, copies of old inscriptions were prepared for use in the schools, a progression toward the notion of the museum began. However, the concept also entails the interpretation of the original material that appear to have been items unearthed by Sir Leonard Woolley in the Babylonian city of Ur's 6th-century BCE levels. According to Woolley's discoveries, the Babylonian rulers Nebuchadrezzar and Nabonidus did indeed gather antiquities in their time. In addition, a tablet documenting 21st-century BCE inscriptions was discovered in a chamber close to the uncovered temple school, along with a collection of antiques. The tablet was regarded by Woolley as a museum label. This finding suggests that Ennigaldi-Nanna, Nabonidus's daughter and the school's priestess, maintained a modest instructional museum on the premises (Lewis, 2021).

Museums do however differ from libraries in that the artefacts kept in a museum are mainly unique and provide the raw material of study and research. The most common items were therefore housed in ‘record’ rooms within a temple. The early inception of a museum as a distinct typology was possibly around 323 BC in Alexandria (Alexander & Alexander, 2008); a research institute that was especially noted for its

scientific and literary scholarship. The Alexandrian Museum was built near the royal palace about the 3rd century BC possibly by Ptolemy I Soter (reigned 323–285/283 BC). The renowned Library of Alexandria formed a part of the museum. The modern museum, as a place where learning through objects are connected, was modeled after the Temple of the Muses. Although there are no direct links between the Temple of the Muses and modern museums, the use of unique objects as sources of knowledge formed the conceptual foundation of museum development beginning in the Renaissance, when the museum was first applied to collections (Simons, 2016).
The name "museum" was resurrected in 15th-century Europe to describe Lorenzo de' Medici's collection in Florence. The phrase ‘museum’ however referred to the collection of artifacts rather than a building typology. The term "museum" continued to be used in Europe till the 17th century to refer to collections of artifacts. Ole Worm's display of collection in Denmark and John Tradescants collection entitled “Musaem Tradescantianum” in Lambeth were called museum by their visitors. Later on, these artifacts were transferred to Elias Ashmole, then in 1675 the collection was given to the University of Oxford. A structure was built specifically to house the donated artifact and was called Ashmolean Museum (Lewis, 2021).

The erection of the world’s first public museum, the Ashmolean in Oxford marked the move of the artefacts and collections from private domains to public displays. Significant historical artefacts started to be chronologically presented in museums. The establishment of the British Museum in London in 1753 marked the institutional structure of a museum. The function of object-based information usage became dominant. During the 19th century, services to educate the working class, which rapidly increased in cities as a result of urbanisation, were provided, and museums were given the mission of training and educating citizens (Günay, 2012). It was not until late 19^{th}C and early 20^{th}C that the building that hosts cultural artefacts became more dominant in the function of a museum.

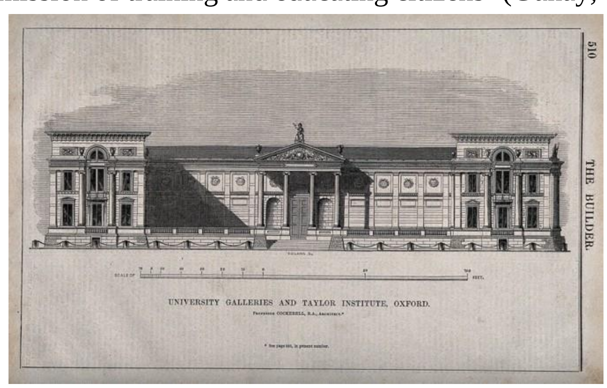

Fig. 2 The Ashmolean Museum, Oxford 1683

2 Museums, Glass, and Daylight

To control the amount of heat and cold air that would be admitted inside a structure, adequate screens were required to alter the effects of external temperature. Different materials were used to control the amount of light, heat and cold air that would flow into a structure. Initially these openings were first covered with thin slabs of marble, mica sheets, and oiled paper. Years later in around 3000 B.C. glass was discovered in Egypt and later on used by the Romans to cover small window openings. Since the discovery of window glazing, humans were able to link the exterior environment to the interior of a structure. Through this invention the natural light and air could be controlled and admitted into the structure and lit up the area. This paved way to the breath taking colourfully lit interiors, years later, of the medieval cathedrals and Baroque churches in the eighteenth century.

The design and function of windows have evolved over time, but its essential role of allowing in light and air has not changed. It wasn't until the 17th century that large windows began to be made of glass in England. In certain situations, such as in medieval times, the shape, size, and placement of windows were functionally connected to daylighting; but, as time went on, the location and form of windows grew more formalized, becoming less closely related to the interior areas they serviced. (Philips, 2004).

Prior 1800, architects used the building skin as the primary mediator between external and interior climatic conditions. Daylighting continued to be primary source of illumination that is determined by window size, orientation, and the configuration of the interior space. Museums' activities were restricted to daylight hours. The introduction of electric lighting during the industrial revolution introduced mechanical devices and enabled control of indoor environment. Light, air movement, humidity, and temperature could be artificially controlled to preserve the collections hosted by the museum buildings. Several architects attempted to combine modern technology with classic architectural concepts for the design of museums in this era. Others, on the other hand, neglected natural design concerns in favor of relying largely on modern technologies in controlling indoor environments with energy reliant methods. During the post-World War II reconstruction, the modern movement, with its energy intensive methods, dominated architecture (Moore, 1985).
During the second half of the 20^{th} C, glazing technologies have become essential and integral part of the design of windows in museums. Over recent decades, a variety of glazing assemblies and glass technologies have been developed to tailor glass characteristics and function as means to control admission of daylight into museums. There are nine basic types of glazing that influence daylighting and solar heating and cooling applications in museums. These types of glass have distinctly different behaviour in the three regions of the radiation spectrum (ultraviolet, visible and near infrared) (Elkadi, 2007).

- Clear glazing
- Fritted and laminated glazing
- Tinted glazing
- Reflective glazing
- Low emissivity (Low-e) glazing
- Applied Films
- Spectrally selective glazing
- Switchable glazing or smart glazing
- Photovoltaic

Apart from clear glazing, all other glazing types have been used to various extents in museums around the World. ***Fritted glazing*** is a simple, cheap, and low maintenance way to provide integral shading devices. This typology is however static and unable to react to different wavelengths. Fritted glass can also provide glare near the windows that could be challenging to curators. ***Laminated glass***, consists of a tough plastic interlayer made of polyvinyl butyral (PVB) bonded between two panes of glass under heat and pressure, has similar advantages and disadvantages of fritted glass.

Tinted glass is the oldest of all the modern window technologies. These types of glass are rarely appropriate for daylighting purposes in museums as they reduce light transmission, distort the colour of the view, and increase radiant heat transmittance.

Reflective glazing is created by depositing very fine semitransparent coatings made of thin layers of metals or metallic oxides on the surface of the glass, producing a mirror like appearance. These characteristics are also not useful to provide adequate daylight in museums. Reflective glazing reflects light along with solar infrared radiation and should not be used in galleries and museums spaces that are designed to receive certain levels of daylight.

Low Emissivity (Low-E) Glazing was introduced in 1989. This type of thin and invisible coated glazing reduces heat transfer through windows. While similar in behaviour to reflective coatings, this type of glazing are used in museums for their low emission and reflection of longwave rather than shortwave heat. These coatings are predominantly transparent over the visible wavelength (300 to 700 nm) and reflective in the longwave infrared. The coatings reduce the harmful ultraviolet rays which cause fading of objects' finishes.

Applied Solar Films exist since 1969. They are thin, transparent sheets that can be applied to the interior or exterior of glass surfaces to change its light-transmitting aesthetics, thermal, safety, and security characteristics. These multilayer assemblies of coatings and polyester films are effective against UV rays (almost 98%) and cheap to apply. They do however, affect, the quality of daylight in the museums' galleries.

Spectrally selective coatings are considered to be the next generation of low-e technologies. These coatings filter out from 40% to 70% of the heat normally transmitted through clear glass, while allowing the full amount of light to be transmitted (DOE and NREL, 1993). They permit some portions of the solar spectrum to enter a building while blocking others. These coatings can produce "customized" glazing systems capable of either increasing or decreasing solar gains according to the desired level of illumination required in various galleries.

Switchable 'Smart' Glazing are very suitable to museums daylight requirements. They include optical switching materials that can be responsive to hourly, daily and seasonal climatic changes. These coatings can control the flow of light or heat in and out of a museum window; providing an energy-management function. Depending on the design, the coatings can control glare, modulate daylight transmittance, limit solar heat gain to reduce cooling loads and improve thermal comfort (Elkadi, 2007).

This type of glazing is available in different products:

- Angle selective glazing
- Liquid crystal assemblies
- The chromogenic phenomenon which includes:
    - photochromic glazing assemblies,
    - thermochromic glazing assemblies,
    - electrochromic glazing assemblies
- Holographic diffractive films
- Prismatic glazing

These products are available to use in different museums and allow tailored technologies that suit different types of displays

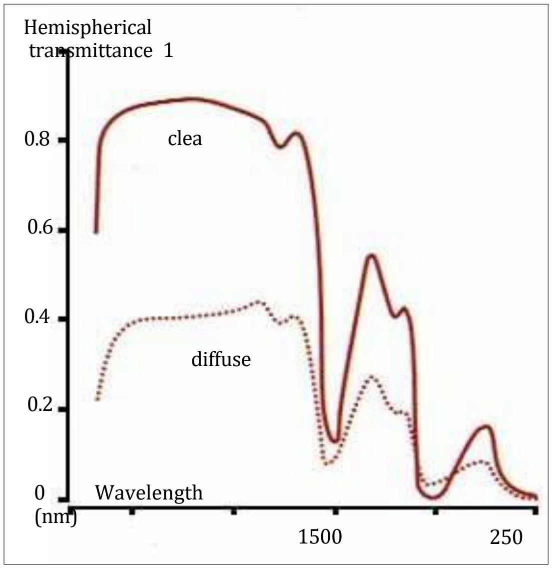

Fig.-3 Optical properties of a typical thermochromic glazing, 1mm thickness thermochromic material (Wigginton, 1996)

Climatic conditions can modify both the quality of light and the magnitude of its three components on the global scale; the focus in museums is on the direct and diffuse radiation. Skylight is largely non-directional and is a product of the scattering of solar radiation in the atmosphere. Direct radiation, on the other hand, is directional depending on the solar azimuth and cloud cover or degree of cloudiness.

The sky itself has a luminance sufficiently high to provide an average of approximately 10000 lux. This can be efficiently used for lighting the interior (Scittich, 2003) as many of the daily visual activities only require around 300 to 500 lux. The moonlight has a brightness of approximately 0.2 Lux. To explain some of these fundamental challenges of daylighting, it could be assumed that the entire sky acts as a uniform hemisphere. The amount of usable daylight in a gallery space is proportional to the amount of sky visible through the lighting hole from that location. If there is no sky visible from a certain position in the room, the available light is insufficient for any basic function (Singh, 2018) but could be sufficient for an object presentation.

Illumination to display artefacts in museums is a complex process that involves many factors including the type and material of the exhibit, the temperature and colour of the light and its positioning and brightness. The science of lighting the museums and galleries indoor environment continuously evolve with changes of knowledge of the impact of direct and indirect daylight on exhibits. UV radiation, which consists of photons with a high energy relative to visible light, can cause physical and chemical changes in sensitive exhibits' materials, causing them to deteriorate. UV degradation is a problem for museums' curators for a wide range of materials hosted in a museum that are designed for usage and storage in different environments. The recognition of the required level of illumination for each exhibit also pauses challenge to the design of museums' indoor environment. The previous knowledge that the light on an artwork should be about three times as bright or intense as the ambient light does not anymore provide absolute fact. While it is proven that the maximum illuminance of a painting for example is around 325 Lux, the minimum requirement to appreciate colours and patterns of an artefact could require much less illuminance. The human eye can distinguish details of an object with less than 10 Lux. An excellent example is presented in the V&A museum in London.

3 The Architecture of Daylight in Museums

The objective of daylighting in contemporary architecture design of museums is to improve natural light in interior areas, considering uniformity, directionality, and glare into consideration. This becomes a nontrivial design challenge due to the dynamic nature of sunlight. Seasonal, daily, and meteorological fluctuations in intensity, direction, and spectral features of light must all be taken into consideration when using daylight in museums. Several innovative solutions to these challenges have relied on a basic understanding of daylight, its properties, and its complicated processes of propagation and interaction with matter to overcome traditional restrictions. When employed and combined in unique ways, the primary propagation properties of light—reflection, refraction, and scattering—can provide both functionality and form in daylighting (Strobach & Boriskina, 2018).

The use of daylighting in museums continues to be a major challenge. The sun's UV rays have the potential to harm museum artifacts in the same manner that they have the potential to ruin construction materials. However, due to climate change and the increasing financial pressure on museums, there is a call to decrease the usage of artificial lighting and cooling systems, which also contributes to the ozone layer's depletion. Scientists and designers have been able to develop techniques to limit the amount of sunlight that enters a building's interior without compromising the advantages of natural illumination throughout time. There was no place better to experiment, implement, and perfect those techniques than museums.

Masters of Daylight in Museums

Kahn regarded the window as the most "marvellous element of the room" that allows the revealing quality of sunlight to endow spaces with their vitality (Guzowski, 2000). His preoccupation of experimenting with light, involved the design of "Keyhole windows" that would give maximum usable wall space due to the vertical slit below, whilst maintaining adequate light from the upper large, wide pane (Kurtich and Eakin, 1993). In 1962, Kahn also attempted to filter light through external screens in a consulate building in Luanda (Elkadi and AL Maiyah, 2020). Details of the USA embassy in Luanda gives insight of the facades details that ensure adequate and appropriate daylight levels. In this experiment, Kahn showed how structures can be shaped to give light. Kahn realised that the utilisation of the different components of daylight could contribute to the richness of the visual experience. It is however, in the Kimbell Art Museum (1966), where Khan excelled in pioneering his silver light inserts (Brownlee and De Long, 1991). Khan created a skylight system by lifting the roof. In Fort Worth, Kahn's strategy in reducing the damaging intensity of the Texas sun was conceived through diffusers inspired by his earlier works. A thin linear skylight and reflector were utilised to elegantly redirect the harsh Texas sunlight to the ceiling vault (Elkadi and Al Maiyah, 2020). The curved ceiling then transfers it to a silvery luminosity that washes the spaces below. With the awareness that colours are portrayed by the mutability of sunlight, varied colour experiences were introduced, exploiting indirect, reflected or harsh daylight (Guzowski, 2000).

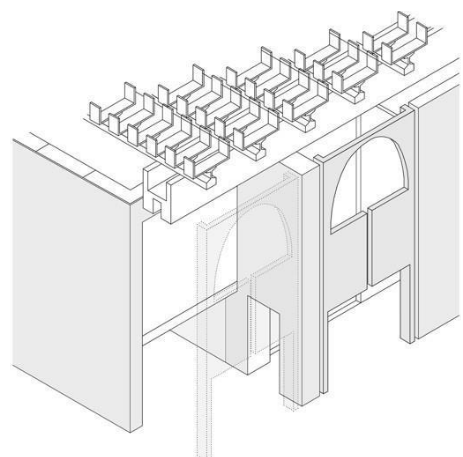

Fig.4 Isometric drawings of sunshades for the U.S. Consulate, Luanda, showing the utilisation of keyhole-shaped openings to screen the sun's glare. (Based on Tyng, 1984)

Frank Lloyd Wright (1867-1959) was true to natural daylight as much as to materiality. He was able to bring light to light in his architecture. Frank Lloyd Wright believed that if we truly understand the movement of the sun, architecture will follow what he referred to as g 'great luminary' (Wright, 1954). In his design of Guggenheim Museum in New York is masterpiece of how daylight could be a key factor in the detailed design of a museum. Throughout the construction of the Solomon R. Guggenheim Museum, Frank Lloyd Wright often disagreed with the museum director on his intention to have paintings floating in daylight throughout the building. Even in the early rendering of the project, light was either brought in under the spiritual dome or shining out at night. Careful detailing of slant walls ensured skylight to illuminate the walls and displays. Lighting issues were only resolved after Wright's death in 1959.

Another Guggenheim Museum provides an excellent example of using daylight not only for its interiors but also to articulate its building form. Bilbao Guggenheim museum by Frank Gehry (1929-) is an excellent example of how the shapes of his planes are accentuated by sunlight and daylight reflected from the river Nervión. The selected exterior materials display a wide range of reflection, absorption and transmission properties and this variation causes the incident light beam to react differently when hitting a physical urban obstacle. When the radiation of light encounters a material obstacle, it may be reflected, absorbed, or transmitted to the other side of the obstacle depending on its internal structure and surface irregularities. Careful application of such knowledge led to excellent display of shades and shadows throughout the building. Gehry also uses the atrium to allow daylight to infiltrate the interiors and create wonderful light display in the heart of the museum. Frank Gehry has also sensitively and creatively used daylight in the design of his other museum buildings. His restoration of the Ontario Art Gallery also provides an example of sensitive intervention that use daylight to enhance a heritage building with typical dark interiors.

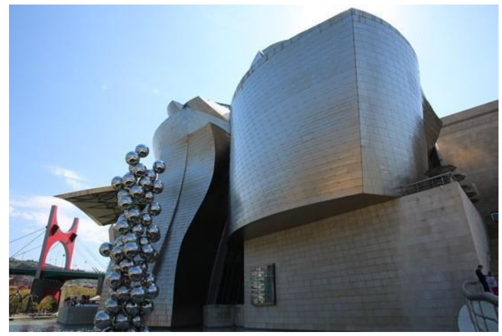

Fig.-5 Giggenheim museum, Bilbao, by Frank Ghery 1997

The ability of daylight to influence the feelings of visitors in a temple or a museum was realised through early history. Whether it is the recession of daylight in the linear procession of a pharaoh's temples, the democratic flow of light in Greek temples, or to heightened spiritual feelings in the Gothic cathedrals, architects have used daylight to influence visual experience of visitors. A well-designed facade can also use daylight to provide a spiritual link between the man-made buildings' interiors and nature. Davey explained the importance of understanding the complexities of buildings that can touch subtler and deeper levels of the psyche (Davey, 2001). A good example of such buildings can be experienced in Ando's Christ church in Oklahoma, the Roman Catholic Cathedral in Liverpool, or the Pola Museum of Art in Japan where the main glass wall has played a major role in the spirituality of the place. Lighting qualities achieved by Paxton in Crystal Palace was compared, by Siegfried Giedion, to the luminous spaces in Turner's painting (Elkadi, 2007). Turner's uses a humid atmosphere to dematerialize landscape and dissolve it into infinity. The Crystal Palace, according to Sigfried, realizes the same intention through the agency of transparent surfaces and iron structural members" (Giedion, 1967).

More recently, many historic buildings are increasingly turned into museums. Without a clear valuation, and an understanding, of the value of daylight in shaping the visual character of a historical building, it would be rather challenging to first establish whether daylight should be taken into account when developing a renovation scheme, and then what might be considered as 'minimal intervention' in terms of preserving its ambient conditions. Many attempts have been made to model and visualise daylight performance from single historic rooms to a whole heritage site. The delicate balance between the visitors' experience and the daylight requirement levels for the exhibits, materials, or even buildings, poses a challenge to heritage conservationists as well as academics. Daylight levels and analysis for the historic Smoking Room at Ickworth House near Bury St Edmunds, Suffolk (Cannon-Brookes et al, 2017) would be very different to that in museums (Al-Maiyah and Elkadi, 2015), or from the daylight requirements needed to maintain an identity in the renovation project of a heritage site (AL-Maiyah and Elkadi, 2007).

The value of daylight and the importance of maximising its effectiveness for illuminating building interiors (which were clearly stated in the UK building performance legislations introduced in 2008 (UK Government, 2008) have been further emphasised with the latest introduction of the new lighting standard.

The EU Strategic Energy Technology (SET) Plan indicates that a future integrated strategy should lead to an optimisation of the use of daylight and ventilation in buildings and, overall, should lead to a better indoor climate quality. In different parts of the world, indigenous buildings have been converted to museums, art galleries, cultural venues and community centres. Maintaining and reusing historic buildings is often seen as a way not only of preserving the physical building fabric 'as a tangible link with the past' but also as an opportunity to preserve the intangible heritage of traditional skills and craftsmanship (Cengiz, 2012). Often, the intention is to provide new accommodation for the storage and exhibition of valuable artefacts. Many historical buildings were originally designed to accommodate different activities to those accommodated in their new use. As most historical buildings were originally designed to maximise daylight, maintaining the 'day-lit appearance' of a building can be problematic in terms of artefact conservation requirements. The preservation of the quality of daylight that originally contributed to their visual identity becomes a very challenging task. Al-Maiyah and Elkadi (2015) showed that maintaining the 'day-lit appearance' of a building can be particularly problematic if the building is to be used as a museum or a gallery owing to the artefacts' conservation requirements. Successful utilisation of daylight can, however, create a better visitor experience and museum environment as well as improving the energy efficiency of a building. In top-lit galleries (in temperate climates), savings in installed lighting loads of the order of 50–60% have been estimated if daylight is properly integrated with artificial lighting (Carver, 1994). Caroon (2010) showed a number of examples where daylighting has been fully utilised in preserved buildings.

In the historic Scowcroft building, Utah, for example, the daylighting in the restored building is effective enough that daytime lighting is not required in 80 percent of the regularly occupied spaces. In other examples, ARUP was able to enhance daylighting in Sydney's 50 Martin Place, where the façades have far less glazing than contemporary buildings, by a new roof structure and the enlargement of the existing narrow atrium (Pettifer, 2014).

Some examples of successful use of daylight in transformed heritage buildings into museums are more successful than others. The monastery of San Agustin in Manila was transformed into a museum in 1973. The use of capiz in the monastery (with its access to the 16th Century church) has provided appropriate daylight levels in the galleries.

Regrettably, the sky lighting in a number of halls was not enough to exhibit large collections that were then, unfortunately, exposed to excessive damaging levels of artificial lighting.

Figure 6 Use of capiz shells to illuminate the interiors of San Augustin Manila

Modelling the performance of daylight in museums heritage buildings is necessary to provide adequate levels that neither alter the ambiance and identity of the place nor damage the exhibits in the new use of the buildings. Al-Maiyah and Elkadi (2015) investigated the opportunities for maintaining the original ambient conditions of renovated historical buildings while meeting the required daylight levels of the proposed new use. The study utilised an annual daylight simulation method and hourly weather data to preserve daylight conditions in renovated historic buildings. The model was piloted in a Turkish bathhouse situated in Bursa, Turkey. The simulation model produces 4483 hourly values of daylight illuminance for a period of a whole year using the computer programme Radiance. The study concluded that daylight characteristics could be maintained when developing a renovation museum scheme in a heritage site.

Chapter 6 Conclusion

Provision of daylighting in museums is a necessary but challenging task. Since the inception of a museum as a building, efforts have been made to maximise the use of daylight while minimise the damage and deterioration that direct sunlight and certain wavelength could do to the exhibits.
Architects must be informed of the requirements of each exhibit, its materiality, colours, and composition in order to allow adequate level of harmless daylight. Many architecture designs, innovations, and construction techniques have been used to control amount of daylight in museums. The paper reviewed key efforts and techniques that have been used since the erection of the first purposefully museum building in Oxford in 1683.

These can be summarised in three different categories:

- Design of openings: Applications of size, shape and orientation of openings are deemed necessary as a first step in controlling admission of daylight and prevention of direct sunlight. The earlier techniques of using atriums to admit reflected daylight is still popular in the design of contemporary museums,
- Construction of filters: Many architects provide extra protection to openings through construction of different layers of filters in forms of louvres, deep recession, or a second skin façade. These techniques in museums facades are inspired by the earlier work of Kahn and Le Corbusier.
- Glass technology: Since the earlier invention of glass in Alexandria, the making of glass has seen tremendous advances to improve its transparency, colours, and size. The most notable development for museums is the use of Low e glazing, spectrally selective coatings, and Switchable glazing. These glazing technologies control transmittance and provide glass windows with the ability to discriminate against certain 'harmful' wavelength. The development of smart switchable glazing and liquid crystal glass was particularly useful innovations for museums. These types of glass inherently provide a change in the glazing optical properties under the influence of light, heat or an electrical field, or by their combination.

With the increasing use of historic buildings to host various collections, from scripts to icons, the control of daylight transmittance has become of major concerns. The sole reliance of artificial light to protect the artefacts, deplete good visitors' experience and prevent the delights of the historic settings, the views from within the heritage building as well as loss of the original ambient light in those historic buildings. Recent long periods simulation data and modelling techniques provide a solution to carefully measure the daylighting requirements and allow opening out and permit daylight in those historic building, improve visitors experience without compromising the protection of the exhibits.

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A review on objects' preservation and visitors' thermal comfort within museums

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Abstract: Museums play a significant role in preserving and showing human culture. Their environmental conditions are considered crucial in preserving their collections as well as ensuring a pleasant experience for their visitors. Ensuring a stable indoor environment is essential to the survival of museum objects and collections. This could be achieved by providing a well-maintained building with efficient environmental facilities. Comfort is also one of the crucial elements that affect the visitors' overall experience and accordingly the museums' success. Recently, finding this balance between reducing the energy demands without endangering the different collections as well as maintaining a thermally comfortable environment for visitors is one of the main challenges for museums. This paper focuses on the conflict and harmony of the environmental requirement recommended to preserve the museums' objects and provide a comfortable experience to their users. It provides a review of the literature of the indoor environmental requirements within museums, considering both the objects and visitors. The findings are to highlight the different requirements and propose a balanced approach to managing them.

Keywords: Museums management, Human thermal comfort, preservation of objects, indoor environmental conditions.

1 Introduction

Management of thermal conditions in museums is critical to the preservation of cultural heritage objects and for the comfort of visitors and staff. Control of T and RH and the maintenance of a stable environment is necessary to prevent object degradation. Daily changes can be particularly harmful, for example, if heating or cooling systems are turned on and off for the comfort of visitors, whilst slower seasonal changes may have less impact. Visitors and staff demand acceptable thermal comfort conditions, access to natural light and good air quality. The conflict between the environmental demands relating to the conservation of objects and visitor comfort is widely acknowledged along with the need to establish a practical compromise in meeting recommended technical standards. In this paper, the aim is to review the literature focusing on the effect of the indoor environment on objects and users in museums.

2 Research Methodology

The focus of the paper involves the relationships between the indoor environment with the museums' objects as well as users. Accordingly, two searches have been conducted to identify the relevant literature for both subjects. The first sought to identify literature concerned with the dual objectives of object preservation and thermal comfort within museums. The key search terms were limited to "preservation", "thermal comfort", and "museum". The search was limited to research papers and review articles. For the visitors' perception part, the search involved reviewing journal peer-reviewed published articles which examined human thermal comfort within museums spaces. The initial keywords used in the search were "thermal comfort" and "museum". However, other keywords appeared from the search including "energy efficiency" which informed the discussion in this paper. For the purposes of this paper the search terms were limited to manage the results. Alternative terms might have included 'conservation' rather than 'preservation', 'museums' rather than 'museum', or 'visitor comfort' rather than 'thermal comfort'.

3 Findings and Discussion

3.1 Indoor environment and Objects:

Recognition of the challenges of managing museum environments for both object preservation and thermal comfort is an established topic in the research literature. Lucchi's (2018) literature review of theories and approaches to preventive conservation in museum buildings from 1965 to 2016 traces the shift from a focus on preservation to a more complex, multi-objective understanding of the requirements for museum indoor environments that includes human comfort and energy efficiency. The literature review for the present paper examines this trend in more detail over the past 30 years with particular reference to the preservation and thermal comfort.

3.1.1 Results of literature search

The search was carried out using three different platforms, Google Scholar, ScienceDirect and Scopus using the exact keywords "thermal comfort" and "museum" and "preservation". The outcomes are shown in Table 1.

Table 1. Results of the literature review search for object preservation and thermal comfort using different platforms

	Google Scholar	**Science direct**	**Scopus**
Results number	2040	14	19
Results since 2000	1910	14	19
Results since 2010	1650	12	15
Sort type	Relevance	Relevance	Number of Citation
Search includes	Exact words	Title – abstract - keywords	Title – abstract - keywords

An analysis of the results is shown in Fig. 1 showing the rapid overall increase in the number of published papers in this field. The Google Scholar search produced a wider number of results based on a full-text search. The results found 2040 papers in total, with 1910 since 2000 and 1650 since 2010. Thus 81% were published over the last 11 years, showing an increased interest in this field of study. More refined advanced searches were carried out using ScienceDirect and Scopus which narrowed the search to the fields of 'Title, 'Abstract' and 'Keywords'. Whilst recognising the limitations of the search strategy, the low number of returns using these key terms, 14 from ScienceDirect and 19 from Scopus, suggests that relatively little research is specifically addressing a multi-objective approach to managing indoor environments in museums. The top ten studies resulting from the Scopus search is shown in Table 2.

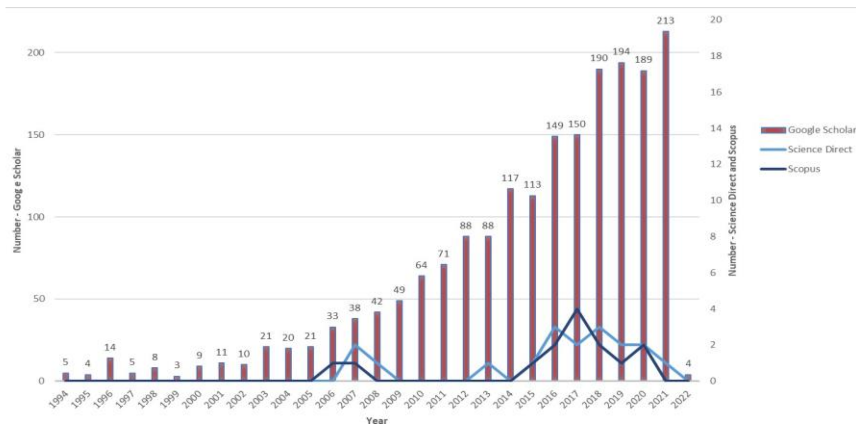

Fig. 1. Search results frequency/year for "thermal comfort" and "museum" and preservation in the different platforms

Table 2. Top 10 documents (out of 19) of "thermal comfort" and "museum" and "preservation" in the Scopus search.

	Title	Reference	Published in	Location	No. of Citation
1	Energy efficiency and thermal comfort in historic buildings: A review	(Martínez-Molina, Tort-Ausina, Cho, & Vivancos, 2016)	Renewable and Sustainable Energy Reviews	Spain	176
2	Energy retrofit and conservation of a historic building using multi-objective optimization and an analytic hierarchy process	(Roberti, Oberegger, Lucchi, & Troi, 2017)	Energy and Buildings	Italy	75
3	Energy conservation in museums using different setpoint strategies: a case study for a state-of-the-art museum using building simulations	(Kramer, Maas, Martens, Schijndel, & Schellen, 2015)	Applied Energy	The Netherlands	57
4	Multi-objective optimization of microclimate in museums for concurrent reduction of energy needs, visitors' discomfort and artwork preservation risks	(Schito, Conti, & Testi, 2018)	Applied Energy	Italy	29
5	Daily natural heat convection in a historical hall	(Balocco, 2007)	Journal of Cultural Heritage	Italy	19
6	Preservation of the artistic heritage within the seat of the Chancellorship of the University of Palermo. A proposal on a methodology regarding an environmental investigation according to Italian Standards	(Costanzo, Cusumano, Giaconia, & Giaconia, 2006)	Building and Environment	Italy	19
7	Assessing visitors' thermal comfort in historic museum buildings: Results from a Post-Occupancy Evaluation on a case study	(Martinez-Molina, Boarin, Tort-Ausina, & Vivancos, 2018)	Building and Environment	Spain	17
8	Integrated maps of risk assessment and minimization of multiple risks for artworks in museum environments based on microclimate control	(Schito & Testi, 2017)	Building and Environment	Italy	17

9	Multi-objective optimization of HVAC control in museum environment for artwork preservation, visitors' thermal comfort and energy efficiency	(Schito, Conti, Urbanucci, & Testi, 2020)	Building and Environment	Italy	15
10	Integrated numerical and experimental methodology for thermal-energy analysis and optimization of heritage museum buildings	(Pisello, Castaldo, Pignatta, & Cotana, 2016)	Building Services Engineering Research and Technology	Italy	11

3.1.2 Focus and method of the resulting studies

Based on the titles and abstracts of the cited papers resulting from the more structured and targeted Scopus search, 10 of the 19 papers were concerned with the management of object preservation and thermal comfort as concurrent objectives, further demonstrating the very limited extent of research in this area. Twelve of the 19 papers have energy efficiency as an objective alongside meeting the needs of preservation and/or thermal comfort, representing a significant trend in the research. Seven of the papers take a three-way approach in managing preservation, thermal comfort and energy conservation concurrently. A significant focus of the research is historic buildings housing museums and particularly with retrofitting to enhance indoor environmental conditions, with 12 of the 19 papers specifically addressing environmental concerns in this context. The complexity of managing indoor environments for object preservation alongside other objectives is addressed in some papers through risk assessment models for degradation of artworks (Kramer et al., 2015; Schito & Testi, 2017). Papers focusing on the retrofitting of buildings utilise dynamic simulation and measurement methods both to model and monitor existing conditions and to evaluate potential modifications to HVAC systems or other building interventions, to establish conditions that do not pose risks to collections whilst meeting the needs of visitors and/or energy-saving (Cadelano et al., 2019; D'Agostino, de'Rossi, Marino, Minichiello, & Russo, 2021; Pisello et al., 2016). For historic buildings regarded as worthy of preservation in their own right, less invasive passive interventions are evaluated in some instances (Cadelano et al., 2019; D'Agostino et al., 2021). Setpoint strategies for T and RH in relation to object preservation and thermal comfort are evaluated through simulations in some papers which seek to establish an acceptable compromise that may fall outside of recommended target values (Kramer et al., 2015; Kramer, Schellen, & Schellen, 2018; Schito et al., 2020). These studies identify RH as the parameter of greatest relevance to object preservation, whilst T is more critical for human comfort.

3.1.3 Indoor environments for object preservation

This section draws on the wider results from the Google Scholar search to discuss emerging themes and to highlight potential areas for future research concerning object preservation and thermal comfort.

3.1.3.1 Risk assessment for object preservation

An increasing number of studies aim to review target values for object preservation to establish greater flexibility to meet multi-objective indoor environmental management needs. Methods for assessing the risk of degradation are implemented to determine allowable ranges and fluctuations under specific environmental conditions and contexts. The literature identifies metrics used as tools for environmental management for preventive conservation including for assessing risk to artefacts (Corgnati, Fabi, & Filippi, 2009; Martens, 2012). The study by Silva, Henriques, Henriques, and Coelho (2016) of conditions in three spaces within a 17th-century Portuguese palace housing a national museum is concerned with reducing energy costs without compromising object preservation and thermal comfort. Through a process of measurement, utilisation of a performance index for the existing HVAC system and risk assessment for object degradation they were able to revise the targets to less demanding ranges. These brought potential energy savings, with limits for T between 13-26°C in all three of the spaces studied, RH limits of 45-66% in two rooms and 55-70% in the other. In another example the recent study by Schito et al. (2020) of a summer exhibition of paper artworks in an Italian museum considered preservation, thermal comfort and energy efficiency. The authors propose a methodology for optimising the management of these three objectives through control of the air handling unit, based on an 'achievement function method' to find the optimal values for the HVAC control variables. Their results showed that improvements could be made in each of the three objective function indices in relation to typical setpoint values (T = 23°C and RH = 50%).

In some cases, studies rely on the availability of local climatic data to assess current and future risks to collections (Lankester & Brimblecombe, 2012). Huijbregts, Kramer, Martens, Van Schijndel, and Schellen (2012) 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 to accurately model future climate scenarios based on different locations to more accurately assess risks to cultural heritage.

3.1.3.2 The impact of visitors on object preservation

Amongst the literature sample, there is limited research on how visitors themselves influence the thermal conditions in museums in relation to preventive conservation. Generally, any impact on preservation from visitors is seen as a negative environmental factor. Visitors are acknowledged to cause fluctuating gains in heat and humidity, as well as introducing particulate matter into gallery spaces. Fluctuations in airflow and ventilation from the movement of visitors is also a factor.

Some research in China engages with the implications for national collections of a rapid increase in the number of museums and the accelerating expansion of tourism. Feng (2016) refers to the impact of visitors at Emperor Qin's Terracotta Museum, where results showed that the museum's air in terms of airborne bacteria and fungi was negatively affected by human activity. Furthermore, the Palace Museum in Beijing, which was receiving an average of over 15m visitors a year, launched a pilot scheme to limit daily visitor numbers to control museum air quality and reduce vandalism. Ferdyn-Grygierek (2016) found visitors had a significant impact on indoor conditions including thermal parameters in a case study of a city museum in Upper Silesia, Poland, and that this varied according to the type of exhibition and the time of year (p.116).

Generally, there is little research presented in the literature which investigates visitor impacts on thermal conditions in museums in real-world examples. However, the closure of museums to the visiting public during the Covid pandemic in 2020-21 has indirectly highlighted the contribution that visitors make to environmental conditions, although research on this has not yet emerged in the literature. Visitors can have a notable impact on thermal conditions in museum interiors, including humidity, ventilation, air movement, CO2 and short term, rapid fluctuations in T and RH. In the UK when museums tentatively reopened following the first period of closure during the Covid pandemic the British Museum noted that "The presence of visitors plays an important part in keeping that humidity stable and we need to be careful as the objects reacclimatise during this first phase of reopening" (Brown, 2020).

3.2 Thermal Comfort Studies in Museums for visitors:

As public institutions, museums are expected to provide a comfortable indoor environment for their visitors as well as staff members. This section focuses on reviewing the literature that is concerned with thermal comfort within these types of buildings.

3.2.1 Results of literature search

The search was carried out using three different platforms, these are Google Scholar, Scopus and Science Direct using the exact keywords “thermal comfort” and “museum”. The search was limited to peer-reviewed research and review articles within the different platforms. The resulted outcomes are shown in Table 3.

Table 3. Results of the literature review search using different platforms

	Google Scholar	**Science direct**	**Scopus**
Results number	6130	29	50
Results since 2000	5710	29	48
Results since 2010	4870	23	36
Sort type	Relevance	Relevance	Number of Citation
Search includes	Exact words	Title – abstract - keywords	Title – abstract - keywords

As shown in the table, google scholar included a wider number of results that were sorted based on algorithms that take into account different parameters including the citation number, authors, and publishers. The results found since 2010, 2000, and anytime were 4,870, 5,710 and 6,130 respectively. This shows that this topic has gained more attention recently as almost 80% of the studies were published in the last ten years. This is also confirmed by the analysis of results adopted from Science Direct and Scopus platforms. Scopus results showed that 70% of the studies were published during the last 10 years. When the search was repeated using only the term “thermal comfort”, google scholar included 262,000 results. This means that thermal comfort studies in museums represent around 2.4% of thermal comfort studies, which is a very small percentage for such important types of buildings. The top ten studies resulted from the Scopus search using the exact keywords of “thermal comfort” and “museum” are shown in Table 4.

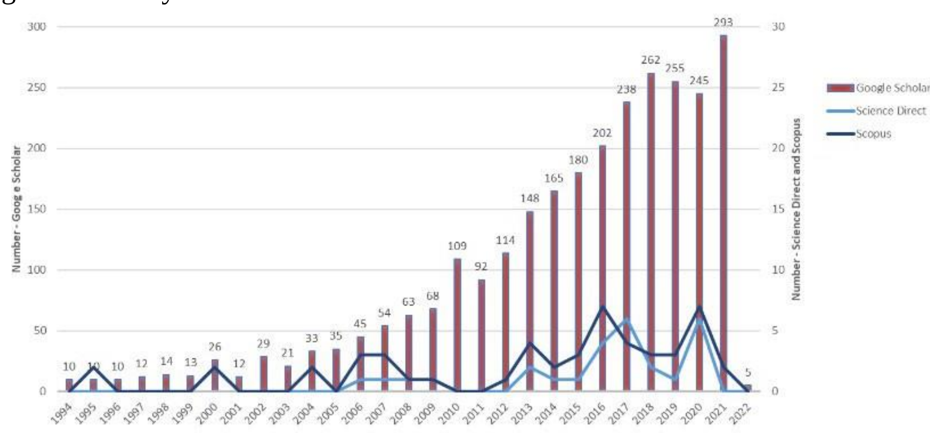

Fig. 2. Search results frequency/year for “thermal comfort” and “museum” in the different platforms

Table 4. Top 10 documents (out of 50) of "thermal comfort" and "museum" in the Scopus search.

	Title	Reference	Published in	Location	No. of Citation
1	Energy efficiency and thermal comfort in historic buildings: A review	(Martínez-Molina et al., 2016)	Renewable and Sustainable Energy Reviews	Spain	176
2	Thermal comfort requirements for occupants of semi-outdoor and outdoor environments in hot-humid regions	(Hwang & Lin, 2007)	Architectural Science Review	Taiwan	107
3	Energy saving strategies in air-conditioning for museums	(Ascione, Bellia, & Capozzoli, 2013)	Applied Thermal Engineering	Italy	76
4	Energy retrofit and conservation of a historic building using multi- objective optimization and an analytic hierarchy process	(Roberti et al., 2017)	Energy and Buildings	Italy	74
5	Energy conservation in museums using different setpoint strategies: a case study for a state-of-the-art museum using building simulations	(Kramer et al., 2015)	Applied Energy	The Netherlands	57
6	A coupled numerical approach on museum air conditioning: Energy and fluid-dynamic analysis	(Ascione et al., 2013)	Applied Energy	Italy	40
7	A sequential process to assess and optimize the indoor climate in museums	(Silva et al., 2016)	Building and Environment	Portugal	36
8	Computational analysis of thermal comfort: the case of the archaeological museum of Athens	(Papakonstantinou, Kiranoudis, Markatos, & NC, 2000)	Applied Mathematical Modelling	Greece	33
9	Dynamic building energy performance analysis: A new adaptive control strategy for stringent thermohygrometric indoor air requirements	(Buonomano, Montanaro, Palombo, & Santini, 2016)	Applied Energy	Italy	31
10	A field study on thermal comfort of occupants and acceptable neutral temperature at the National Museum in Malaysia	(Yau, Chew, & Saifullah, 2013)	Indoor and Built Environment	Malaysia	31

3.2.2 Focus and methods of the resulted studies:

Different methods were employed in the resulting studies according to their focus. In this section, Scopus results are used, given the availability to sort the result by the number of citations. It is clear from Table 3 that many of the most cited documents are focusing on energy efficiency which could be explained by the awareness of climate change and sustainability. Particularly with the building sector being found as one of the largest energy end-use sectors (Doornbos, 2016; Yang, Yan, & Lam, 2014). Energy efficiency research gained attention since 2005, which has significantly increased from 2010 (Kramer et al., 2015; Martínez-Molina et al., 2016). These studies included overviews on energy efficiency measures (Kompatscher, Seuren, Kramer, van Schijndel, & Schellen, 2017), HVAC system designs (Ascione et al., 2013) and opportunities and limitations of passive and local conditioning. However, very few studies focused on the effect of the alteration of indoor climate setpoints on energy consumption (Kramer et al., 2015; Kramer, van Schijndel, & Schellen, 2017).

The strictly controlled temperature and relative humidity required for the preservation of objects involve a significant intake of energy. The fluctuation of relative humidity was found to have higher risks on objects than fluctuation in temperature (Martens, 2012), which allows saving energy by applying more relaxed adaptive temperature limits rather than set points strategies. In their simulation study, Kramer et al. (2015) used the adaptive temperature guidelines of Van der Linden, Boerstra, Raue, Kurvers, and De Dear (2006) which are based on ASHRAE-Standard-55 (2010) to assess thermal comfort. Their developed adaptive thermal limits were based on the PMV model using indoor environmental variables. However, according to De-Dear and Brager (1998), the PMV model is only valid in air-conditioned buildings but not naturally ventilated ones. Adaptive models are then suitable for informing the energy-based decisions and temperature setpoints for HVAC buildings.

3.2.3 Indoor thermal comfort in museums

Thermal comfort represents the "condition of mind that expresses satisfaction with the thermal environment" and is assessed by subjective evaluation (ASHRAE, 2009). This is generally assessed by identifying the users' thermal comfort perception within the indoor spaces and studied using both objective monitoring and subjective measurements (Martínez-Molina et al., 2016). The objective monitoring involves the micrometeorological measurements that identify the environmental conditions in the studied spaces, while the subjective measurements include the users' thermal perception. The thermal sensation is the term identifying the users' subjective assessment of their conscious feeling that grades their thermal environment from warm to cold sensations, while thermal comfort identifies their satisfaction with this feeling. The seven points ASHRAE scale is the most commonly used scale in thermal sensation research (Doornbos, 2016; Vesely, Zeiler, & Li, 2015). The general six factors that contribute to thermal comfort are air temperature, mean radiant temperature, relative humidity, air velocity, metabolic rate, and clothing. Additionally, thermal adaptation factors including physical, physiological, and psychological adaptation are proved to be playing a significant role in thermal comfort analysis. Personal factors such as age and gender are also found to affect human thermal comfort (ASHRAE, 2009). Different studies have identified the effect of these different factors on users' thermal comfort (Halawa & Van Hoof, 2012; Mishra & Ramgopal, 2013; Schellen, van Marken Lichtenbelt, Loomans, Toftum, & De Wit, 2010).

Several studies investigating thermal comfort in museums used numerical analysis, computational modelling and experimental studies (Ascione et al., 2013; Kompatscher et al., 2017; Kramer et al., 2015; Kramer et al., 2017; Papakonstantinou et al., 2000; Saraoui, Belakehal, Attar, & Bennadji, 2018). However, these studies lack the inclusion of the human factors and subjectivity of the thermal experience and the complex interactions between the users and their surrounding environment. Few studies used both objective and subjective measurements in order to assess thermal comfort in museums (Doornbos, 2016; Karyono, Sri, Sulistiawan, & Triswanti, 2015; Martinez-Molina et al., 2018; Yau et al., 2013). Doornbos (2016) used both objective and subjective measurements aiming to develop the users' comfort levels in the museum Hermitage in Amsterdam. In their study, the Actual Mean Votes (AMV) results conducted from the surveys were found to indicate warmer thermal feeling when compared to the Predicted Mean Votes (PMV) that were calculated based on objective measurements. Accordingly, the AMV was the selected index used in developing the temperature limit within the museums' spaces. A total of

1250 surveys were used; however, the author clarified that additional surveys were needed to verify both lower and upper limit of comfort levels.

Martinez-Molina et al. (2018) conducted a post-occupancy evaluation in order to assess thermal comfort in museum buildings. A total of 440 surveys were collected to gather the users' thermal sensation votes during the study. The study showed that the PMV model was not precisely representing the actual thermal sensation votes. The users also reported thermal dissatisfaction during the cooling seasons.

Karyono et al. (2015) conducted a thermal comfort study comparing three main naturally ventilated buildings, including a cathedral, a museum, and a market. A sample of 219 participants was collected for the three buildings, from which 77 were from the museum. Thermal sensation votes were gathered according to the ASHRAE 7 points scale. The neutral temperature in the museum was calculated to be 27.7 ºC and the comfortable temperature levels ranged from 27 to
28.4 ºC.

Yau et al. (2013) also used both PMV and AMV to determine users' thermal comfort. A sample of 28subjects contributed to their study which used the ASHRAE 7 points scale to determine their thermal perception. In their conclusion, the authors highlighted that only 78% of the users were satisfied with the thermal conditions which indicate that they didn't satisfactorily meet the ASHRAE Standard 55.

Very few studies focused on the subjective experience of users in museums. The majority of the resulting studies were also found to include a small sample size, which makes it hard to generalise their results to the wider population.

3.2.4 Thermal comfort in various types of buildings and contexts:

As previously mentioned, the search conducted on Google Scholar using the keywords "thermal comfort" included 262,000 results. However, only 2.4% of these results had museums as their case studies. Most thermal comfort studies are having office buildings, classrooms, and residential buildings as their case studies. However, the type of occupancy in these buildings varies from museums which affect their users' thermal comfort sensation. The time of exposure in office buildings for example varies between 7-8 hours throughout the weekdays, while the museum visits 'average time is 70.7 minutes (Jeong & Lee, 2006). This time of exposure is a variable of the psychological adaptation factors affecting thermal comfort analysis. Users' expectations in another adaptation factor that affects human thermal sensation, which might lead to less rigid comfort guidelines (Fountain, Brager, & De Dear, 1996; Halawa & Van Hoof, 2012). Kramer et al. (2015) explained in their study that users' have lower thermal comfort expectations when visiting a historic building when compared to a modern air-conditioned one. The activity type is another difference between both buildings that affect the metabolic rate for users. In museums, visitors are mostly walking around the different spaces within the building, while in office buildings, users are mainly sitting on their desks. Clothing resistance is another factor that showed variation in both building types (Doornbos, 2016). In their study, (Karyono et al., 2015) found that the human comfort ranges for users in the bank Mandiri museum were wider than in Jakarta central Cathedral. These variations were explained by clothing and metabolic rate, yet adaptation factors are also influencing users' sensation. Accordingly, to identify thermal comfort levels within museums, it is important to rely on studies that are conducted in this type of buildings. Understanding the users' experience within museums is important in order to develop adaptive temperature limits for both objects and users (Doornbos, 2016).

Thermal comfort is also a contextual study as their analysis and outcomes differ according to the local climatic characteristics of the place. In addition to being influenced by the local context, thermal comfort is also affected by cultural characteristics (Kenawy & Elkadi, 2021; Rupp, Parkinson, Kim, Toftum, & de Dear, 2021). According to Scopus results, a percentage of 64% of publications are conducted in Europe. This shows the need for other studies that consider the different climatic classification and cultural zones.

4 Conclusions and further research

The main purpose of museums consists of preserving their collection of objects for the future generation. Accordingly, one of their main roles is to maintain the physical state of these objects and delay their natural process of decay. The environmental conditions are accountable for the decay of various materials and accordingly needs to be efficiently managed (Cassar, 1991). The display of these objects is another classic role of museums, and recently many museums favoured having additional activities including having restaurants, cafes, and shops among other income- generating ideas. This increased their role as public institutions and accordingly their responsibility to provide a thermal comfortable place for their users.

Recent literature takes a risk-assessment approach to investigate the implications of flexible T and RH target values on object preservation to allow for other environmental objectives. This research typically focuses on artworks and organic materials which are hygro-thermally sensitive. However many museums house a diversity of objects which include organic, inorganic and composite materials. Selection of suitable environmental ranges is therefore a compromise in considering multiple risk factors for different objects. Strategies for more diverse collections and other object categories are not well represented in the literature, although some valuable work in relation to museums housing in-situ archaeological remains is emerging from China (Luo, Gu, Wang, Tian, & Li, 2016; Luo, Wei, Song, Wang, & Gu, 2017).

Thermal comfort is one of the requirements that influence the visitors' experience within museums (Jeong & Lee, 2006). However, the focus on visitors has been only addressed recently, after other extensive studies that focused on the preservation of the buildings and their objects as their main assets (Martinez-Molina et al., 2018). This shed light on the need for more studies that take into consideration the human thermal perception and comfort in museums (Schito et al., 2020). This paper acknowledges the challenges facing the balance between visitors' thermal comfort, conservation requirements as well as energy efficiency considerations and endorse other studies in identifying the need to consider thermal requirements for both objects and visitors (La Gennusa, Lascari, Rizzo, & Scaccianoce, 2008; Luo et al., 2016; Martinez-Molina et al., 2018).

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Chapter 10 The Complexity of Daylighting Design Practice in Museum Environments

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Abstract: In our recent literature review of research papers on the management of microclimates in museums published over the last twenty years it was evident that the emphasis was primarily on thermal conditions with less concern for the visual environment. However, lighting conditions and in particular daylighting is important in varying degrees both to the impact that it has on the preservation of the artefacts and to the experience of visitors. This paper presents a more focused literature review which traces developments in lighting studies for museums over the last thirty years. It investigates shifts in scholarly interest in museum lighting conditions and the extent to which natural lighting is addressed alongside other factors. It also examines regulations and standards for lighting in museums and how these are applied in practice to create appropriate environmental conditions and to enhance the visual experience. Developments in lighting technologies have provided a focus for scholarly interest in museum lighting where it is understood to mitigate some of the harmful effects of natural light on certain artefact types. Both daylight and artificial lighting can be manipulated by the creative designer as interpretive tools and for aesthetic effect. Many historic museum and gallery buildings were designed with the management of natural light in mind, and the deleterious effects of daylight particularly on painted surfaces have been long understood. Subsequent developments in the field of museum lighting often led to the refurbishment of historic gallery spaces to largely block natural light. Designers of contemporary museums must balance the complexities of artefact preservation, aesthetics, and visual comfort in their schemes, mindful of the appropriate regulations and standards. Specific case studies allow us to examine these trends in the introduction of lighting in museum galleries and particularly developments in the use of daylighting in historic and contemporary museum buildings.

Keywords: *Museums, Daylighting, Visual environment, Lighting technologies, Standards*

1 Daylighting Practice in Museums and Galleries: A brief historical overview

The modern purpose-built public museums of the late 18th and early 19th centuries were dependent on daylight from rooflights, windows, domes, and cupolas to illuminate the exhibits for the visiting public. For the display of works of art, top lighting became the norm (Lawrence, 2015, p.1). Top lighting maximised available wall space for exhibits whilst offering a relatively even distribution of illumination, albeit variable depending on outdoor conditions. Lawrence (2015) characterises daylight at this time as a commodity in short supply in the smoke-laden atmospheres of polluted industrial cities. Glass was initially expensive until technological developments allowed the manufacture of affordable larger panes which opened up new architectural possibilities. Techniques were also developed for surface treatments of glass such as grinding and frosting for both decorative and functional purposes. This combined with the use of fabric blinds enabled some control over daylight entering museum interiors.

Developments in artificial lighting technology offered potential societal benefits by allowing public buildings such as museums to open in the evenings or under dull conditions as well as overcoming some of the challenges with the variability of daylight. By the middle of the 19th century gas lighting was employed in some museums, although initially it offered poor quality of illumination relative to daylight. However whilst artificial light mitigated some of the deleterious effects of daylight, gas lighting prompted concerns about risks to human health and to exhibits from combustion products as well as the impact on the aesthetics of artworks for the viewer (Quill, 2019; Swinney, 1999, p.114-5).

Electric lighting offered a less polluting, more controllable and more economical alternative to gas. Technological developments including the introduction of fluorescent tubes to which UV sleeves could be added to limit damage from UV radiation hastened the elimination of natural lighting from museum galleries. This was fuelled by a growing scientific understanding of the degradation of organic and certain inorganic materials through exposure to daylight (Druzik and Eshøj, 2007). Garry Thomson's recommendations on light levels and maximum annual dosages for different sensitivities of materials were widely adopted and went on to influence international lighting guidelines (1978, 1986). Thomson's initial lighting recommendation of 50/150 lux, later refined to 50/200, were set on the basis that 50 lux is the lowest light level at which most people can perceive full colour under incandescent light. Museums generally sought to exclude daylight from galleries and Thomson's recommended levels could be achieved with relative ease using electric lighting.

The publication by the International Commission of Illumination of its guidelines on lighting museum objects in 2004 shifted the focus from illumination levels to total exposure over time, assessing risk from visible and non-visible light as well as considering energy use. LED lighting emerged as the preferred artificial lighting technology for museums, offering greater protection from UV and IR damage as well as energy saving benefits and an ability to mimic daylight. A reassessment of the role of daylight in museums over the past two decades acknowledged the important contribution it makes to the visitor experience as well as to reducing energy costs. Architects began to design contemporary museum schemes which allowed daylight into the building using innovative glazing methods, informed by computer simulation and modelling. Solar screens, new types of filters, shading systems and blind materials were implemented to manage daylight.

2 Daylight and Museum Environments

Lighting and its management is an important activity in museums, which must balance the risk of damage to historic artefacts against the viewing needs of visitors. The appearance of objects to the visitor depends on the spectral power distribution of the light source, the reflection and refraction of the surface of the object, and the response of the human visual system (Druzik and Eshøj, 2007, p.53). Lighting design must take into account a range of possible impacts on the visual system, including glare, reflection, brightness, contrast, adaptation, colour rendering and colour temperature. On the other hand, visible and non-visible light can result in cumulative and irreversible damage to light-sensitive artefacts, including fading, weakening and disintegration, and deterioration resulting from heat. There is now general acceptance that total dosage of lighting relative to the light-sensitivity of materials is more important than prescriptive 'lux laws'. Whilst dosages are relatively easy to predict and control with artificial lighting, more variable and unpredictable daylighting requires different strategies. Various standards and guidelines exist for the management of museum lighting, including IES 1996, CIE 157:2004, CIBSE 2015, but the practical application of these in real-world situations is highly complex. Decision-making must take account of multiple variables, not only preventive conservation requirements and visitor needs, but also costs, longevity, maintenance, energy consumption, aesthetic design etc (Garside et al, 2017). This renders light as arguably the most challenging environmental parameter for museum management.

As noted above, the modern purpose-built museums that emerged in the 18th and 19th centuries were designed to take advantage of daylight for the benefit of the viewing public. Advances in glazing technology and other daylight management strategies were employed to control daylight. Early introductions of artificial light offered a less satisfactory experience. Daylight is understood to offer more favourable viewing conditions for visitors, contributing to feelings of comfort, health and well-being particularly where connections with the outside are made, as well as providing faithful colour rendering. However daylight is also unpredictable and variable in its intensity, colour temperature and spatial distribution so that it is harder to manage in museum contexts. Where museums are housed in historic buildings either purpose-built or adapted for museum use, the building itself may be regarded as worthy of preservation in its own right. In such cases, the daylight qualities of the interiors must be factored into the decision-making process to maintain an authentic experience for visitors as far as possible. Any alterations to the historic fabric in order to manage the lighting of exhibits must be carefully considered, particularly where the historic building has legal protection. Many historic artefacts, especially artworks, were intended to be viewed in natural lighting conditions and this provides a philosophical rationale for the use of daylight in museum interiors.

Until relatively recently historic trends in museum lighting resulted in the elimination of daylight from museums to prevent damage to artefacts. However in the last two decades increasing concerns about climate change has provided an impetus to return to natural light where possible in order to reduce energy consumption and its associated costs. This return to daylight and the implications in terms of current research and practice provide a focus for this review paper.

3 The state of art in day/lighting museums_ literature review

A literature search was conducted online to identify relevant publications on museum lighting practice/research over the last three decades. The search was conducted on the ScienceDirect and Google databases using the search terms 'lighting' and 'museums'. Over 102 papers were found focusing on lighting and museums. The sample was divided between the authors and key articles were reviewed by both authors. Only peer-reviewed journal articles written in English were included in the final review sample presented in this review paper. Other publications including editorials or posters were excluded. Also excluded are conference papers and those which are primarily architectural lighting and design papers and do not address preservation/conservation issues to any extent. As a key selection criterion, focusing the review on the content and the findings of peer-reviewed journals is believed to be essential to identify the trends in daylighting studies and the state of art, emerging knowledge, and research in the field of museum lighting over the selected time period. In line with the criteria stated, the final sample size was adjusted to nearly 70 papers. In reviewing the papers, the following information was identified, collected, and mapped: region of research, museum type, collection type studied, standards and regulations refereed to or utilised, and lighting type (whether natural, artificial or mixed). Given the richness of natural light, the variety of aspects associated with its presence affecting objects and visitors alike, and the overall lighting design practice in museum environments, research on day/lighting in museums could be classified as quantitative and/or qualitative in nature. The qualitative dimension of day/lighting studies is often associated with visitors' 'perception', visual perception of exhibited objects, the quality of the ambient conditions, sense of place, and visual dis/comfort. The quantitative dimension on the other hand is mainly related to the degradation of artefacts, the safety of the lighting conditions, energy efficiency considerations, and compliance with standards. As part of the inspection and mapping of the sample, the focus of the papers was identified by mapping the main issues each paper addressed under the following issues/aspects: preservation, experience, design, lighting technology, and energy efficiency. Table 1 provides an overall view of view the sample, the focus of papers, their scope, and emerging trends.

The analysis of the sample provides interesting observations and insights into the recent publications in the field. Light as a topic/study focus has captured scholars' interest for several decades and this interest has been more evident in recent ten years. The majority of the papers reviewed in the sample were published in the last decade (2010-2021) that is 57 out of 66 (or 86%) with only a fraction around 14% of the sample was published in the 1990s and 2000s. Purpose-built museums and converted heritage buildings covered in the studies are cases mainly situated in geographical regions across Europe and Asia. Only a handful of studies published the findings of buildings located in other geographies (across America and Africa). As anticipated artworks including paintings, sculptures, photographic materials, calligraphy, and archaeological materials were the most studied objects given their sensitivity to the light levels and the impact of the of its rendering quality on the representation of artefacts. In terms of focus and distribution and whether the papers were daylighting-focused studies or artificial lighting-oriented studies, at the first sight, it seems that the number of studies examining daylighting performance of museums, the quality of the visual environment and methods of optimization is fewer than those studies focusing on artificial lighting. However, a further inspection of the content of the dual-focused papers covering artificial and natural light (18 papers) may suggest that the majority of this fraction of the sample was mainly advocating the use of natural light supplemented by artificial lighting. Interestingly this aspect of the analysis looking at the type of lighting investigated and the distribution of the papers is very much a reminder of the endeavour or rather the struggle that often museum personal face between daylighting optimisation and management and ease of use of artificial lighting in a museum highly demanding visual environment.

It is well recognised that Indigenous/ heritage buildings around the globe were often built in response to certain environmental conditions and cultural norms. The majority of these buildings/structures were designed to take advantage of the daylight conditions characteristics of their region (principally relying on daylight as the source of illumination. In converting these heritage assets to museums as a way for extending the lifetime and sustaining their presence/existence, museum personnel/ curators are often faced with the challenge of preserving the authenticity of the ambient lighting conditions and the need to reduce their deleterious impact on the sensitive pieces of the collections. However, the review identified a few interesting cases where the use of recent technological surveying techniques, the integration of shading features, latest glazing types, and in-situ monitoring has helped in preserving the authenticity of the natural light, its presence shaping the character and image of the place while also managing its deleterious effects on the artefacts.

Archaeological on-site museums are a very specific type of museum, where the artefacts are often exhibited in their original site and manlily climatized to certain environmental and daylight conditions. Only one paper was identified among the sample addressing the specificity of these museums and the sensitivity of the objects to environmental and daylight conditions. Unlike objects exhibited in showcases, unearthed objects are exposed to low ambient light levels, and hence the admission of natural light including the direct component of light (sunlight) through the use of skylight could damage these valuable objects. While the presence of a controlled natural light could add to the quality of the exhibit, the understanding of the climatization of artefacts and the context should suggest more settled daylight or lighting strategy/approach

4 Key findings of the review

In addition to the summary provided above, more detailed information about the review findings is given below.

4.1 Quantitative and Qualitative Dimensions of Museum Lighting

The need to balance conservation requirements for objects with visitor comfort and visual perception in relation to colour rendering and colour temperature are common themes in the literature sample. Standards and guidance formalise these requirements with objective industry parameters (Garside, 2017). However an emerging theme in the literature relates to the qualitative aspects of the historic lighting context in which objects were originally experienced (Luengo, 2020; Schielke, 2020). Many objects in museum collections were intended to be experienced or used in particular lighting conditions, and in the case of works of art the lighting environment is of particular importance for the visitor's authentic experience of the work as intended by the artist. The architectural spatial and lighting characteristics of the original context combined with daily and seasonal fluctuations in daylight may all have contributed to this experience. Schielke (2020) proposes that the selected colour temperature and lighting methods should consider the era and historical background in which the artwork was created, such as the daylight or candlelight in the artist's studio (p.22). He argues that where authentic presentation is important the lighting concept should take historical lighting conditions into consideration or risk 'falsifying' the artistic statement (p.23). Luengo's paper on the historic spatial context for the illumination of Baroque paintings uses simulation of the architectural spaces of churches and palaces in which they were displayed to investigate the original lighting conditions (Luengo, 2020). Luengo argues that the lack of attention paid to the original illuminative context means that objects may be displayed inaccurately, and he suggests that contemporary design tastes may take precedence over delivering a more authentic experience. Luengo acknowledges the problems that may arise with this approach and the lack of current research to support it. Advances in lighting studies in the field of architectural history using historical research, in-situ analysis and simulation have much to contribute to this aspect of museum lighting design. Xiangfeng and Shangyu (2021) also highlight the importance of understanding historic lighting contexts in their proposal for optimisation of daylight design for a simulated sculpture exhibition hall. They argue that this understanding is necessary for the appropriate cultural reading of sculpture through illumination of texture and shadow which expresses the three-dimensional form (p.3).

Of equal importance, where objects are exhibited in historic buildings which are of cultural significance in their own right retaining the historic lighting qualities and characteristics of the interiors must be considered as part of the authentic visitor experience, regardless of whether the building is purpose built or adapted for museum use. This is discussed in a number of papers where historic collections are exhibited in historic buildings which in some cases constitute the original display context. Frame et al (2018) examine how the in-situ passive conservation needs of Tudor tapestries hung in the Great Hall of Hampton Court Palace were balanced with retaining the significance and 'sense of place' of the historic interior of the Hall. The Hall's historic leaded stained glass windows and interior illumination were a significant characteristic of the interior but posed a risk to the tapestries from exposure to UV radiation. At the time of publication research was in progress in relation to secondary glazing using advanced materials and techniques as a mitigation measure which would not harm the appearance or fabric of the historic windows and retain the ambient lighting qualities (p.591).

4.2 Integrated research application for the daylighting optimization in museum settings (methods)

The lighting studies examined in this paper demonstrate the use of new technologies in their research methodologies, including simulation and computer modeling. Some papers focus on single issues of object preservation or visitor comfort and perception, whilst others take a multi-objective, integrated approach (Balocco and Volante, 2018; de Graaf, 2014; Leccese, 2020).

Simulation for the optimisation of daylighting is a common research method in the literature sample, generally validated with on-site measurements. Leccese et al's (2020) case study of the Monumental Charterhouse of Calci near Pisa, Italy utilised a novel climate-based daylight simulation and dynamic daylight metrics to assess lighting condition and test the effectiveness of four potential lighting interventions to address conservation and visitor needs. This method, the authors argue, produces reliable results which avoid the need for prolonged measurement campaigns. They note, however, the relative lack of research into the impact of daylight on both object conservation and visitor requirements. Furthermore, Leccese's work is one of a number of studies that draw on climate data to inform the simulation and modeling (see also Pinella et al, 2016; Marzoul, 2020; Brzezicki and Billger, 2021). However this relies on the availability of local and regional climatic and meteorological data to inform the modeling process and ensure the accuracy of the daylighting scenarios. Simulation techniques also offer opportunities to evaluate the potential for restoring natural light into historic spaces housing collections (Berbar, 2015, Pinilla et al, 2016). Fathy et al (2020) demonstrate the use of innovative daylight performance metrics and simulation modelling using pixelated facades for distributing daylight to inform facade design that meets preservation standards and visitor needs. Studies by Zianfeng and Zhu (2020, 2021) adopt simulation methodologies to evaluate possible daylighting scenarios for the exhibition of Chinese sculpture, calligraphy and painting which respond to particular cultural readings of these artworks.

Simulation studies are also used in the literature sample to assess risks of photodegradation (Balocco and Frangioni, 2010) as well as energy consumption in relation to lighting (de Graaf, 2014; Mayorga et al, 2016; Hassanizadeh and Noorzai, 2020). Where visitor comfort or perception is a focus for the research, surveys and questionnaires may be used alongside simulation studies (Zhisheng et al, 2020; Gao et al, 2020). The effect of daylight on the visitor experience is investigated in a number of the papers (Ajmat et al, 2011; Ahmad et al, 2017). Kaya and Afacan (2018) study the effect of daylight design features on visitor satisfaction using a questionnaire and daylight simulation at the Istanbul Modern Art Museum. Their findings show that certain daylight design features (such as location, window size) are important regardless of weather conditions and that glare prevention/control is also crucial in visual comfort. The authors argue that this more 'user-centred' approach to visual comfort and visitor satisfaction is lacking in current design literature,

Some lighting studies adopt experimental methods, particularly with regard to assessing photodegradation and damage risk assessment. Samples of materials are exposed to different light sources under laboratory conditions and any photodegradation is monitored. These studies focus on a limited range of artefact types, including painting pigments, paper artwork, and textiles, and are typically concerned with artificial light sources, particularly LED lighting, rather than natural light (Dang, 2020; Bayev et al, 2019; Luo et al, 2019; Piccablotto et al, 2015). There is evidence in this research that LED lighting can cause some photodegradation despite perceptions of its safety in relation to object preservation, and this is an important area for further research (Ishii et al, 2008; Piccablotto et al, 2015).

Recent research in the literature sample seeks to advance techniques for measuring and monitoring lighting in museums. Nishanova (2018), for example, demonstrates the use of timelapse photography as a method for monitoring fluctuations in daylight and to identify 'hot-spots' within an exhibition room for the placement of data loggers. Mardaljevic et al (2021) implement a novel high-dynamic range camera-based approach for measuring the cumulative daylight dose in historic spaces where artefacts are displayed. These new techniques offer significant potential to enhance the understanding of daylighting conditions in museum environments.

5 Emerging practices and applications_ General Case Studies:

Alongside the case study museums covered in the sample, some of the emerging day/lighting design practices adopted in some of the most prestigious museums in the UK offer practical confirmation of the significance of understating the context and the objects to inform the design approach.

5.1 Victoria and Albert Museum, London

Since 2001 the Victoria and Albert Museum in London has been undertaking a major programme of development called Futureplan. A key goal is to create new galleries whilst also restoring some of the historic character of the Grade I listed museum building, parts of which date back over 150 years. Many of the historic galleries were originally designed to be illuminated by natural light, but during the 1970s windows and skylights were obscured, ceilings lowered and some galleries enclosed in internal white boxes which cut out daylight and other architectural features of the interiors. Gallery refurbishments have sought to reinstate or introduce natural light alongside artificial lighting, thereby revealing the historic beauty of the interiors as well as reducing energy consumption, reconnecting with the outdoor urban setting and enhancing staff and visitor wellbeing. Examples include the Medieval and Renaissance galleries completed in 2009, incorporating the ‘Daylit Gallery’ created from an underused outdoor space, where the natural light was utilised creatively for different atmospheres and dramatic effects appropriate to the theme of the exhibits, and the Europe galleries completed in 2015 which removed internal cladding and revealed previously obscured windows to introduce natural light into the historic interiors

5.2 Mary Rose Museum, Portsmouth

The Mary Rose Museum located in the historic dockyard in the naval city of Portsmouth was completed in 2013 and houses the wreck of a 16th-century warship sunk in the waters of the Solent in 1545 with the loss of 465 crew members. The wreck was raised from the seabed in 1982 along with hundreds of artefacts, and initially housed in a temporary structure. The new museum was designed by Wilkinson Eyre with interiors by Pringle Brandon Perkins+Will. The vulnerable wreck and artefacts required strict environmental controls including daylight regulation. Whilst not all the artefacts are vulnerable to the deleterious effects of daylight, many are highly photosensitive including the wreck itself. In this case natural lighting was excluded throughout despite the potential impact on visitor experience and wellbeing. The designers opted for low level, atmospheric LED lighting which emulated the claustrophobic below-deck conditions of the vessel, with highlighted exhibits and dramatic audio-visual effects to communicate the narrative of the ship and its loss.

Chapter 11 Conclusions

The analysis of the sample provides interesting observations and insights into the recent publications in the field. Light as a topic/ or study focus has captured scholars’ interest for several decades and this interest has been more evident in the last ten years. looking at the type of lighting investigated and the distribution of the papers this aspect of the analysis can be seen as a reminder of the endeavour or rather the struggle that often museum personal face between daylighting optimisation and management on hand and ease of the use of artificial lighting on the other hand in a highly demanding visual environment. Whether the building is purpose-built or adapted for museum use, several authors proposed that the selected lighting methods and colour temperature should consider the era and historical background in which the artwork was created, such as the daylight or candlelight in the artist’s studio. Likewise, where objects are exhibited in historic buildings which are of cultural significance in their own right retaining the historic lighting qualities and characteristics of the interiors must be considered as part of the authentic visitor experience. Alongside the case study museums covered in the sample, some of the emerging day/lighting design practices adopted in some of the most prestigious museums in the UK offer practical confirmation of the significance of understating the context and the objects to inform a better lighting design approach.

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Year			Country/region of first author				Region of research				
1990s	2000-10	2011-21	Europe	Asia	America	Africa	Europe	Asia	America	Africa	Not specific Or general /various
3	6	57	38	21	4	3	23	19	7	2	9
Museum type											
Various (Incl. general, historic or contemporary)	Art museums or gallery	Provincial, state museums or natural history	Historic buildings	Experimental, optical laboratory/chamber, or showcases	Archaeological museum	n/a or unspecified					
6	15	2	14	8	1	4					
Collection type											
various (Incl. skeletons, fossils, life-sized, scale models, and thematic areas), historic house collections	Artworks (Incl. polychrome, paper and silk, paintings, sculptures, photographic materials), sculpture, calligraphy, or artwork and archaeology)	General, and other (Incl. reproduced original paintings, unearthed structures, streets, buildings and drainage systems, frescoes (fresco surfaces), prints of maps)	Textiles (silk fabrics) with natural dyes, tapestries	n/a or not specific							
7	33	7	3	4							
Standards and Regulations											
International and national	Not specific	National (Incl. UNI 10969 Italian standards 2002, UNI 10829, Italian standards 1999)	IEEE802.15.4 standard, ZigBee specification	International (e.g.CIE) Or international + Thomson, ISO Blue Wool standards, Annual exposure limits by IESNA 1996, Heritage Collections Council 2002, Canadian Conservation Institute, 2003, CIE 157, 2004, CIE 157:2004, DIN EN 12464-1 (2011), IESNA							
6	3	5	1	22							
Lighting type											
Natural (Daylighting)	Artificial and natural	Artificial various									
18	18	23									
Issues											
Preservation (Incl. colour, 'colour shift', noticeable change in colour, daylight safety , preventive conservation, tapestry conservation, control object damage)	Issue: Experience (comfort, clarity, colour temp and rendering, psychology, Museum lighting, communication, presentation and perception, good visibility of artifacts, visual discomfort or glare issues, light efficacy and quality, visual perception/'wellbeing' and communication, comfortable light environment, persevering the original the light–space) design, maintaining 'the sense of place'/ aesthetic ambiance)	Issue: Design (e.g. atmosphere and immersion), exhibition lighting design, exhibition and display types, roof design, automatic control of natural and artificial light, daylight design features, natural light restoration design for exhibition spaces)	Issue: Energy Efficiency/saving								
49	47	29	11								
Issue: Lighting technology											
Fluorescent to LED Or LED (Incl, white LED light sources, UV-blocked HA lamp and LED lamps, Commercial white LEDs and a Telelumen multi-LED system	LED; DALI intelligent digital lighting control system	Other (e.g. incandescent and experimental 3 band source)	Halogen or low-voltage (5.5-12 V) and line-voltage (120 V) halogen lamps								
17	1	3	2								

Table 1. Summary of the literature review

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

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Energy efficiency
Standards

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, manage- ment 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.

1. Introduction

Museums are repositories for cultural heritage and are responsible for the care of collections for the benefit of present and future genera- tions. Key to this stewardship role is the management of indoor condi- tions to prevent deterioration of vulnerable objects. Preventive control measures are required to keep the indoor microclimate within conser- vation 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 col- lections. 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 arte- facts 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 man- agement systems in museums fail to respond to adverse and unstable climatic conditions vulnerable artefacts will inevitably deteriorate and

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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 optimization 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 [2,10]. 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. Fig. 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 Figs. 2–5.

The majority of the surveyed articles fall under the first category 'empirical' (N = 38) (Figs. 1 and 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

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	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			

Figure 1.

Fig. 1. Classification of the reviewed papers by. Geography: (Author's Institute-Outer ring, Region of research), Paper type, Collection typology, Standards.

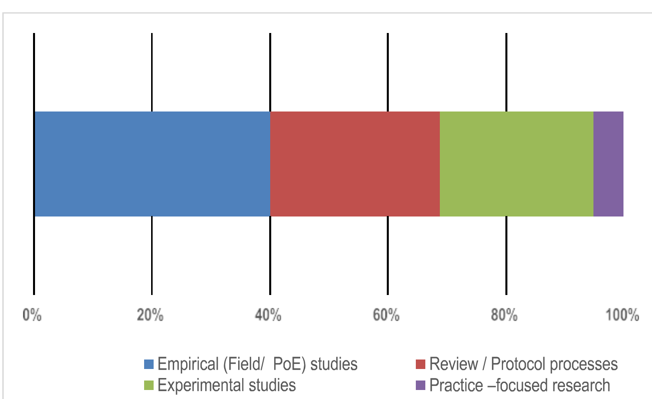

Fig. 2. Classification of the sample by paper type.

Fig. 3. Materials/Collection Type covered across the sample.

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) [32,63,64], 'simultaneous performance index' (SPI) [67] together

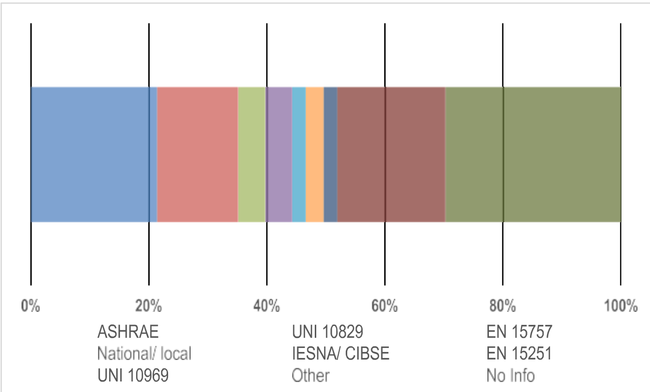

Fig. 4. Standards refereed to across the sample.

Fig. 5. Regional distribution of papers in the sample (distribution by lead author's institution and by region of the study).

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: 18–24 °C, 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 (Fig. 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.

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 Terracotta 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 h 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 min. 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 24 °C can only be delivered with the provision of air conditioning during the summer period. Recorded temperature values varied on average from 17 to 28 °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 (Fig. 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).

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 (Fig. 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. Mun- do-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].

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 contextualized targets for a certain region [11, 105,106]. 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 16 °C < T < 25 °C, 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 A), 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 been 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 acclimatization, 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 contextualized and more tailored standards across different regions.

Chapter 12 Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Professor Hisham Elkadi reports financial support was provided by The Arts and Humanities Research Council.

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Chapter 14 Appendix A. Supplementary data

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Managing microclimate challenges for museum buildings in Egypt

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abstract

Global challenges of climate change, environmental control, and energy conservation are persisting. In museum buildings, facing these challenges is prominent to achieve the sustainability of our cultural her- itage. Controlling the microclimate of the indoor environment in exhibitions where artefacts are con- served, stored and exhibited is a critical challenge that faces museums not only in Egypt but worldwide as well. The aim of this paper is to analyze the main operational practices for rational envi- ronmental control that consider preservation and conservation requirements. In order to achieve the objective of this paper, a literature review of recent papers discussing this problem has been performed and analyzed. Then, a survey was conducted to analyze the operation practices in museums in Egypt. At last, environmental assessment criteria were suggested to manage the museum indoor environment to conserve energy and preserve artefacts. The findings of this paper could guide those involved in decision making and setting legislations in Egyptian museums.

1. Introduction

The change in climatic conditions documented over the past dec- ades is mainly a reaction to the human intervention of the climate system [42]. As a result of climate change, the amount of precipita- tion increased, the sea level arose, and the climatic zones shifted. This led to variation in the relative humidity content, which in turn increased the risk of unfavorable indoor microclimate that can dam- age the building and threaten the culture heritage [19].

Egypt is vulnerable to risks of climate change. It is characterized by hot and dry climate as most of its land is desert, the exception is in the Mediterranean coast which can be semi-arid. In the period between 1961 and 2000, the average maximum and minimum temperature increased with a rate 0.34 °C and 0.31 °C per decade. The Intergovernmental Panel on Climate Change (IPCC) reported that Egypt will become hotter and drier [10]. According to Domroes and El-Tantawi [9], there was a warming tendency across the stations all over Egypt from 1971 to 2000 which affected neg- atively the air quality and increased the heat stress on buildings. Projected temperature reported that it increased around 3–3.5 °C over Egypt [15]. In museum buildings, this problem was more seri- ous as it had an effect on the valuable collections inside. The impli- cations of climate change influenced the microclimate of the artefacts and could cause damage to them. Nevertheless, the impact of climate change was not the same on all buildings, it relied largely on its location and construction properties. Climate change models were developed to predict the extreme and average upcoming environmental conditions [5,21,46]. Adaptations were then needed to be made to reduce the risks of climate change on museums buildings according to the surrounding conditions.

Due to the fact that the museum environment was complex in its nature and that it could not be simplified in a single set of requirements, there had been an immense increase in awareness worldwide about controlling the museum indoor environment to conserve the artefacts during the past forty years [47]. Accordingly, applying environmental control system was essential to stabilize museum's displays. The complexity of complying with the require- ments of various artefacts at various seasons and weather patterns impede a successful preservation. Facing these challenges, environ- mental control with a monitoring and evaluating system was essential to detect and measure all environmental aspects of the

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indoor conditions. This helped also in the documentation process which was particularly important not only for preventive conservation, but also for the intervention process [1].

In this paper, it is aimed to analyze the environmental control procedures that are followed in six Egyptian museums and to reflect on the measures needed to be taken. Thus, a comprehensive literature review of recent papers discussing the problem has been performed to understand the challenges facing the future energy demands in Egyptian museums. Then, a survey was conducted on six museums to investigate the applied control strategies. After- wards, the authors proposed assessment criteria for exhibition spaces to collect environmental data about the museum exhibi- tions. It aimed at identifying the current status to build on, detect changes and act upon for planning further possible interventions and corrective actions.

2. Climate change and museums

Earth's climate was changing in response to an array of harmful emissions, which was a result of human activity, especially, the release of greenhouse gases. Changes to the carbon cycle were geologically significant, their effect may likely include higher temper- atures, reduction of polar ice cover, modified precipitation and biotic patterns [26]. These variations could leave a serious impact on the built environment. According to various studies, buildings were assessed according to performance indicators, such as space heating and cooling loads, as well as, the risk of overheating [35]. In 2015, Paris agreement adopted to set the specific goal of pur- suing efforts to limit warming to 1.5 °C by 2030, in addition to increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emis- sions development. The key to achieving that near future ambition was the actions taken by subnational and non-state actors, includ- ing regional and local governments and businesses. Enhanced monitoring and reporting of non-state actions and the resulting emissions' reductions were essential aspects to making pledged actions transparent and credible [45].

2.1. The impact of climate change on museums

Weather patterns and temperature variations affected the long- term preservation of the world's cultural heritage, and artefacts. Threats of climate change left an impact on both indoor and out- door environments. In museum buildings, it is essential that the designer should be careful about the physical and chemical param- eters that influence the museum building envelop, the exhibited collections and also the visitors [38]. If environmental control pro- tocols to museum artefacts were ignored, this would lead to a tremendous effort exertion in order to meet their preservation requirements. Bertolin [6] has presented several studies that showed the significant impact of climate change on collections and heritage buildings. The museum regulations and design stan- dards should always stay up to date. So, in order to remain effec- tive, an adaptation plan to the changing climate is a must for historic buildings, public monuments and archaeological sites, keeping in mind that such needs come at great cost; therefore, it must be well-planned in advance. Accordingly, the development of more efficient, affordable, and environmentally sustainable sys- tems was more important than ever [20].

Huijbregts et al. [19] suggested a simulation approach for assessing the impact of climate change on typical museum objects situated in historic buildings. They applied the expected future outdoor climatic data to simulate indoor environmental condition and they found an increase in indoor temperature and relative humidity (RH) which had the highest damage risk on the artefacts.

2.2. Climate change projections in Egypt

Egypt is situated in a location that is influenced by many factors as landscape and different low–high pressure areas, where they contribute into dividing Egypt into distinguished climatic regions. Egypt's Northern region enjoys a Mediterranean climate while the rest of Egyptian land lies in the dry arid region. The climate is generally hot and dry in the summer and moderate in winter with little rain which increases on getting near to the coast. Accordingly, Egypt is highly vulnerable to climate change impacts. According to the Intergovernmental Panel on Climate Change (IPCC), Egypt's Nile Delta is one of the world's three ''extreme" hot- spots where future projections indicate that Egypt will suffer from sea level rise, water scarcity, increase in the frequency and inten- sity of extreme weather events such as heat waves, flash floods, heavy rains, sand and dust storms [39].

These changes might lead to possible deteriorations on both indoor and outdoor environment, especially, in the domain of Egyptian museums indoor conditions throughout its different cli- matic regions. This by default can leave an impact on the environ- mental monitoring strategies. There should be an effort on developing a microclimate that suits each collection specific typol- ogy and needs in order to achieve artefacts preservation, energy conservation and human comfort [25,43].

Environmental aspects that were affected severely by climate change were temperature and relative humidity (RH) [38]. They should be controlled and stabilized over time for artefact preserva- tion while keeping thermal comfort and energy use to the mini- mum. It was reported that higher temperature caused an increase in the evaporation rate and molecular movement leading to structure disarrangements of fiber materials [17]. A survey was conducted by the Grand Egyptian Museum- Conservation Center (GEM-CC) showing severe cases of deterioration that they received resulted from high temperature and RH as shown in Fig. 1. The sur- vey confirmed that the environmental factors; temperature and relative humidity were the main factors for the organic object's deterioration causing oxidation, fractures and cracks [1].

3. Approaches for environmental control

There were general guidelines for environmental control that considered objects sensitivity requirements and users comfort; however, they only counted for the effect of single parameters and not for their cumulative effects. This emphasized the signifi- cance of preventive conservation as a holistic approach that con- sidered sustainable principles for energy and cost without risking objects requirements and comfort needs [31]. Applying methods and procedures for controlling microclimate inside the building is a challenging task consisting of interrelated factors. The specific nature of the building construction, its geographic location, the context around the building, as well as the internal loads of light- ing and visitors were all changing factors that contribute to the fluctuation of the indoor conditions. This differed from one build- ing to the other located in the same city. So, a deeper level of inves- tigation should be assigned to ensure the efficiency of the applied environmental control systems for hygrothermal risk management in museums [13]. In this section, energy strategies and monitoring methods suggested for museums were presented to analyze their potentials in extrapolating their results to other cases in Egypt. Several studies provided a guidance in assessing the indoor envi- ronmental conditions of museums and advocates for monitoring environmental conditions to identify abnormalities and to control them [7,14,16,31,32].

Fig. 1. Negative Impacts due to high fluctuation in temperature and Humidity and poor storage conditions a.Oxidation and carbonization (Textile). b. Fractures (Ivory). c. Cracks, deformation and weakness (Composite Material) [1].

3.1. Energy efficiency

Environmental control systems not only to ensure the safety of the artefacts from environmental conditions, but also to minimize the energy consumption and thermal comfort. Energy strategies adopted in museum buildings were related to building design as well as the operation of the HVAC system which controls temper- ature, relative humidity, and air quality in the indoor space. It should be adapted according to thermal loads in order to keep the levels of these parameters to the accepted defined ranges. Thermal loads were caused mainly by either the outdoor condi- tions, equipment or the number of visitors inside the space. The challenge of creating a good indoor environment for artefacts and visitors is in reducing the energy consumption needed to maintain both criteria. Deploying efficient HVAC (heating, ventila- tion and air conditioning) system that respond to space require- ments while minimizing energy consumption was inevitable for the sustainability of results. In addition, studying the influence of local climate where the building situated was vital, and the set points should be adjusted based on the outdoor climate for reduc- ing consumption [23].

Schito, Conti, Urbanucci, and Testi [44] applied multi-objective optimization for the control of HVAC strategy in a museum in Pisa, Italy to find the best control strategy. Three objectives were con- sidered in a pareto front optimization; energy saving and visitors' thermal comfort, without the compromise of artefacts preserva- tion. Simulation results showed an improvement compared to applying a typical fixed point. Zaki, Khalil, Bialy, and AbdelMak- soud [48] studied the implementation of HVAC system in Tutan- khamun gallery in the Egyptian museum. They conducted a CFD simulation to compare between natural ventilation and the use of HVAC system inside the gallery regarding energy savings and satisfying museum standards. Elhariri and Taie [12] developed a prediction model for the indoor environmental conditions using algorithms of machine learning. They aimed to introduce an energy-efficient HVAC control strategy that maintains preventive conservation requirements as well as visitors' comfort. The key benefit of applying this model was predicting the future indoor temperature, RH, CO_2, and light, thus avoiding possible sensor nodes failure and controlling HVAC system in an efficient way. The model triggered the HVAC system to work only when abnor- mality in indoor conditions was predicted.

Rick Kramer, van Schijndel, and Schellen [24] studied the effect of changing set points for temperature and RH instead of focusing on the HVAC system itself. Using a simulation-based approach, twenty locations of different weather conditions were investigated under six different levels of climate control that follow the arte- facts class categorization by AHSRAE [4]. Then, they developed a set point algorithm to adjust the temperature and RH values across the seasons in respect with artefacts and thermal comfort needs, and the relative energy savings reached up to 74%. In [23], they found that allowing temperature to float during closed times with- out letting any fresh air (100% recirculation) was the best strategy experimented for saving energy.

Other studies focused on energy reduction through daylight. It was important to consider the illumination requirements for each material type and minimize the exposure to light to prolong their lifetime. In case of natural light, it provided better color rendering and visual comfort; however, the problem lied in the UV rays that causes more damage to objects. So, integrating movable shades to have full control of the amount of light was important to get ben- efit from daylight [36]. Also, energy savings through the use of LED lights was investigated which showed reductions in annual energy consumption, energy cost, and maintenance cost, and CO_2 emis- sions [41].

Lucchi [29] suggested SOBANE strategy (screening, observation, analysis, expertise) for evaluating environmental, energy perfor- mance and human comfort in museums. This strategy is initially proposed in [34] as a risk-prevention strategy to make preventive actions faster and more effective. In [29], it was adapted to aid decision makers in finding the optimal plan for actions related to energy and environmental management. The first level was screen- ing in which museum performance was assessed. Performance assessment of current situation required accurate data collection. The second level was the observation level for detection of risks causes based on the primary assessment which were then quanti- fied through the acquired measurements in the analysis level. Lastly, the expertise level was providing guidelines for solutions to energy, environment and human comfort. Lucchi [30] presented a simplified evaluation method considering the screening method where environmental as well as energy performance were assessed. It was then applied to 50 museums in different countries in Europe. Cacace, Giani, Giovagnoli, Gordini, and Nugari [8] pro- posed a methodology to collect data regarding the museum envi- ronment and to evaluate environmental conditions in exhibition and storage areas. They described a web-based tool that allowed to search, manage and analyze internet-intranet data which was used together with the ''Conservation Condition Data Sheet'' that accompanies the object.

A special attention should be paid to historic buildings where the required interventions could be difficult and limited. So, risk assessment and adaptation measures should consider the impact of these interventions including socio-environmental related pro- cesses and practices as well as the impact of climate change [18]. Thus, reiterations of risk assessment could be useful for updating corrective actions and analyzing the risks related to them over time [30]. Lucchi [32] assessed the environmental risks for a museum in Italy through applying an operative strategy showing the possible compatibility between conservation and human com- fort. Nevertheless, deploying HVAC systems were not enough to ensure the stability of indoor microclimate environment. A moni- toring system that controls the operation of HVAC and light system was playing a vital role in making the system efficient.

3.2. Monitoring strategies

Monitoring and controlling the indoor microclimate of muse- ums and showcases inside was extremely important to minimize the harmful effects of environmental factors including tempera- ture, relative humidity, light, and pollutants. Environmental mon- itoring dashboards gained an increasing importance as they easily allowed checking on the adjusted values. On the long term, they provided conclusions on seasonal variations to adjust the operation of the control system accordingly. Studies emphasized on wireless sensor monitoring, remotely accessible and real-time control interface to ensure ease-of-use and high accuracy results while avoiding technical problems [2,3,28].

There were key features required in the monitoring dashboard to make it a user-friendly prototype. Basically, visual elements like charts, graphs were essential to express trends of data. Real-time data with notifications or alerts received promptly was vital to resolve issues and reduce damage risks. This brought the need of remote access to these data through smart phones and the web. Options of filtering data with date range selector gave possibility to compare data and metrics with different time periods. Also, the option to export results in readable format was essential [33]. Lombardo et al. [27] proposed a new system architecture for real-time monitoring of microclimate in museum environments which was deployed in the museum of faculty of Art of Sohag uni- versity. Alsuhly and Khattab [2] developed an Internet of Things (IoT) based system for controlling and monitoring indoor museum environment. They provided a unique feature that allows data pro- cessing to be done at two levels: locally for quick actions to respond to time critical situations and globally for data storage and analysis through a cloud.

3.3. Countries involved in preventive conservation

Upon studies by [31], in terms of preventive conservation appli- cation in museums regarding; environmental agents of deteriora- tion, damage preservation, environmental monitoring, and other aspects that were in direct contact to museum environments; it was concluded that Europe was considered as the main contributor of publications by 74.5%, whereas America 18.2% and other inter- national publications 7.3%. Italy was considered as the main con- tributor to publications in the previously mentioned domains by a 40.2%. It was followed by Great Britain (26.8%), Greece (3.7%), Denmark (3.7%), Sweden (1.2%), France (7.3%), Norway (1.2%), Spain (1.2%) and Germany (1.2%), not to mention the contribution of European standards and directives in the general domain of pre- ventive conservation by a (13.4%). Upon these statistics, further investigation trials were performed regarding the domain of pre- ventive conservation and environmental monitoring in Egyptian museums.

4. Challenges in the Egyptian museums' operation

Egypt is characterized by its great heritage and large collections of artefacts that narrates the civilizations it passed by. There are dozens of museums all around Egypt which encompasses valuable artefacts that need high attention regarding environmental condi- tions. However, not all these museums are built to suit this func- tion. In addition, they may lack a proper monitoring and environmental control system to overcome the fluctuations of inside temperatures and humidity, light and air quality. This can return to the lack of resources and skill limitations. In museums, it is important to provide a well-designed exhibition spaces and controlled environment for the artefacts to protect them from damage. Moreover, it is equally important to monitor the con- trolled space to ensure that it maintains the preservation require- ments. This is especially when the building is not equipped with HVAC system.

In the Grand Egyptian Museum Conservation Center (GEM-CC), the theoretical studies have recommended that in order to pre- serve the artefacts made of various materials, and in different con- ditions; it was essential to adjust some parameters such as light, standard temperature, relative humidity and pollution [1]. Other museums may not have the facilities or the capacity to apply envi- ronmental control. Various cases of deterioration were reported from the environmental conditions and pollutants.

In this regard, it was essential to study the current challenges that faces Egyptian museums to achieve the sustainability of our cultural heritage and artifacts. It was needed to check if any of the environmental control procedures were applied to control the microclimate of the indoor environments in exhibitions. Between over hundred museums in Egypt, a selected sample was investigated which enclosed twelve museums distributed across the country. Then, a survey was conducted on six museums located in upper and lower Egypt as shown in Fig. 2, which were built or renovated during the last 20 years, and were originally designed to function as a museum specified as a historical or archaeological museum.

A questionnaire, as shown partially in Fig. 3, was designed to figure out what were the means of applied operations in the selected Egyptian museums. It was divided into 6 sections; whereas section 1 was for general information that was related to the personnel answering the questionnaire. Section 2 was con- cerned with general information about the museum itself, such as the museum's name, type, location, date of establishment or renovation, governing body, daily working hours and the types of exhibits displayed. It was also concerned with the methodology of fixation of the exhibits, their condition and if there were any reg- ulations related to controlling the number of visitors per exhibition space or not. The last question in this section was mainly involved with whether the museum was indeed applying a certain environ- mental control system or not. As for section 3, it was mainly con- cerned with the museum's lighting; inquiring whether the museum was following luminance values or not, if UV filters were installed to the existing luminaries and if the halls were provided with natural lighting or not. Section 4 was concerned with the museum building envelope; from opening treatments and glazing

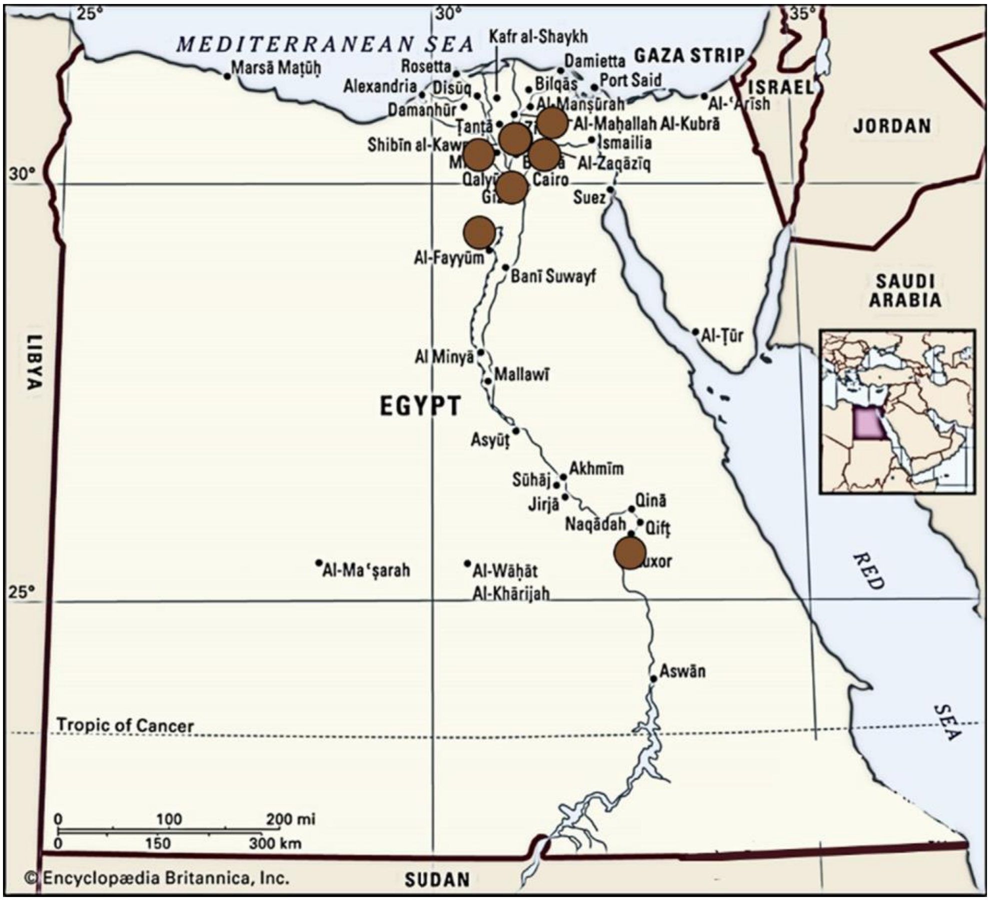

Fig. 2. The map of Egypt with illustrated locations of six studied museums. Source: adapted from Britannica Encyclopedia.

to the building insulation. Regarding section 5 and section 6, they were related to active and passive techniques respectively. The importance of these aspects have been previously highlighted in the aforementioned literature for risk management in museums. Thus, the questionnaire was targeting to give a clear picture of the museum management procedure.

Answers to the designed questionnaire were analyzed, then questions were simplified and further developed into an environ- mental assessment sheet; indicating the environmental perfor- mance of museums related to artefacts preservation, energy saving, and comfort level. Therefore, a checklist was designed to rate exhibition spaces based on the building and space level. This can act as a risk assessment to pinpoint the problems existed and corrective actions needed to be taken by the museum manage- ment. The checklist was a form of a yes or no answers so it cannot indicate the quality of the applied systems; however, it provided an overall view about the eligibility of the space and the building. As shown in Table 1, the proposed Environmental Assessment Sheet (EAS) was concerned mainly with general points regarding the building, whether there were staff training, periodic mainte- nance, and public involvement or not. As for the space level, it focused on finding if the basic requirements for artefacts exist, which were HVAC system, lighting control, pest control, and mon- itoring system.

4.1. The Egyptian museum

The questionnaire was sent to one of the curators working in the Egyptian museum which is considered to be a history and archaeology museum, located in Greater Cairo. It was established with a governmental governing body. The museum's working hours were 10 hours per day. Most of the exhibits were discursive (static 2D and 3D), some others were interactive and immersive.

The exhibition scenario was designed to be a mix between a combined and an idea based approach that might be related to a certain timeline. The exhibits were displayed in various means ranging from showcases, fixed to base and fixed to walls. Most of the displayed exhibits were in good condition and when any dete- rioration was detected, the case would be investigated and the rea- son to that would be reported.

The museum had no monitoring system for environmental con- trol and the factors behind that were the lack of resources and organizational or communicational challenges. As for the museum lighting, the museum depended mainly on natural lighting in most of the exhibition halls. Curators in the museum tried to control the ranges of natural light exposure. As for the artificial lighting lumi- naries, they were not equipped with UV filters.

Windows of the building were mostly opened all the time; with a single pane glazing type. Regarding the building's insulation, there was no type of insulation installed. HVAC system was installed only in specific galleries [48]. Accordingly there were no control for indoor environment in terms of temperature and rela- tive humidity except in those galleries.

4.2. Islamic art museum

An interview was held with the director of the conservation department of the Islamic art museum. The Islamic art museum is an art museum, located in greater Cairo and was established in 1881 then renovated and opened to the public by 2010. The museum has a governmental governing body. The daily working hours of the museum were 8 hours, where most of the artefacts

Section 2: General about the Museum	علم بخصوص المتحف
2.13. Do you apply a Monitoring system for Environmental Control in the museum?	هل لديكم انظمة لرصد التغيرات في الظروف البيئية داخل مبنى المتحف؟
o Yes نعم	o No لا
If yes What are the measurements taken? ما هي طبيعة القياسات التي يتم رصدها؟	**If No** A. What are the factors hindering the application of applying a monitoring system? ما هي الظروف والعوامل التي تحول دون تطبيق أنظمة رصد؟
o Temperature درجات الحرارة o RH- Relative Humidity الرطوبة النسبية o Carbon dioxide levels مستويات غاز ثاني اوكسيد الكربون o PM - Particulate Matter o Motion detection رصد الحركة o Light intensity مستويات الاضاءة	o Lack of resources نقص في الموارد o Technical & sociotechnical اسباب تقنية o Physical space الفراغ بشكل عام o Organizational or Communication challenges تحديات منظمية o Regulations ضوابط
	B. What is the frequency of taking the readings? إلى اي مدى زمني يتم متابعة القراءات الناتجة عن الرصد؟ o Hourly على مدار الساعة o Weekly بشكل اسبوعي o Monthly بشكل شهري o Other اخرى

Section 3: Concerning the Museum Lighting	بخصوص الإضاءة داخل مبنى المتحف
3.1. Are the required illuminance values in museums taken into consideration or not?	هل يتم مراعاة قيم الاضاءة المسموح بها داخل المتحف؟
o Yes نعم Please state the ranges used يرجى توضيح نطاق القيم المستخدمة	o No لا
3.2. Are the luminaires equipped with UV filters?	هل يتم تركيب فلاتر للأشعة فوق البنفسجية بوحدات الاضاءة؟
o Yes نعم	o No لا
3.3. Are there any exhibition halls that are provided with natural light?	هل يتم استخدام الاضاءة الطبيعية في صالات العرض بالمتحف؟
o Yes نعم	o No لا

Section 4: Concerning the Museum Building Envelope		بخصوص الغلاف الخارجي للمبنى المتحفي
4.1. What is the shading system installed on the windows?		ما هي طبيعة عناصر التظليل المستخدمة على نوافذ الاضاءة؟
o Louvers كاسرات شمسية	o Perforated screens الواح مفرغة	o Other, please mention أخرى ، يرجى التوضيح
4.2. What is the type of the glazing mounted?		ما هو نوع التزجيج المستخدم بالنوافذ؟
o Single pane احادي التزجيج	o Double pane ثنائي التزجيج	o Other, please mention أخرى ، يرجى التوضيح
4.3. Is there any insulation installed in the building envelope?		هل تم تركيب اي من انواع العزل للغلاف الخارجي للمبنى؟
o Yes نعم		o No لا

Fig. 3. Sample of the questions in the designed questionnaire.

were discursive (static 2D and 3D). The approach to the exhibition scenario was an idea-based approach relying on a specific timeline. The means of exhibits display varied from showcasing to fixed-to- base and fixed-to-wall. A few fabric based exhibits had a bad con- dition due to the focused artificial light on them, but rather than that, most of the exhibits were in good conditions. There were no regulations related to controlling the number of visitors per exhi- bition space.

The applied monitoring system was installed for certain types of showcases, and specifically to monitor the changes on tempera- ture, relative humidity and light. The readings were usually recorded on a monthly basis. The monitoring system used for envi- ronmental control was not up to date with the latest technologies due to the lack of resources and it has stopped working due to maintenance issues.

The museum's artificial lighting system were halogen lamps with no specific ranges of illuminance provided. There were also no UV filters installed to the lighting fixtures which led to the appearance of colour fading to a group of books. Most of the exhi- bition halls were exposed to natural lighting through the building's

Table 1
Environmental Assessment Sheet (EAS) for Exhibition Spaces.

		YES	NO
Building Level			
Name:			
Location:			
Surrounding Context:			
Management policy			
	Staff Training	h	h
	Public Involvement	h	h
	Periodic Maintenance	h	h
Building Envelope		h	h
	Insulation	h	h
	Openings with shading systems	h	h
	Glazing with UV filters	h	h
Score			
Space level			
Space ID:			
Space Dimensions:			
Orientation:			
Objects Conservation			
	HVAC system	h	h
	Set points for Temperature and RH follow preservation standards	h	h
	Adjusted along seasons	h	h
	Turned off in closing time	h	h
	Show cases available for special care	h	h
	Light Control	h	h
	Illuminance levels follow preservation standards	h	h
	Sensor based	h	h
	Luminaires equipped with UV filters	h	h
	No Direct Sunlight	h	h
	Pollution and Pests	h	h
	Natural ventilation avoided	h	h
	Traps for pests	h	h
	Sealed windows	h	h
	Visitors control	h	h
	No Equipment that generate heat	h	h
Monitoring System			
	Temperature	h	h
	Relative Humidity	h	h
	Light	h	h
	UV-rays	h	h
	CO2	h	h
	Air Particulate Matter (PM)	h	h
	Sound	h	h
	Motion detection	h	h
Score			

openings and due to museum open plan distribution. A mesh per- forated screen was installed to the building openings which dis- persed natural light rays; decreasing the change of getting hit by direct sunlight as shown in Fig. 4. The windows of the building itself were glazed with a single pane glazing.

A central HVAC system was installed and worked for 8 h daily, but there were no different set points for cooling and heating per exhibition space and the control settings of the HVAC system did not have any differences concerning seasonal variations through- out the whole year.

4.3. Luxor museum

According to El-Gohary, Marouf, and Metwally [11], Luxor museum reported that rising temperatures and RH and having a percentage of pollutants affected negatively wooden bases and sped up the deterioration of organic materials and stone. Neither monitoring devices nor filters were used to control those damages inside the museum. The questionnaire was sent to one of the museum curators in order to get acknowledged of how the museum is operated. The Luxor museum is a history and archaeol- ogy museum, located in upper Egypt. It was established in 1975, under a governmental governing body. The exact working hours of the museum were not declared. It hosted discursive artefacts (Statics 2D and 3D). The artefacts' allocation approach was a mix of a scenario-based approach and environmental control-based approach. An allocation scenario was developed to fit with the timeline of the artefacts taking into consideration the environmen- tal aspect as shown in Fig. 5.

The museum exhibits were displayed in showcases, some were fixed-to-base or fixed-to-wall. The conditions of the exhibits in dis- play were well preserved, but if a bad condition case was discov- ered; restoration regulations were followed. There were no regulations declared related to controlling the number of visitors per exhibition space. The museum has a monitoring system for environmental control, with a wide range of measurements for; temperature, relative humidity, light intensity and UV-rays treat- ments. These readings were taken regularly on weekly basis.

As for the lighting of the museum, ranges of luminance mainly relied on the type and the composition of the artefact; each had its own allowed ranges of illumination, but the actually used ranges were not declared. Luminaries were not equipped with UV filters and no exhibition halls were provided with natural lighting. So, most of the museum halls were always lit by artificial lighting.

The museum building envelope clearly had no shading system installed on the windows, where the glazing used throughout all the openings were double-paned. An HVAC system was installed to the museum with no set-points neither for cooling nor for heat- ing. Switching on the AC depended mainly on the working hours of the museum. The control settings of the AC system did not differ throughout the different seasons of the year. The museum did not depend on natural ventilation, but if used there was no means to control neither temperature nor relative humidity.

4.4. The Egyptian textile museum

The questionnaire was sent to the director of the Egyptian tex- tile museum which was considered to be a history and archaeology museum, located in Greater Cairo. It was established between 2000 and 2010 with a governmental governing body. The museum working hours were 8 hours per day. Most of the exhibits were dis- cursive (static 2D and 3D).

The exhibition scenario was designed according to an idea- based approach that might be related to a certain timeline. Most of the exhibits were displayed in showcases preventing visitors from touching so as not to damage the displayed objects. There were a few recorded cases of deterioration with undeclared reasons.

The museum had a monitoring system for environmental con- trol, which was mainly involved with relative humidity measure- ments conducted on daily basis. However, the lack of resources may hinder the advancement of the monitoring system.

As for the museum lighting, the luminance levels were not con- sidered for sensitive materials like textiles, which might be greatly affected by different levels of illumination. The luminaries of arti- ficial lights used inside the exhibition halls were equipped with UV- filters, while natural lighting was not used inside the exhibi- tion halls. Windows of the building were completely closed all the time; with a single pane glazing type. Regarding the building's insulation, there was no type of insulation installed. Active strate- gies such as an HVAC system was installed which was working

Fig. 4. Islamic museum showing the books had color fading (left), showing the screens put on the building windows' and separate showcases (right). Source: Researchers.

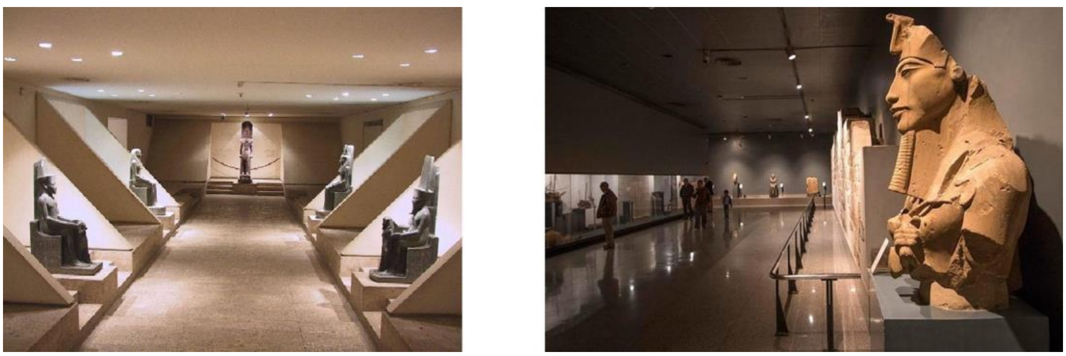

Fig. 5. One of the exhibition halls with exposed statues allocated according to a scenario-based approach (Left), one of the exhibition halls with both exposed statues and showcased artefacts allocated according to a mix between a scenario-based approach and an environmental control one (right).

Fig. 6. The museum building approach (left), the main interior exhibition hall, showing the different types of artefacts present in the museum (right).Source: Researchers.

8 hours per day with control settings that differ throughout the dif- ferent seasons across the year.

4.5. Fossils and climate change museum

Based on an observational visit to the fossils and climate change museum shown in Fig. 6, which is one of the natural history muse- ums in Egypt, located in Upper Egypt, the questionnaire was filled. The museum was established between 2010 and 2020 with a gov- ernmental governing body. The museum working hours were 10 hours per day where most of the artefacts were discursive (sta- tic 2D and 3D).

The exhibition scenario was designed to achieve an open stor- age visual approach. Artefacts were displayed in showcases, fixed-to-base and fixed-to-wall. Most of the displayed exhibits were in good condition and well preserved, where there were no recorded cases of deterioration.

The museum did not have a monitoring system for environmen- tal control, this was due to the lack of resources. As for the museum's lighting, the illuminance values were not taken into consideration with no UV filters installed to luminaries used. Nat- ural lighting was provided in some of the exhibition halls, without the use of any shading elements fixed to the building's window openings. The glass used was double pane glazing.

There was an HVAC system that typically worked for about 12 hours per day. The control settings of the HVAC system did not differ throughout different seasons of the year. There were no passive strategies applied at the museum for controlling the temperature and relative humidity; only active strategies repre- sented in having an HVAC system.

4.6. The national museum of Egyptian civilization

The national museum of Egyptian civilization museum lied under the category of history and archaeology museums. It was located in Greater Cairo – Egypt, and it was established between 2010 and 2020; under a governmental governing body. The Museum's working hours were 8 hours per day, housing discursive artefacts.

The exhibition scenario was an open storage-based approach, where some exhibits were displayed inside glass showcases as shown in Fig. 7. Most of the artefacts were well preserved. There were no regulations related to the number of visitors per exhibi- tion hall. Regarding environmental control aspects, the museum did not apply any monitoring systems, and that was due to regula- tion matters.

There were no illuminance values considered, and the luminar- ies were not equipped with UV-filters. There were no exhibition halls that were provided with natural lighting. The building envel- ope was well insulated. One of the applied active strategies that was the HVAC, mostly switched on for 8 hours per day with no dif- ference in set points with respect to seasonal changes.

5. Discussion

Based upon the previously studied cases of museums in Egypt; a comparison was held between them to reach an understanding of the Egyptian museums' operation and risk assessment. Six muse- ums were surveyed. Some of them were in greater Cairo, others were in upper Egypt, and it was possible to see how museum cura- tors and directors deal with different environmental conditions in the surrounding context. The museums had different exhibitions display scenarios. These scenarios were categorized into four approaches as shown in Fig. 8; idea-based approach, object- based, combined and open storage approach. In the object-based approach, exhibits were selected from the collection and arranged while paying attention to their environmental requirements for light, temperature and humidity according to the objects type and sensitivity. The idea-based approach presented exhibits sepa- rately with a certain scenario for enhancing visitors' experience and space perception. Whereas in the combined approach, exhibits were selected and displayed according to a certain exhibition sce- nario while paying attention to their preservation requirements. In the open storage approach, exhibits were arranged without previ- ous selection as all objects were displayed all the time. About 43% used the combined approach between the artefacts allocation according to a certain timeline or type, in addition to taking the environmental aspect into consideration. Whereas, 57% were either following an idea-based approach or an open storage

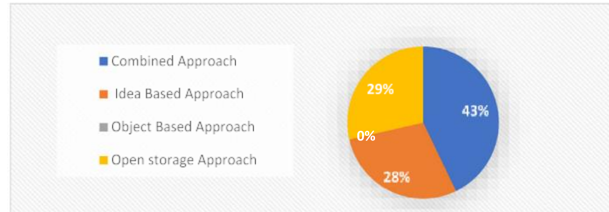

Fig. 8. A comparison for the adopted display scenario in the studied museums.

approach. Exhibits that needed special care in showcases were well preserved in most cases.

Due to lack of resources and regulations factors related to the governing committee, 80% of the studied museums had no moni- toring systems for environmental control. About 60% did not follow the illuminance standards recommended for sensitive materials. Whereas, all the museums' luminaries were not equipped with UV filters. Regarding the usage of natural light in the exhibition halls; only one museum which was the Islamic art museum allowed controlled natural light to enter the museums' exhibition halls, through a mesh screen that was installed at each and every opening. Fossils and climate change museum, as well as, the Egyp- tian civilizations museum were the only museums in the studied cases that had a building envelope insulation installed. That gave us a percentage of 60% of the studied museum sample with no insulation, and the rest 40% were well insulated from outside envi- ronmental conditions. The entire studied sample of museums had an installed HVAC system. However, only one museum which was the Egyptian textile museum had control settings and set points that differed from season to season throughout the whole year while other museums did not change their control settings which implied an excessive use of energy consumption.

According to the undertaken survey and its results illustrated in Fig. 9, corrective actions were needed for environmental control. Before applying any environmental strategy and taking decision for any intervention plan, assessment of the current situation of the building was required. The evaluation was suggested here to be on the scale of the space to ensure the efficiency of the applied system as one strategy might be the best for one space but not for the other.

It is evident form the results that most of the studied museums lacks a monitoring system for preventive conservation. Maceli et al. [33] reported the problems experienced by practitioners in environmental monitoring which were related to 1) technical, socio technical problems like sensor failures, poor interpretation of data, unawareness of technical options, useless device alerts in unstaffed locations. 2) lack of resources; budget limitations and

Fig. 7. One of the showcases hosting pottery works (left), one of the exposed artefacts composed of wood (right).Source: Researchers.

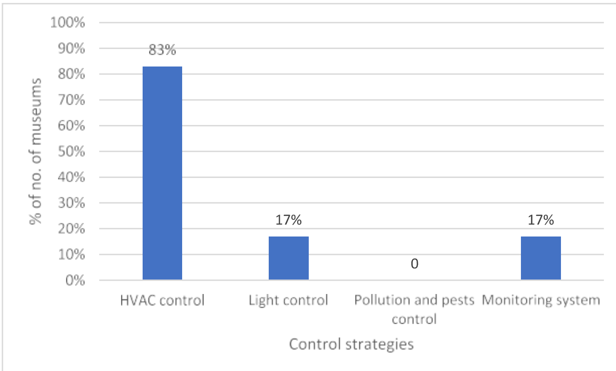

Fig. 9. The percentage of the surveyed museums that applied environmental control strategies.

unskilled staff 3) physical space; limitations in sensors placement, changing physical space, large devices obscuring object display, 4) Data context; variances on data can be hard to explain, 5) Commu- nication with other stakeholders for required actions, 6) Organiza- tional; facing staff resistance in complying with environmental procedures, and integrating sustainability practices within profes- sional guidelines. The aforementioned factors could be faced in the Egyptian context so more investigation was required for each case to find the exact reasons hindering the adoption of environmental monitoring. Osman [40] addressed the problems for conservation management for heritage buildings in Egypt and proposed amend- ment plans. Further research should focus on this issue to find solutions that can overcome the limitations and challenges faced in museums in Egypt.

A successful example that was recently designed and con- fronted serious challenges was the Grand Egyptian Museum (GEM). The whole collection of King Tutankhamun was displayed in the GEM after being transferred from the Egyptian museum in El-Tahrir. This specific collection comprises of about 5640 pieces of different materials having different conservation needs. They were transported to the conservation center in the Grand Egyptian museum (GEM-CC) where they were preserved. GEM-CC was com- pleted and opened in 2010 which hosted the whole collection of Tutankhamun providing an appropriate environment for its preservation and proper conservation treatments. Kamal, Elkhial, and Tawfik [22] have presented a survey on the collections' mate- rial and their condition, then they assessed the risks and damage resulted from the previous location. They also reported on the pre- ventive conservation actions fulfilled in designing the new location of the collection.

The materials and conditions of the objects were investigated and documented. About 59% of the objects were inorganic, they showed signs of the least deterioration as they were composed of chemically stable substances, like gold, rocks and stones. However, metals and alloys undergone some corrosion patterns. Whereas, the organic objects which represented about 24% of the collection were found to be the most deteriorated due to improper former display or storage conditions. The rest 17% of the artefacts were composite materials. They were most prone to damage as they consisted of different materials and possibly have different response to environmental conditions [22].

In GEM, an HVAC system was designed to provide stable tem- perature ranges from 21 to 25C° for 3 m height inside the space and relative humidity ranges from 35% to 55% taking into account the impact of the visitors. The building was well sealed to keep the conditions of the space within the desired range after turning the HVAC off besides, temperature and RH were monitored to control unlikely fluctuations. The operating system in GEM was designed to employ HVAC system only during opening hours for achieving visitor's comfort, while using passive RH buffer and humidity absorbers in the showcases besides the active RH system for poor conditioned objects. Lighting was also considered in GEM. Light was one factor that triggers irreversible damage to the artefacts which can be caused by all wavelengths of light and the scale of influence depends on the sensitivity of objects and duration of exposure [37]. So, in GEM, the collection was categorized into three groups based on their sensitivity of light; highly sensitive, moder- ate, low. The strategy aimed to decrease both light intensity and duration of exposure to light especially for the highly sensitive materials. Besides, high-efficient lighting fixtures were installed. At night indirect wall and ceiling lighting can illuminate the gallery with 10–50 lx in addition to remotely controlled lighting in the showcases. Besides, Lighting fixtures in the GEM had the highest efficiency of LED technology and color rendering index > 90/95/97 for better visual comfort [22].

6. Conclusions

The problem of climate change causes extreme weather condi- tions that have not existed before. Increasing temperatures to unprecedented values is now a fact that form a stress on museum's energy operational budget. Resulted fluctuations in temperature and humidity can cause severe damage to the artefacts. Climate change not only affect the temperature, but also it can worsen the air quality inside the museum spaces and increase pollution rate. Therefore, the microclimate should be continuously moni- tored and controlled as damages occur when the system fails to respond to such fluctuations. Reaching a stable indoor environ- ment that meet the requirements of artefacts as well as visitors' satisfaction with the least energy consumption is the optimal required objective. An adaptation plan should be developed to effi- ciently operate the buildings in respect of preventive conservation, energy efficiency and human comfort.

Preserving artefacts from the outside harsh conditions is con- sidered a main function of museum buildings. Besides, they pro- vide their visitors the artistic pleasure and useful information about the displayed artefacts. Both visitors' comfort and artefacts preservation requirements should be considered while designing or adapting museum spaces. The environmental control process is concerned with adjusting principal factors; temperature, relative humidity, light, and pollution. The accepted ranges depend on the material type of the objects and their conditions. A case by case analysis ensure minimizing any further damage that could happen due to environmental factors.

Monitoring and controlling museums indoor environment are crucial for achieving the function of the museum. In Egypt, there are several climatic regions that impose different preservation requirements and continuous monitoring of their environment. In addition, the context of the building for example whether it is located in a dense urban area of high pollution rate or beside a waterfront are all significant factors affecting the microclimate.

Tight climate guidelines may lead to huge energy consumption. To ensure that what is designed is working on the real ground, a monitoring system that detects any malfunction should be a part of the space. However, challenges in environmental monitoring are experienced widely and hence preventive measurements should be reflected.

To conclude, climate change problem and other challenges that may face Egyptian museums should be handled through preven- tive conservation plan. Aside from developing standards that are convenient to prolong the lifetime of the artefacts, we suggest here an environmental data sheet to assess any exhibition space in museum buildings in a simple form of a checklist. Combined with the conservation data sheet for each object, it acts as a simple evaluation method to rate the status of the space and management procedures to find if it is convenient to house the intended arte- facts or not. A data entry form will be developed later via the inter- net to facilitate the use of the EAS allowing the analysis of data combined with the condition data sheet of each object displayed in the space.

Declaration of Competing Interest

The authors declare that they have no known competing finan- cial interests or personal relationships that could have appeared to influence the work reported in this paper.

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