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Innovative and affordable service for PC monitoring of individual Cultural Artefacts during display, storage, handling and transport

Compilation Document

Establishing common language and concepts to be used in the CollectionCare project

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Abstract

This compilation document reports on the baselines and starting points from which the development of the different elements of CollectionCare system will begin and establishes the language and concepts to be used during the whole project.

The document covers the state of the art concerning preventive conservation and the related international standards on temperature, relative humidity, radiation, air pollution and vibrations for cultural heritage collections, as well as the European standards on microclimate field monitoring. Previous and present object- or collection monitoring systems are reported as well, to outline the starting points on preventive conservation monitoring systems, on which the CollectionCare system will be developed.

The various material types chosen for CollectionCare (canvas paintings, metal, paper, and wood) are described with a focus on their structure and degradation phenomena, as well as related degradation models. This is followed by a presentation of state of the art of the technical aspects of CollectionCare, such as sensors, wireless technology, cloud computing and user interfaces with a first approach to how the CollectionCare product can be designed.

Abbreviations and Acronyms Glossary

AB	Advisory Board
AES-CBC	Advanced Encryption Standard-Cipher Block Chaining
AH	Absolute Humidity
AIDIMA	Technological Institute of Furniture, Wood, Packaging and Allied
AP	Air Pollutants
API	Application Programming Interface
ASHRAE	American Society of Heating, Air- Conditioning and Refrigerating Engineers
ATOS	Atos Spain SA
AWS	Amazon's Web Services
BDA	Big Data Analytics
BLE	Bluetooth Low Energy
CA	Consortium Agreement
CASC	Cloud API Service Consistency
CBC	Conservazione Beni Culturali Soc. Coop.
CCI	Canadian Conservation Institute
CE	Conformité Europée ne (European Conformity)
CEC	Climate Evaluation Chart
CEN	European Committee for Standardization
CES	Consumer Technology Association
CENELEC	European Committee for Electrotechnical Standardization
CFS	Costs for certificates on financial statements
CH	Cultural Heritage
CKAN	Comprehensive Knowledge Archive Network
CO	Confidential
CPU	Central Processing Unit
CSV	Comma Separated Value
CULTURARTS	Culturarts – Generalitat (former Institut Valencià de Cultura)
CWITT	Low Cost and low Energy GNSS-based Wireless Tag for asset Tracking and monitoring
D	Deliverable
DBMS	Database Management System
DDBB	Databases (computer)
DCAT	Data Catalog Vocabulary
DESCA	Economic, Social, Cultural and Environmental Rights
DFA	Diputación Foral de Álava
DM	Dissemination Manager
DMP	Data Management Plan
DOC	Document file format
DP	Dew point
DRIVER	Digital Repository Infrastructure Vision for European Research
EC	European Commission
ECCN	Export Control Classification Number
ECDSA	Elliptic Curve Digital Signature Algorithm
EM	Exploitation Manager
EMCC	Electromagnetic Compatibility Certification

EMC	Equilibrium moisture content
EPS	Encapsulated PostScript
EU	European Union
FAIR	Findable, Accessible, Interoperable and Reusable
FTIR	Fourier-transform infrared spectroscopy
FM	Frequency modulation
GA	Grant Agreement
GHz	Gigahertz
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPRS	General Packet Radio Service
GSM	Global System for Mobile communications
GUI	Graphical User Interfaces
HDFS	Hadoop Distributed File System
HTTP	Hypertext Transfer Protocol
HVAC	Air conditioning systems
HvK	Hizkia Van Kralingen
HW	Hardware (computer)
Hz	Hertz or cycles per second
IaaS	Infrastructure as a Service
ICCHT	International Conference on Cultural Heritage and Tourism
ICCROM	International Centre for the Study of the Preservation and Restoration of Cultural Property
ICCTMHS	International Conference on Cultural Tourism, Museum and Heritage Studies
ICOM	International Council of Museums
ICOMOS	International Council of Monuments and Sites
ICT	Information and Communications Technologies
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IEEE	Istoriki Ethnologiki Etaireia Elladas
IIC	International Institute for Conservation of Historic and Artistic Works
IMU	Inertial measurement unit
IoT	Internet of things
IP	Intellectual Property
IPCE	Institute of Cultural Heritage of Spain
IPR	Intellectual Property Rights
IRP	University Institute of Heritage Restoration
ISCR	Instituto Superiore per la Conservazione ed il Restauro
ISM	Industrial, Scientific and Medical
ISO	International Organization for Standardization
IT	Information Technology
ITACA	Institute of Information and Communication Technologies
IVC	Institut Valencià de Cultura – Filmoteca Valenciana
JPG	Joint Photographic Experts Group
JSON	JavaScript Object Notation
KADK	Det Kongelige Danske Kunstakademis Skoler for Arkitektur, Design og Konservering

KMKG	The Koninklijke Musea voor Kunst en Geschiedenis
KPI	Key Performance Indicator
L	Light
LA-ICP-MS	Laser Ablation Inductively Coupled Plasma Mass Spectrometry
LED	Light-emitting diode
LOI	Letters of Intents
LoRa	Long-Range
LoRaWAN	Long-Range wide-area network
LPWAN	Low-power wide-area network
LQI	Link Quality Indicator
LSIWC	Latvijas Valsts Koksnes Kimijas Instituts
Lux	Lumens per square meter
Lx*h	Lux multiplied by hours
M	Milestones
m	Month
MBDAaaS	Model Based Big Data Analytics-as-a-Service
MBytes	Megabytes
MC	Museum Committee
MHS	Monitoring Heritage System
MHz	Megahertz
MISRA	Motor Industry Software Reliability Association
MIUR	Ministero dell'Istruzione, dell' Università e della Ricerca
Modbus	Modicon serial communications protocol
MQTT	Message Queue Telemetry Transport
MR	Mixing Ratio
μW/lm	Micro Watt per Lumen
NADFAS	National Association of Decorative & Fine Arts Societies
NB-IoT	Narrowband-Internet of Things
NFC	Near Field Communication
NICAS	Netherlands Institute for Art and Science
NKF	The Nordic Conservation Association
NoSQL	Not only Structured Query Language
NOX	Nitrogen oxides: Nitric oxide (NO) and nitrogen dioxide (NO2)
NWO	Netherlands Organization for Scientific Research
OA	Openly Accessible
OAML	The Ethnographic Open Air Museum of Latvia
ODM	The Association of Danish Museums
OPD	Opificio Pietre Dure
OTA	Over-the-air
PAB	Project Advisory Board
PALS	Positron Annihilation Lifetime Spectroscopy
PC	Preventive Conservation
PCA	Principal component analysis
PCB	Printed Circuit Board
PCDP	Project Communication and Dissemination Plan
PDF	Portable Document Format

PS	Postscriptum Pliroforiki Epikoinonias Epe
PU	Public
QR	Quick Response
Ra	Radiation
R	Report
RDBMS	Relational Database Management System
RDC	De Danske Kongers Kronologiske Samling
REST	Representational state transfer
RF	Radiofrequency
RFID	Radiofrequency identification
RH	Relative Humidity
ROI	Return on Investment
RoMM	Review of Material Modelling
RSSI	Received Signal Strength Indication
SAXS	Small-Angle X-Ray Scattering
SB	Secure Boot
SC	Steering Committee
SEM	Scanning Electron Microscopy
SFU	Secure Firmware Update
SGF	Sigfox Wireless SA
SH	Specific Humidity
SLKS	Department of Castles and Culture
SPI	Serial Peripheral Interface
SQL	Structured Query Language
SSH	Social Science and Humanities
T	Temperature (Air Temperature)
TByte	Terabytes
TC	Technical Committee
TEI	Technological Educational Institute of Athens
TEM	Transmission Electron Microscopy
TIFF	Tagged Image File Format
TM	Technical Manager
TRL	Technology Readiness Levels
Ts	Surface temperature
TU/e	Technische Universiteit Eindhoven
UART	Universal Asynchronous Receiver/Transmitter
UI	User Interfaces
UX	User Experience
UNB	Ultra-narrow band
UNESCO	The United Nations Educational, Scientific and Cultural Organization
UPV	Universitat Politècnica de València
URO1	Sapienza Università di Roma
UV	Ultraviolet
UW	University of Warsaw Biological and Chemical Research Centre
V	Vibrations

W	Watt
WiFi	Wireless Fidelity
WP	Work Package
WS	Workshop
XCT	X-Ray Computed Tomography
XLS	Excel Spreadsheet
XRF	X-Ray Fluorescence Spectrometry

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1. Introduction

This report is part of the CollectionCare project, Horizon2020 Grant Agreement number 814624 with the overall aim to develop an Innovative and affordable service for preventive conservation monitoring of individual cultural objects during display, storage, handling and transport.

This report represents deliverable 1.1. (D1.1.) with due date end of month 4, (June 2019). The aim of D1.1. is to make a compilation document with the technical language and concepts used by each discipline represented in the project, in order to establish a common baseline to be used during the whole project. The report is carried out during work package 1 (WP1) "Definition of CollectionCare system requirement", and will be used as a baseline document for the development of CollectionCare system in WPs 2-4.

WP1 and D1.1. is led by KADK and D1.1. will be disseminated at a public level.

D1.1 defines the baseline and starting point for the CollectionCare project and suggests possible directions to take the collaboration. According to the work package description of WP1 in Grant Agreement, the report is the result of task 1.1., which has the main objective to put in common, with all project partners, the baselines and starting points from which the development of the different elements of CollectionCare system will begin. Information and knowledge is therefore compiled from all partners.

In this report, as well as in the CollectionCare project as such, we work with a unified use of terminology for conservation of cultural heritage as described in CEN standard EN15898 Conservation of Cultural Property - Main general terms and definitions, 2011. Page numbers mentioned in this section refer to this standard. *Cultural heritage* is explained as "tangible and intangible entities of significance to present and future generations. *Object* is described as single manifestation of tangible cultural heritage" (page 7) but it is noted that "The term "object" is used in this standard as a common denominator for cultural heritage, both immovable and movable. In specific professional contexts, other terms may be used: e.g. "artefact", "cultural property", "item", "ensemble", "site", "building", "fabric"." Therefore, some chapters and reports in this project may use the word artefact. *Conservation* is explained as "measures and actions aimed at safeguarding cultural heritage while respecting its significance, including its accessibility to present and future generations" (page 10). In this project the term conservation will be used. *Preventive conservation* is "measures and actions aimed at avoiding or minimizing future damage, deterioration and loss and, consequently, any invasive intervention" with the note that "in the field of movable heritage, "preventive conservation" is generally indirect; namely, these measures and actions are carried out within the immediate environment of the object" (page 10-11).

Structure of the D1.1. report

Based on the formal requirements and intentions for this deliverable, it consists of an introduction to the state of the art for climate standards for collections of cultural heritage (CH) as well as specific recommendations for each of the chosen object types. Descriptions of the five chosen environmental parameters (T, RH, Ra, AP and V) and an overview of the related standards are provided, as well as standards on microclimate field monitoring. The included preventive conservation standards are international standards such as CEN standards and ISO standards, supplemented by guidelines, which have become internationally known and recognized, such as the ASHRAE Handbook chapter 23 and the guidelines from Garry Thomson's book "The Museum Environment". National standards are only included when specifically relevant.

The sections about international standards are followed by a presentation of previous and present object- or collection monitoring systems. Furthermore, descriptions of the four chosen object types (canvas paintings, metal objects, paper objects and wooden objects) and their related degradation models are given.

Following object types, a presentation of the technical possibilities and considerations for the CollectionCare product are presented in the chapters on sensors, wireless technology, cloud computing and user interfaces.

At the end of each chapter in the document, there is a list of literature used.

2. Preventive conservation – standards and regulations for environmental parameters

For CollectionCare five various environmental parameters were selected: Temperature (T), Relative Humidity (RH), Light (L), Air Pollution (AP) and Vibrations (V). Regarding light in museums and collections, both visible light and UV radiation are important parameters and therefore the term Radiation (Ra) will be used in the following, as it covers both types.

For T and RH it is worth specifying that one cannot speak of avoiding or minimising the amount of T and RH in the same way as with radiation, air pollution and vibration. T and RH are parameters influencing the environment at all times with impact on the cultural heritage objects. From a collection risk and deterioration perspective, T and RH only pose a risk of deterioration, if we speak of incorrect T and incorrect RH, being either too high, too low or too much fluctuation.

Speaking of incorrect T and RH, all of the five parameters stated above can be described as 'agents of deterioration' to museum objects; a concept which was introduced by the Canadian Conservation Institute (CCI 2019). The five parameters have been widely discussed by conservators and other museum professionals throughout the years, and this is, among others, reflected in environmental guidelines and standards on the subject.

Because of the importance of compliance with the standards and regulations for preventive conservation of objects in the CollectionCare project, the development of standards and regulations in general, will be shortly summarized in the following.

Introduction to international standards and recommendations

Until the 1970s, the guidelines and recommendations for the museum climate were primarily based on observations and experiences and were often determined by e.g. the capacity of the heating systems, available light sources or economic constraints. Usually there was no specifics or real data as to how the earliest recommendations were derived. It is only relatively recent that research has provided a general scientific basis for determining appropriate values for the museum climate (Erhardt et al., 2007).

By the 1960s and 1970s specifications for the museum climate were demanded in connection to building new museums and the consciousness of the importance of the 'environmental impact' on cultural heritage introduced a broad discussion on museum climate and 'environmental management' in the 1970s and 1980s (Michalski, 1993; Lucchi, 2018).

In 1978, Gary Thomson's book 'The Museum Environment' was released. The book played a unique role in the early days of environmental standards, as it examined and presented the available knowledge and scientific evidence and provided the basis for preventive conservation of cultural heritage. Thomson's book is considered to be the source of the '20/50' standard, which was taken up as the unchangeable point of reference for many museums and international standardisation committees all over the world. With these strict and fixed target levels of 20°C and 50% RH for the museum environment, many museums and galleries followed a policy of close control of environmental conditions in order to minimise damage to the objects in their care. (Henderson & Dai, 2012; Lucchi, 2018; Erhardt et al., 2007; Bickersteth, 2014; Atkinson, 2014).

At that time there was no real alternative to Thomson's book (Henderson & Dai, 2012), but later on more scientific research was conducted, which resulted in the publication of more specifications and guidelines on museum climate.

In 1999 The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) published a book, which contained a chapter dedicated to Museums, Galleries, Archives and Libraries (ASHRAE 2015).

In the first edition of the book, the parameters considered were temperature and RH, while the revised edition incorporated issues on pollution. Instead of rigid values, the ASHRAE introduced four allowable intervals with different indoor conditions and exposure durations related to the sensitivity and the fragility of objects. The ASHRAE guideline introduced the concept of 'adaptive comfort' as a balance between conservation and comfort requirements. It also changed the perspective of preventive conservation, remarking the importance of the environmental design and management procedures (Lucchi, 2018). The ASHRAE Handbook is edited every fourth year.

In 2004 a technical committee (TC 346) was established under the framework of the Comité Européen de Normalisation (CEN), or European Committee for Standardisation, with the main objective 'to develop, with a need-based approach, specific normative documents in the field of conservation of cultural heritage'. One of five working groups within the technical committee was 'CEN/TC 346 Environment'. The objective of this working group was to formulate specifications, measurements and methods to control the environment of collections, historic houses and outdoor monuments (Johnsen, 2012). From this working group three standard documents are selected for CollectionCare (see table 2.1), whereas one is about lightning for indoor exhibitions.

In addition to the European Committee for Standardisation (CEN), there is also the International Organisation for Standardisation (ISO), which have contributed with standards especially related to archive and library materials.

In 2009, the National Museum Directors' Conference (NMDC) of the UK published in draft the 'Guiding Principles for Reducing Museum's Carbon Footprint', which were agreed by the International Group of Organizers of Large-Scale Exhibitions, the Bizot Group. Their aim was to encourage museums to adopt a less energy-intensive approach to care and loan of collections to reduce their carbon footprint and energy use, and they proposed to do so by relaxing environmental standards (Staniforth, 2014; Atkinson, 2014; Bickersteth, 2014).

In 2014, two of the largest international conservation organisations, International Institute for Conservation of Historic and Artistic Works (IIC) and International Council of Museums – Committee for Conservation (ICOM-CC) respectively, worked together on a common set of environmental guidelines called 'The IIC/ICOM-CC Declaration on Environmental Guidelines'. These common guidelines arose from the wish by both professional conservation organisations to show leadership on an issue which has caused some division within the profession and accordingly some confusion in the wider museum sector (Bickersteth, 2016). The IIC/ICOM-CC Declaration on Environmental Guidelines refers to three sets of guidelines from the Bizot Group, AIC and AICCM respectively.

In the last two decades, the museum microclimate has been discussed in two important conferences: the 'Museum Microclimates' conference held in Copenhagen in 2007 and the 'Climate for Collections – Standards and Uncertainties' conference held in Munich in 2012 (Padfield & Borchersen, 2007; Ashley-Smith et al., 2012).

The very strict control of the museum environments, e.g. in maintaining the '20/50' standard, may require considerable use of energy. Today it is the general perception that, in the long term, such tight control is expensive, difficult to achieve in many cases and unsustainable (Atkinson, 2014). There has been a growing movement towards green/sustainable museums, where indoor museum environments are managed in a responsible and efficient manner, especially in terms of reducing energy consumption and carbon emissions, while at the same time maintaining high standards of collection care (Bratasz, 2012). This is reflected in more relaxed recommendations in the most recent guidelines, starting with the Bizot group in 2009 onwards.

Based on the above introduction 10 standards or guidelines have been found relevant for CollectionCare. They will be presented in the following Table 2 In the following sections 2.1 - 2.4 the standards and guidelines will be explained and compared in relation to the specific environmental parameter.

Year	Source/standard number	Title
1986	Garry Thomson Second edition (Book)	The Museum Environment
1999	American Society of Heating, Refrigerating, and Air-Conditioning Engineers Inc. (ASHRAE).	Chapter 23: Museums, Galleries, Archives, And Libraries
2009	The Bizot Group (NMDC)	Guiding Principles for Reducing Museum's Carbon Footprint
2010	EN 15757	Conservation of Cultural Property – Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials
2010	ISO 4866	Mechanical vibration an shock – Vibration and evaluation of their effects on structures
2014	IIC/ICOM-CC	Declaration on Environmental Guidelines
2014	CEN/TS 16163	Conservation of Cultural Heritage – Guidelines and procedures for choosing appropriate lighting for indoor exhibitions
2014	Wei, W., Sauvage, L. & Wölk, J.	Baseline limits for allowable vibrations for objects. In: ICOM-CC 17th Triennial Conference. Melbourne.
2016	ISO 11799:2015 (second edition)	Information and documentation – Document storage requirements for archive and library materials
2018	EN 16893:2018	Conservation of Cultural Heritage – Specifications for location, construction and modification of buildings or rooms intended for the storage or use of heritage collections

Table 2. Chronological overview of important guidelines and international standards related to control of environmental parameters (T, RH, Ra, AP, V) for conservation purposes of the collections.

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Staniforth, S. (2014). Environmental conditions for the safeguarding of collections: Future trends. Studies in Conservation, 59(4), pp. 213-217.

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2.1 Temperature and Relative Humidity

Incorrect temperature (T) and relative humidity (RH) are critical parameters in environmental diagnostics as they play a key role in all the deterioration mechanisms affecting cultural heritage (Camuffo, 2014). Since temperature governs the relative humidity behaviour, the two environmental parameters are discussed together in this section.

The relative humidity is the ratio (expressed as a percentage) between the mass of water vapour, present in a volume of atmosphere, to the largest amount possible of the same variable at the same temperature and pressure (WMO 1966). RH represents the actual degree of saturation of the pure water vapour. It is expressed on a percentage scale from 0% i.e. dry air, to 100% i.e. saturation of pure water vapour (Erhardt & Mecklenburg, 1994; Staniforth, 2006; Thomson, 1986).

Another definition of the relative humidity is the ratio between the partial pressure of the water vapour and its saturation vapour pressure (condition of saturation of pure water vapour). The latter depends exponentially on the temperature, justifying the inverse relationship between RH and T. If temperature decreases and the moisture content of the air remains the same, the RH rises, and vice versa. RH is also controlled by the amount of moisture dispersed in the air (namely the Mixing Ratio (MR) of moist air). If the moisture content changes, but the temperature does not, the RH can change (Staniforth, 2006).

The indoor climate is subject to a continuous and wide variability. T and RH are the most relevant control variables in the conservation of objects housed in museums (Camuffo, 2006). Objects, depending on their material and age, react to trends and fluctuations in temperature and relative humidity. The response of materials, which is a form of adaptation to climate variability, may be harmful for the internal stresses of objects or for other potential causes of damage (Becherini et al., 2010).

Some museum objects are displayed in display cases or microclimate frames to protect the objects against the detrimental effects (e.g. dimensional changes) of incorrect RH fluctuations or other unwanted impacts. If the air volume is small compared to the volume and mass of a hygroscopic object within the well-sealed enclosure, the actual influence of RH fluctuations will be tiny, since the air volume holds minimal amounts of water (vapour) in comparison with the water contained in the object itself. With only tiny amounts of water being exchanged between the air volume and the object, the resulting dimensional change will be tiny as well (Camuffo et al. 2000)

When the RH is too high or too low, or if it fluctuates very often (either on a daily or seasonal basis) and space gradients are experienced as well, it can be potentially harmful for many objects collected in museums, as RH affects deterioration mechanisms which are mainly the biological, chemical and mechanical degradation.

At high RH (usually above 75%) and with T above 20°C, there is a real risk of biological and microbiological damage, as the colonization and growth of microorganisms and insects' habitat are favoured (Sedlbauer, 2002; Erhardt & Mecklenburg, 1994; Staniforth, 2006; Thomson, 1986).

RH together with T influences chemical degradation of most types of materials, as many chemical reactions depend on the presence of water (or high RH). Furthermore, chemical degradation is increased with increased T. To cite a few, the corrosion of metals is favoured by elevated RH, while organic and hygroscopic materials (e.g. canvas, paper and wood) are strongly affected by high RH, resulting in fading, loss of strength, crosslinking and hydrolysis (Erhardt & Mecklenburg, 1994; Thomson, 1986).

In hygroscopic organic materials, T and RH fluctuations cause dimensional changes with internal strain and stresses. The material structure of this type of objects favours the exchange of vapour and heat between the material and the surrounding air. This may cause changes in the moisture content inside the materials that consequently will undergo changes in their dimensions and, hence, in their mechanical properties. At low RH, materials may lose ductility, shrink, stiffen, and become less able to withstand deformation. A consequence of these changes in mechanical properties is fracture sensitivity or embrittlement and in worst cases direct physical damage such as cracking and breaking of materials. At high RH organic materials swell and some materials such as glue lose strength. (Erhardt & Mecklenburg, 1994; Staniforth, 2006).

Most mechanical damage is due to RH fluctuations and can especially be severe in objects composed of different materials (composite objects) which react differently to the changes in RH and are not free to expand or contract. An example of this is canvas paintings.

It is common practise in the museums to set up temperature ranges at the comfort level for visitors. This range is relatively narrow and therefore the relative humidity is the most fluctuating parameter of the climate inside museums (Erhardt & Mecklenburg, 1994). However, temperature can seriously have a direct effect on collections. Indoor temperature can increase (e.g. due to the heating system, mass tourism, warm outdoor climate, and the use of electric light sources incandescent lamps), causing adhesives to fail and in general increases the rate of chemical degradation. On the contrary, cold temperatures can cause materials to become more brittle and even cause breakage (Staniforth, 2006).

When it comes to storage buildings the climate and recommendations can be slightly different, as one does not have to apply temperature ranges to a human comfort level.

The safety range of relative humidity and temperature beneficial for the conservation of preserved objects in museums and storage facilities are issues that are widely addressed in the field of preventive conservation.

In the following section, selected standards and guidelines for T and RH in collections on display and in storage buildings will be presented.

Standards and guidelines on temperature and relative humidity suitable for conservation purposes of the collections

Table 2.1 gives an overview of selected standards related to temperature and relative humidity to minimise degradation of objects in collections of cultural heritage. It shows the recommended values and ranges.

Specifications and standards generally consider three principal temporal components of the indoor climate (T and RH): long-term average levels, usually the annual average, seasonal cycles and short-term fluctuations (Bratasz, 2012). This is shown in Table 2.1.

Year	Source or standard number	Temperature (°C)	Relative humidity RH (%)			Remarks
			Long-term level	Seasonal cycle	Short-term fluctuations	
1986	Garry Thomson *The Museum Environment* Second edition (Thomson 1986)	Winter 19 °C ± 1 Summer up to 24 °C ± 1	50 or 55% The level may be fixed higher or lower, but for mixed collections should be in the range 45-60%	No specification	± 5%	Class 1 – appropriate for major national museums, old or new, and also for all important new buildings
		Should be reasonable constant to stabilise RH	40-70%			Class 2 – to avoid the major dangers while keeping cost and alteration to a minimum. For example important historic houses and churches.
1999	American Society of Heating, Refrigerating, and Air-Conditioning Engineers Inc. (ASHRAE). Chapter 23 Museums, Galleries, Archives, and Libraries (ASHRAE 2015)	Between 15 and 25 °C ± 5 in seasonal cycle ± 2 in short term fluctuations	50% (or historic annual average for permanent collections)	No change	± 5%	Class AA – no risk of mechanical damage to most artefacts and paintings. Some metals may degrade if 50% RH exceeds a critical RH. Class of control: Precision control, no seasonal changes.
		Between 15 and 25 °C + 5 and –10 in seasonal cycle ± 2 in short term fluctuations	50% (or historic annual average for permanent collections)	± 10% or no change	± 5-10%	Class A – Small risk of mechanical damage to high-vulnerability artefacts. No mechanical risk to most artefacts, paintings, photographs, books. Class of control: Precision control, some gradients or seasonal changes.
		Between 15 and 25 °C +10 in seasonal cycle, but not above 30°C ± 5 in short term fluctuations	50% (or historic annual average for permanent collections)	± 10%	± 10%	Class B – Moderate risk of mechanical damage to high-vulnerability artefacts, tiny risk to most paintings, most photographs, some artefacts and books. No risk to many artefacts and books. Class of control: Precision control, some gradients plus winter temperature setback.
		Between 15 and 25 °C - Rarely over 30, usually below 25	50% (or historic annual average for permanent collections)	Within 25 to 75% year-round	Within 25 to 75% year-round	Class C – High risk of mechanical damage to high-vulnerability artefacts, moderate risk to most paintings, most

Year	Source or standard number	Temperature (°C)	Relative humidity RH (%)			Remarks
			Long-term level	Seasonal cycle	Short-term fluctuations	
						photographs, some artefacts and books. Tiny risk to many artefacts and books. Class of control: Prevent all high-risk extremes.
		Between 15 and 25 °C	50% (or historic annual average for permanent collections)	Reliably below 75%	Reliably below 75%	Class D – High risk of sudden cumulative mechanical damage to most artefacts and paintings because of low-humidity fracture, but avoids high-humidity delamination and deformations. Mold growth and rapid corrosion avoided. Class of control: Prevent dampness.
		-20°C ± 2	40%	± 10%		Archives, libraries. Cold store. Chemically unstable objects usable for millennia. RH fluctuations under one month do not affect most properly packaged records at these temperatures.
		10°C	30-50%			Archives, libraries. Cold store. Chemically unstable objects usable for a century or more. Such books and papers tend to have low mechanical vulnerability to fluctuations.
		No specification	0-30% RH not to exceed some critical value, typically 30%			Special metal collections. Dry room.
2009	The Bizot Group (NMDC 2019)	16-25°C (stable temperature)	40-60% (stable RH)		± 10% (per 24 hours)	For many classes of object(s) containing hygroscopic material (such as canvas paintings, textiles, ethnographic objects or animal glue)

Year	Source or standard number	Temperature (°C)	Relative humidity RH (%)			Remarks
			Long-term level	Seasonal cycle	Short-term fluctuations	
2010	EN 15757 Conservation of Cultural Property – Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials.	No specification	Historic yearly average	Historic seasonal cycle. This cycle is obtained by calculating, for each reading, the central moving average (MA) which is the mean of all the RH readings taken in a period composed of 15 days before and 15 days after the time at which the average is computed.	The lower and upper limits of the target range of RH fluctuations are determined as the 7th and 93rd percentiles of the fluctuations recorded in the monitoring period, respectively.*	When RH is stable, there is no need to change the environment. *If the above procedure determines that RH fluctuations depart less than 10% from the seasonal RH level, the 10% RH threshold can be accepted under responsibility of a qualified conservation professional.
2014	IIC/ICOM-CC Declaration on Environmental Guidelines (Velios 2014; ICOM-CC 2019)	16-25°C	40-60%		± 10% (per 24 hours)	Bizot Interim Guidelines for Hygroscopic Materials.
		15-25°C ± 4°C (per 24 hours)	45-55%		± 5% (per 24 hours)	The AICCM recommended Interim Temperature and Relative Humidity Guidelines (for storage or display of general collection materials).
		15-25°C	45-55%		± 5% (Yielding a total annual range of 40% minimum to 60% maximum) Fluctuations should be minimised.	AIC Interim Guidelines endorsed by the Association of Art Museum Directors.
2015	ISO 11799 Information and documentation – Document storage	16-23°C (Room)	30-40%			Fair (long-term storage)
		8-16°C (Cool)	30-40%			Good (long-term storage)

Year	Source or standard number	Temperature (°C)	Relative humidity RH (%)			Remarks
			Long-term level	Seasonal cycle	Short-term fluctuations	
	requirements for archive and library materials	0-8°C (Cold)	30-40%			Very Good (long-term storage)
		-20-0°C (Sub-zero)	30-40%			Necessary for some materials as colour photos and film (long-term storage)
2018	EN 16893 Conservation of Cultural Heritage – Specifications for location, construction and modification of buildings or rooms intended for the storage or use of heritage collections	Low relative risk: <–10°C Medium relative risk: –10-4°C High relative risk: > 4°C	Within the range 30-65%: - Low relative risk: 30-35% - Medium relative risk: 35-40% - High relative risk: 40-65%			Chemically stability: high sensitivity, e.g. plastics, film. High sensitivity to hydrolysis due to RH, e.g. leather, textiles previously acidified by pollution.
		Low relative risk: <6°C Medium relative risk: 6-14°C High relative risk: > 14°C	Within the range 30-65%: - Low relative risk: 30-40% - Medium relative risk: 40-45% - High relative risk: 45-65% Some inorganic materials, such as metals, will benefit from RH below 30%			Chemically stability: moderate sensitivity, e.g. paper. Moderate sensitivity to hydrolysis due to RH, e.g. some wood pulp papers.
		Low relative risk: <16°C Medium relative risk: 16-22°C High relative risk: >22°C	Within the range 30-65%: - Low relative risk: 30-50% - Medium relative risk: 50-60% - High relative risk: 60-65%			Chemically stability: low sensitivity, e.g. ceramics, glass. Low sensitivity to hydrolysis due to RH, e.g. rag paper, polyester film.
			30-65% Higher risk of physical damage from 30-50% Lower risk of physical damage from 50-65% Under 30%: organic materials can become less flexible, increasing the risk of damage mainly by mishandling. Above 70%: stability decreases in some materials, e.g. wood.			Mechanical stability (safe range for most non composite, non-constraint hygroscopic items to avoid mechanical damage

Year	Source or standard number	Temperature (°C)	Relative humidity RH (%)			Remarks
			Long-term level	Seasonal cycle	Short-term fluctuations	
			Above 65-70% at 20°C Above 55-60% → Upper limit of 65% to avoid mould germination. The risk of mould is increasing with higher RH. Note that mould germination and growth are temperature dependent.			Risk of mould

Table 2.1. Overview of standards and guidelines on temperature and relative humidity suitable for conservation purposes of the collections

For collections in Europe, Thomson recommends relatively strict and fixed target levels with a long-term RH average of 55% and the target temperature fixed to 19-24°C. The upper danger limit is set to 65-70% RH to avoid mould growth and the lower danger limit is set to 40% RH to avoid embrittlement and cracks of materials. The recommended value of 55% RH for European collection is the mean between the two danger limits (Thomson, 1986). On the other side, since the 1980s, the approach has been changed into a more relaxed specification in terms of seasonal and daily cycles (Bratasz, 2002).

The ASHRAE Handbook recommends for permanent collections in museums, art galleries, libraries and archives: 50% RH (or historic annual average) and T between 15-25°C. The ASHRAE has gone a step further, by specifying five classes of climate control from AA to D. Furthermore, the guidelines specify two types of climate recommended especially for archives and libraries only and one type of climate suitable for metal collections. For the five classes of climate control (AA to D) the limit values for the seasonal cycles range from no permissible fluctuations at all in class AA, to class D where all fluctuations are allowed as long as the RH is below 75% to prevent dampness.

The specifications for class AA to D also state that the fixed long-term RH level can be either 50% or it can be the historic annual average for the museum's permanent collection.

This relates to the theories of acclimatization and the term 'proofed fluctuations'. The acclimatization of sensitive objects to the environment within which they have been preserved for a long time has been widely used to establish the criteria for climate control and Michalski introduced the term 'proofed fluctuations' (Bratasz, 2012; Michalski, 1993). 'Proofed fluctuations' was defined as the largest RH or T fluctuations to which object has been exposed in the past. The risk of mechanical damage from fluctuations smaller than the proofed value is expected to be extremely low.

This means that, if the past fluctuation was enough to cause fracture, then the object has fractured and the crack just opens and closes when the RH and temperature fluctuates instead of triggering new cracks (Michalski, 2007; Michalski, 2014). The proofed fluctuations concept eliminates any need to elaborate mechanical response calculations and allows a risk assessment based on past climate records alone. But as Bratasz underlines, the concept of acclimatization (and proofed fluctuations) has to be checked carefully in each case, as physical damage can be cumulative rather than catastrophic, therefore T and RH fluctuations, even if not exceeding the historic levels, can still be risky for the objects. Furthermore, conservation treatments can erase the safety margin developed in objects by their acclimatization to historic conditions and hereby change, sometimes radically, the dimensional and mechanical properties of the original artistic materials (Bratasz, 2012; Michalski, 2014).

The guidelines by the Bizot Group can be perceived as more relaxed (than for example Thomson's guidelines), as they recommend a RH in the range of 40-60% and a range of temperature from 16-25°C. These guidelines by the Bizot Group can in fact be compared with those recommended in the recent edition of the ASHRAE Handbook chapter 23, for collections classified as the control classes A and B (Atkinson, 2014), and these guidelines are showing the development towards a relaxation in guidelines for museum environmental conditions.

The concept of historical climate, i.e. climatic conditions to which an object has been exposed for a long period under reasonably acceptable conditions and to which it has acclimatized, was officially introduced for the first time in the standard EN 15757:2010 and used to establish the criteria for the climate control (Bratasz, 2012). Similar to the principle of proofed fluctuations, the European Standard EN 15757:2010 recommends that the historical climate be maintained, especially as far as RH is concerned. However, this is on condition that conservation experts have found the organic and hygroscopic objects in good conservation conditions. The European Standard EN 15757:2010 suggests how to evaluate the seasonal and the short-term fluctuations related to RH ranges. The most appropriate target range should not exceed the historical variability to which the object has become acclimatised and should be based on all available past climate records covering a period of one or more calendar years. It follows that the energy spent on environmental control can often be reduced.

The IIC/ICOM-CC Declaration on Environmental Guidelines refers to three sets of guidelines from the Bizot Group, AIC and AICCM respectively, which overall recommends a long-term stable RH in the range 40-60% with short-term fluctuations of ± 5-10% and a stable temperature between 15-25°C ± 5°C. These guidelines are also (like the Bizot Group and EN 15757:2010) based on more relaxed standards.

The ISO 11799:2015 provides recommendations for four types of environments for storage of archive and library materials, which are classified as 'Fair', 'Good', 'Very Good' and 'Necessary for some materials'. For all of the four types of environments, the temperatures are fairly cold and lower than the 'human comfort zone', but the relatively cold temperatures are well suitable for long-term storage purpose, which is also the scope of the standard.

The scope of the European Standard EN 16893:2018 is to give specifications and guidance for the location, construction, modification and arrangement of buildings intended for the storage or use of cultural heritage collections. The standard includes a table on the relative risk of damage and deterioration due to T and a table on the relative risk of damage and deterioration due to RH. These tables are divided into risk factors, such as chemical stability, mechanical stability and mould growth. They show T and RH ranges of high, medium and low risk related to objects of high, moderate or low chemical and mechanical sensitivity, respectively. The range of RH with risk of mould growth is also given. It is worth noticing that the standard does not give any clear recommendations on T and RH ranges targeting to buildings intended for storage or use of heritage collections, but it provides only a guidance on the ranges in which the relative risks factors are present.

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2.2 Radiation (visible light and UV)

Light (natural or artificial) is one of the environmental parameters affecting the conservation of museum objects. From a conservation point of view, radiation is potentially responsible for the photochemical damage; nevertheless, illumination is necessary for visitors to see the objects. Since the resulting damage is caused by chemical reactions, it is generally accepted that it is a cumulative damage. Even in the absence of chemical degradation, lamps located in the proximity of the surface can cause elevated temperature on the surface of the objects, affect surface relative humidity and induce internal stress. Since the achievement of a compromise between these conflicting needs is not trivial, lighting in museums have been extensively debated by experts over the years in order to ensure adequate conservation minimizing the interaction of the objects with the electromagnetic radiation.

The visible light (VIS) is the portion of the electromagnetic radiation to which the human eye is sensitive (CEN/TS 16163:2014). The visible spectrum ranges approximately from 400 to 760 nm including all colours from violet (400 nm) to red (760 nm) (Bullock, 2006; Thomson, 1986). The ultraviolet radiation (UV) and infrared radiation (IR) are outside the visible range, the former is at shorter wavelengths, the latter is located at longer wavelengths (Bullock, 2006; Thomson, 1986). VIS, UV and IR are emitted to various extent by all natural and artificial lighting sources (CEN/TS 16163:2014).

The energy emitted per unit time by a light source into a region of space can be measured in Watt (W, radiant flux) or in lumen (lm, luminous flux). The amount of luminous flux distributed over a surface (illuminance) is measured in lux, i.e. lumens per square meter. The UV radiation for a particular light source is commonly expressed as a proportion of UV radiation to visible light and measured in microwatts per lumen (μW/lm) (Bullock, 2006). Radiation provides energy for a potential chemical deterioration (Bullock, 2006; Thomson, 1986). Photochemical damage (e.g. colour changes and changed mechanical properties) is cumulative and irreversible (Bullock, 2006) and its intensity is as a function of the material vulnerability. For this reason, the procedures for choosing appropriate lighting systems must consider both the annual luminous exposure (ALE) and the sensitivity of the materials to light. The dose ALE is measured in lux × hours and is calculated by multiplying the amount of luminous flux (lux) and the duration of exposure (in hours). The higher the dose, the more severe will the damage to the objects be (Bullock, 2006).

According to the standard CIE 157:2004, cultural objects (depending on materials) can be grouped into four categories according to their sensitivity to light exposure: insensitive, slightly, moderately and highly light responsive materials. Organic materials are particularly affected by photochemical deterioration, but sometimes inorganic pigments can react to light as well.

Among the materials selected for CollectionCare, only pure metals and most inorganic pigments are insensitive to radiation. Paper and textiles (e.g. canvas) are classified as highly radiation-sensitive materials since UV radiation can cause them to yellow and make their fibres weaker and brittle. Wood is considered a highly to moderately sensitive material, as light can heavily affect its colour. Paintings made in oil, tempera or acrylic media are usually considered moderately sensitive to light and their varnishes can yellow, darken, crack, lose their gloss and become harder to remove due to UV exposure (Bullock, 2006; Thomson, 1986).

In the following section some of the most used standards and guidelines on the topic are presented.

Standards and guidelines on radiation for conservation purposes of the collections

Table 2.2 gives an overview of selected standards related to the appropriate lighting for collections of cultural heritage, specifying the maximum total luminous exposure recommended for the different classes of light sensitive materials.

Year	Source or standard number	Visible light (lx)			Maximum level of UV (µW/lm)	Remarks
1986	Garry Thomson *The Museum Environment* Second edition (Thomson 1986)	Moderately sensitive material e.g. oil paintings: 200 ± 50 lux (alternatively an annual exposure of not more than 650 kilo lux-h) Sensitive materials e.g. textiles: 50 lux (alternatively an annual exposure of not more than 200 kilo lux-h.			Proportion of UV in the light source not to exceed 75 µW/lm	Class 1– appropriate for major national museums, old or new, and also for all important new buildings
		Moderately sensitive material: Absolutely no sunlight. (Illuminance kept within the low hundreds by use of the light meter and manual control of blinds) Sensitive material: 50 lux (alternatively an annual exposure of not more than 200 kilo lux-h.			Proportion of UV in the light source not to exceed 75 µW/lm	Class 2 – to avoid the major dangers while keeping cost and alteration to a minimum. For example important historic houses and churches.
2014	CEN TS 16163 Conservation of Cultural heritage – Guidelines and procedures for choosing appropriate lighting for indoor exhibitions.	Upper limit annual luminous exposure: No limit	Annual exposure time: No limit	Illuminance: No limit	75 µW/lm	No sensitive materials E.g., most metals, stone, most glass, ceramic, enamel, most minerals.
		Upper limit annual luminous exposure: 600.000 lux·hours (lx·h) per year	Annual exposure time: 3000 h per year	Illuminance: 200 lx	75 µW/lm	Low sensitive materials (ISO Blue Wool Standard 7 & 8) E.g. most oil and tempera paintings, fresco, un-dyed leather and wood, horn, bone, ivory, lacquer, some plastics.
		Upper limit annual luminous exposure: 150.000 lx·h per year	Annual exposure time: 3000 h per year	Illuminance: 50 lx	75 µW/lm	Medium sensitive materials (ISO Blue Wool Standard 4, 5 & 6) E.g. most textiles, water colours, pastels, prints and drawings, manuscripts, miniatures, paintings in distemper media, wallpaper, and most natural history exhibits, including botanical specimens, fur and feathers.
		Upper limit annual luminous exposure: 15.000 lx·h per year	Annual exposure time: 300 h per year	Illuminance: 50 lx	75 µW/lm	High sensitive materials (ISO Blue Wool Standard 1, 2 & 3) E.g. silk, colorants known to be highly fugitive, most graphic art and photographic documents.
2015	ISO 11799:2015 Information and documentation –	Light should be kept at a minimum. Direct sunlight shall be excluded.			Windows should be blocked, or as a minimum be	No specific target limits.

Year	Source or standard number	Visible light (lx)	Maximum level of UV (µW/lm)	Remarks
	Document storage requirements for archive and library materials.	Windows should be blocked, or as a minimum be screened by curtains or blinds, and/or by solar filtering on the window glass (IR, UV, visible radiation).	screened by curtains or blinds, and/or by solar filtering on the window glass (IR, UV, visible radiation).	
2018	EN 16893:2018 Conservation of Cultural Heritage – Specifications for location, construction and modification of buildings or rooms intended for the storage or use of heritage collections.	Windows shall include a UVA filter or be covered. UVA filters should be tested once a year	Windows shall include a UVA filter or be covered. UVA filters should be tested once a year	Refers to the standard CEN/TS 16163

Table 2.2. Overview of standards and guidelines on radiation for conservation purposes of the collections.

The first two guidelines presented in Table 2.2. specify the annual maximum tolerable values of both visible light exposure and UV radiation, while more recent standards do not give any quantitative threshold. The limits recommended in the EN 16893:2018 standard refers to the standard CEN/TS 16163.

The recommendations given in Thomson's "The Museum Environment" is followed by the standard CEN/TS 16163. Both suggest 200 lux for low to moderate sensitive materials and reduce the illuminance for sensitive materials to the minimum threshold limit for visibility (lux or lux*h). The maximum level for UV radiation is set to 75 µW/lm for all classes of materials, chosen as it represents the amount of UV produced by tungsten lamps, which have been regarded as safe for lightning exhibits until the present time. The standards CEN/TS 16163 states that lower levels of UV, e.g. 10 µW/lm, can be attained either by using UV absorbers on windows and electric light sources, or by employing sources with minimal or zero UV output, such as most white LEDs (CEN/TS 16163).

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2.3 Air Pollution

Airborne pollutants can be defined as chemical agents in the form of both gases and particulate matters. Objects inside museums can be threatened both by outdoor pollutants and by pollutants generated from indoor sources.

Air gaseous pollutants

In the outdoors, the concentrations and the chemical composition of air gaseous pollutants are as a function of climate, geography, number and type of industry/vehicular traffic close to the interested area, etc. There are several main outdoor gaseous pollutants that can be found inside museums and suppose a risk to museum collections (Staniforth et al., 2006; Grzywacz, 2006; Tétrault, 2003). They are:

- nitrogen oxides (NOx), an outdoor photochemical smog component from vehicular pollution
- acidic nitrogen gases (HNO_2, HNO_3)
- ozone (O_3), naturally present in the atmosphere as a major constituent of photochemical smog and indoor-generated by photocopiers, laser printers or air-purifiers
- sulphur dioxide (SO_2), a primary outdoor pollutant from the combustion of coal and other fossil fuels
- carbonyl sulfide (CSO), a primary and secondary outdoor pollutant
- reduced sulphur gases, such as hydrogen sulphide (H_2S), outdoor-generated from natural sources and industrial processes, as well as indoor-generated by off-gassing from construction materials

The indoor-generated gaseous pollutants that pose risk to museum collections are usually off-gassed from paints, boards, carpets, cleaners and so on (Staniforth et al., 2006; Grzywacz, 2006; Tétrault, 2003). They are:

- hydrogen sulfide (H_2S)
- organic carbonyl pollutants, both primary and secondary pollutants:
- aldehydes, such as formaldehyde (HCHO) and acetaldehyde (CH3CHO)
- organic acids, such as acetic acid (CH3COOH) and formic acid (HCOOH), i.e. oxidation-products from acetaldehyde and formaldehyde, respectively
- total Volatile Organic Compounds (VOCs), such as hexane (C6H14) and toluene (C7H12), off-gassed from construction materials, solvent-based paints, primers, varnish, aerosol sprays and cleaners.

Particulate matter

The particulate matter (PM) is potentially one of the most harmful pollutants to cultural heritage, simultaneously representing an agent of chemical degradation and an aesthetic issue due to dust. There are two potential sources of PM in museums: outdoor-generated PM (such as external environment, gas exhaust, pollen, combustion, salt spray in marine environments, etc.) and indoor-generated PM (such as people, candles, plaster surfaces, deterioration, etc.). Any chemical reaction between a pollutant and an object causes damage to the object, but the deterioration process can take place at different rates. In many cases, the rate of deterioration is slow and may not cause any noticeable changes except over many decades, because the damage may be at a molecular level. However, irreversible chemical changes in the materials may have occurred. As well, a sudden exposure to high concentrations of a harmful gas can cause rapid deterioration. (Grzywacz, 2006; Staniforth et al., 2006).

SO_2 can cause embrittlement of paper, weakening of textiles and in the presence of moisture, corrosion of metals. NOx's can cause fading of pigments and dyes (in synergy with light) and also weakening of textiles. Ozone attacks many materials and can for example cause fading of pigments and dyes, and VOC's corrode metals. (Staniforth et al. 2006)

There are many parameters affecting the degree at which objects might be attacked by pollutants and all play a role in the overall risk of damage. For example what the object is made of and the specific composition of these materials, the quality of the materials and the object's history, the storage and environmental conditions (e.g. light, RH and temperature), as well as past conservation treatments.

Standards on air pollution

Table 2.3 gives an overview of selected standards related to relevant air pollutants for conservation purposes of cultural heritage collections and shows the specific guidelines on target levels for collections.

Year	Source or standard number	Major outdoor pollutants in ppb (parts per 10^9)			Major indoor-generated pollutants in ppb (parts per 10^9)						Remarks
		NO_2	O_3	SO_2	H_2S	Acetic acid	Formic acid	Formalde-hyde	VOC's	Fine particles	
1986	Garry Thomson *The Museum Environment* Second edition (Thomson 1986)	Below 5.2 / Below 10 µg/m³	Below 1 / Below 2 µg/m³	Below 3.8 / Below 10 µg/m³						80% efficiency on Eurovent 4/5 filter	Class 1 – appropriate for major national museums, old or new, and also for all important new buildings
		*	*	*						*	Class 2 – to avoid the major dangers while keeping cost and alteration to a minimum. For example important historic houses and churches. *= Special areas and cases can be kept free of air pollution by the use of room or case devices.
1999	American Society of Heating, Refrigerating, and Air-Conditioning Engineers Inc. (ASHRAE). Chapter 23 Museums, Galleries, Archives, and Libraries (ASHRAE 2015)	<0.05 to 2.6	<0.5	<0.04 to 0.4	<0.010	<5	<5	<0.1 to 5		<0.1 µg/m³	Sensitive materials
		2 to 10	0.5 to 5	0.4 to 2	<0.100	224 40 to 280	42 to 78	10 to 20	<100	1 to 10 µg/m³	General collections
2018	EN 16893	10	10	1	10	100					Paper

Table 2.3. Overview of standards and guidelines on key air pollutants for conservation purposes of the collections.

The recommendations on air pollution in museum environments by ASHRAE 2011 and EN 16893:2018 are based on the publications by Grzywacz 2006 and Tétreault 2003.

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2.4 Vibrations

Vibrations are the oscillating motion of an object relative to a fixed point of reference (Canadian Conservation Institute 2019) and can cause cumulative mechanical damage to objects as they are a form of cyclic loading. Over time, repeated vibrations can lead to accumulated damage in the form of cracks or deformation. These breaks or micro-tears are irreversible. Therefore, it is important not to reach these limits. The visible failure, causing irreversible damage to the object, can occur when the threshold limit of the materials is exceeded. The so-called fatigue limit is defined as the maximum amplitude of cyclic stress that can be applied to the material before failure occurs. The tolerable duration and number of repetitions of the cycles are a function of the stress level induced to the material. An impact is a very short shock and high-speed loads can cause immediate visible damage, since the material is not able to adapt to the intense and fast deformation. However, even smaller cyclic shock loads can be responsible for cumulative damages that may not be immediately visible.

The standardization about vibrations in the field of cultural heritage conservation requires deep knowledge of the relationship between cyclic stress levels and damage (Wei et al., 2014). In fact, the response and vulnerability of art objects to vibrations is extremely variable, as each object responds differently to vibration input due to its size, shape, material composition and mass distribution (Johnson and Hannen, 2015). The subject began to be explored in “Art In Transit – Handbook for Packing and Transportation of Paintings” (Richard et al., 1991; Mecklenburg, 1991). However, very little regulations about the allowable levels of vibrations to avoid damage to objects are available to date.

Standards on vibrations

Table 2.4 gives an overview of selected standards and guidelines related to vibrations in collections of cultural heritage and shows the specific guidelines.

Year	Source or standard number	Vibration limit (mm/s)	Vibration frequencies (Hertz Hz)	Remarks
2014	Wei et al., 2014	2 mm/s for duration of up to six month (Background level, e.g. street traffic, is around 1 mm/s.)	50 Hz (1 Hertz is one cycle per second)	2 mm/s limit is being proposed as a low-risk limit and not a guarantee for no damage. The vibration limit is especially for paintings, but appears also to be suitable for other types of objects.

Table 2.4. Overview of standards and guidelines on vibrations for conservation purposes of the collections.

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3. European Standards on Microclimate Field Monitoring

Microclimate plays a fundamental role in preventive conservation as the micro-environmental conditions surrounding the objects can favour the acceleration of deterioration processes (Camuffo, 2013). Temperature, relative humidity, vibration and other physical parameters are key variables directly or indirectly involved in these mechanisms and should be measured to understand their role in the ongoing change in material properties and decay, and to control them at levels sustainable for conservation in various situations (e.g. exhibition, storage and transport).

Among the European standards concerning microclimate for Cultural Heritage, EN 15758:2010 and EN 16242:2012 are specifically devoted to the measurement of air and surface temperature of objects, and air relative humidity:

- EN 15758:2010 "Conservation of Cultural Property - Procedures and instruments for measuring temperatures of the air and the surfaces of objects";
- EN 16242:2012 "Conservation of cultural heritage - Procedures and instruments for measuring humidity in the air and moisture exchanges between air and cultural property".

These documents contain recommendations for measurements to ensure the safety of objects and they are addressed to any person with the responsibility of the object, its environment, its diagnosis, the conservation or maintenance of buildings, collections, or single object.

Regarding microclimate measurements, any measurement should represent the actual quantity to be monitored. Each measurement can be considered as the synergistic effect of the separate contribution of the methodology followed by the operator and the instrument used (Camuffo et al., 2010).

Operative procedure

When choosing an operative procedure, the highest intrinsic safety to cultural objects should be guaranteed; perturbation or bias caused by operational errors should be avoided and sampling conditions should be carefully chosen. Furthermore, quality of microclimate data should be assessed before any further analysis aimed at microclimate characterisation.

Key concepts

The following key concepts are derived from the above-mentioned European Standards:

Measuring location

The locations of the measuring point should be selected in such a way that they are representative of the environment under investigation. Measurements in locations affected by disturbing factors should be avoided. The measuring instruments should be placed at the level of the object if air stratification is present.

Sampling frequency

When the environment cannot be considered stationary, variations of the quantities should be measured as a function of time according to a precise plan, which takes into account specific problems to be studied. Sampling frequency should be adapted to the time scale, the dynamics and the fluctuations of the phenomena under investigation; so that the shortest variation of interest is well documented.

Length of monitoring period

At least full year measurements are most satisfactory but more limited seasonal periods can be considered depending on the problem studied.

Instrument

Regarding instruments to use when measuring, remote or non-contact sensor should be preferred, if possible. The instrument should be carefully chosen according to its metrological features.

“Sensor” is the device that senses either an absolute value or a change in a physical quantity and converts it into a useful signal for an information-gathering system. “Probe” is a device placed in or on the object to make measurements or to protect the sensor. For example, one "probe" could contain a temperature “sensor” and a humidity “sensor”.

Key concepts and definitions

Calibration

Instruments should be calibrated periodically so that they achieve a high level of accuracy. At least one reference instrument shall be provided with a calibration certificate issued by an accredited laboratory and used for checking the calibration of other instruments by comparison.

Measuring range

Interval of values that are intended to be measured, or that are potentially measurable, or that have been measured, specified by their upper and lower limits.

Repeatability

Ability of the measuring instrument to reproduce the same output when successively measuring the same value of the air or the surface under investigation, taken under the same conditions.

Resolution

Smallest difference between indications of a displaying device that can be meaningfully distinguished.

Response time

Time interval between the moment when the parameter under investigation is subjected to a specified abrupt change and the moment when the response reaches and remains within specified limits around its final steady value.

Time constant

Time interval between the moment when the air, or the surface temperature, is subjected to a specified abrupt change and the moment when the response reaches about 63% around its final steady value.

Stability

Rate at which characteristics change in the course of time.

Uncertainty

Non-negative parameter characterising the dispersion of the value attributed to a measured quantity. It includes everything under the condition of use, stated by the supplier/manufacturer.

3.1 Measuring temperature (EN 15758:2010)

Key variables

- Air Temperature (T) – Temperature read on a thermometer that is exposed to air in a position sheltered from direct solar radiation or other energy sources
- Surface Temperature (Ts) – Temperature of a given surface of an object; it can be measured with contact thermometers, quasi-contact total radiation thermometers or remote infrared thermometers.

Operative procedure

Care should be taken to shield sensor from radiation sources at different temperature levels through screen made from reflecting materials and with adequate ventilation.

A measurement should not be made before a period has elapsed equal to at least 1.5 times the time constant of the sensor.

Minimum requirements for measuring instruments

These characteristics should be considered to be minimum requirements. The "desirable" response time would be a considerable benefit for spot readings or continuous monitoring of short-term effects.

3.2 Measuring Humidity (EN 16242:2012)

Key variables

- Relative Humidity (RH) – Ratio of the actual vapour pressure of the air to the saturation vapour pressure. RH can be directly measured or it can be either calculated from wet-bulb temperature or dew-point temperature.
- Mixing Ratio (MR) – Ratio of the mass of water vapour to the mass of dry air, i.e. the ponderal mixture of these two gaseous substances.

Operative procedure

An accurate determination of relative humidity requires particular care because the measurement depends both on the temperature of the air and of the instrument.

The response time should be considered in order to obtain meaningful results: the sensor attains the equilibrium after a period of approximately twice the response time.

The probe should be shielded if it is likely to be exposed to radiation sources.

Periodic checking and maintenance are required at least once a year; in case of polluted air or marine environments the period will have to be shorter.

If the surface temperature is different from the air temperature, the RH should be calculated from the actual surface temperature and humidity mixing ratio of the air in the proximity.

Minimum requirements for measuring instruments

These characteristics should be considered to be minimum requirements. The "desired" uncertainty is preferable for indoor measurements, for example in museums or showcases.

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EN 16242 Conservation of Cultural Property – Procedures and instruments for measuring humidity in the air and moisture exchanges between air and cultural property. European Committee for Standardization, Brussels, 2012.

3.3 Monitoring during transport

The CEN standard on transportation (16648:2015 Conservation of Cultural Heritage - Transport methods) provides guidance and principles to be considered when moving cultural heritage objects. This standard will constitute the principle guideline for the work in CollectionCare regarding this specific area. This standard mostly defines roles and logistics during the process of transporting cultural heritage objects.

The CEN standard 15946:2011 Conservation of Cultural Property - packing principles for transport, specifies how to pack the object in such a way that it can be considered ready to be moved. In this standard it is not specified how sensors/loggers should be installed in crates and/or packing materials. The cultural heritage transport company Van Kraligen (HvK) occasionally receives requests from museums to add a data logger into the crate. In these cases the data loggers are provided by the museum itself. The company then assists during packing or provide advice on how to add and/or attach the data logger safely to the crate.

Further practical experience from HvK regarding the transport process is described here: Van Kraligen and other companies transporting cultural heritage, work by the request of the owner or lender of the object (mostly museums). These often have specific standards for transport and packing developed by themselves and referring specifically to their objects. Such requirements depend on the materials of the object.

Many museums request that a crate with a cultural heritage object is brought to them 24-hours before they pack the object so it can acclimatise to the local environment. The packing is often determined by the conservator of the museum. Normally they request crates that adapt to the ambient environment as slowly as possible to allow the object time to equilibrate. This means that good insulation of crates for cultural heritage object transportation is very important.

For a regular transport in a European climate, HvK normally maintains an RH around 50% allowing fluctuations between 45-55%. Temperature average will be kept at 20°C allowing fluctuations between 18-22°C. If desired, T and RH can be monitored in the loading area of the truck.

4. Object/collection monitoring systems

4.1 Complete solutions

In this section, we provide some examples of complete solutions for cultural heritage monitoring.

4.1.1 eClimateNotebook®

eClimateNotebook® is a web-based tool for environmental data management and analysis. eClimateNotebook® is created by the Image Permanence Institute, which is a department under the College of Art and Design at Rochester Institute of Technology, New York, USA.

With the web-based tool, it is possible to upload monitored data of T and RH and create graphs. Only parameters such as locations and time periods can be included by the users. Furthermore, it is possible to set limits for T and RH.

This tool provide automated analysis of the quality of the storage environment and the risk of environmentally induced decay, and can accurately help the user and objectively determine the quality of each monitored location, compare one location to another and document changes over time. The metrics can be used to identify:

- The rate of chemical decay in organic materials
- The risk of mould growth
- The risk of mechanical damage due dampness, dryness or fluctuations between the two
- The risk of metal corrosion

The eClimateNotebook® has a professional level, which includes a searchable database of information associated with every monitored location that one can customize to meet the needs. Furthermore, it includes a management tool called 'Storage Planning' that can help providing the more favourable environment for the preservation of materials in a given collection.

The provider also recommends its PEM2 data loggers for measuring T and RH. These data loggers need user intervention to download data using a USB cable.

4.1.2 Object Centered Environmental Analysis Network (OCEAN)

OCEAN is a climate monitoring programme based on radio telemetry. It was first introduced as a small prototype system in some exhibitions at the Victoria & Albert Museum (V&A) (U.K.) in the late 1980s, but in 2001 the V&A embarked on plans to establish a large scale, distributed and fully networked climate monitoring system to cover the whole of the V&A estate.

In 2003 Hanwell Instruments Ltd (today Hanwell Solutions Ltd) was appointed as project partner, thus the project became an attempt to combine the cumulative practical experience of the V&A staff with the technical expertise of an external company in order to produce a robust and user-friendly environmental monitoring system.

The key requirements for the system were:

- The ability to cope with > 1000 monitors, collecting a variety of environmental data, dispersed across multiple locations with ability to raise alarms if conditions deviate from specifications.
- To provide access to all real time and historic data and provide other products ranging from a simple overview of the environmental conditions at a specific site down to current values at a specific sensor location.
- Each end user should have their own customized view of the system, depending on their area of responsibility.
- The level of system access should be controlled based on individual users.
- The system must offer a quick visual inspection of conditions in all relevant locations.
- Report generation facilities should be automated and comprehensive and under the control of the end user. Depending on access level the report should range in complexity from a simple summary up to data analysis.
- Automated periodic reports should be available.
- A simple calculation representing an overall assessment of conditions should be available.
- There should be a full calibration/audit regime in place. Calibration without breaks in monitoring cycle.
- Minimum intervention should be required by the system administrator under normal circumstances.
- The system should cope with short-term power and network failures.

The OCEAN system at the V&A consists of a thousand or more environmental sensors over a range of geographically separated sites. The sensors records T and RH and are combined with the museum's networking facilities. Each sensor is assigned to a site, a division, a department, section and subsection.

The users communicate with the server via software, which has been customized for this project. In the interface, the sensors are represented as small, coloured icons on a floor plan of each site. Each icon is coloured red, yellow or green depending on reasonably acceptable T and RH conditions for the materials. Red represents a current alarm condition, yellow a previously recorded alarm condition that has not been handled yet and green indicates acceptable T and RH values. Any icons can be expanded to show live values and to allow access to graphing. The software allows full planning, translation, and zooming across the site and allows sensors to be located hierarchically, rather than geographically.

Furthermore, the user can select and filter all of the sensors within his view and generate an Adobe PDF report in an optional level of details, for any time period of interest.

Hanwell did promote OCEAN in Europe as a product for a period, but one of the barriers to its wider spread was that the design was based on mapping using fully fledged CAD drawings of the buildings. This was available at the V&A, but it seemed to not be routinely available at other museums, hence all mapping solutions had only limited applicability.

4.2 Relevant EU projects

In this section, we present the most relevant EU projects related to preventive conservation monitoring systems. Some of these are more focused on heritage building monitoring, but the underlying problems and technologies are similar.

4.2.1 SMooHS

SMooHS: Smart Monitoring of Historic Structures (7th FP; Project ID: 212939). Its objective is to develop a smart monitoring system using wireless networks of miniaturized robust sensors for minimally invasive installation at historic structures. As the focus is on historical buildings, the sensors and their connectivity (fixed monitoring system) is not suitable for movable objects. However, we consider both systems complementary, since the data of both projects can help to have a broader vision about the preventive conservation of the historical cultural heritage and will be useful for pre-normative conservation studies.

4.2.2. SHBuildings

SHBuildings project: Smart Heritage Buildings (Funding: InterregIVB-SUDOE & European Regional Development Fund). This project focuses on the monitoring of energy requirements, relative humidity, temperature and detection of wood pests in heritage buildings. The sensor node used in the SHBuildings project for wood studies was developed by ITACA-UPV in collaboration with AIDIMA in 2007 for a static measurement applied to a building. Miniaturized sensors exist that can perform both static and moving measurements, incorporating the latest advances in connectivity.

This project also includes MHS proposal, developed to monitor in real time the aspects that affect the conservation of cultural heritage and manage it easily from a single gadget. This monitoring system has emerged from the following projects related with cultural heritage conservation:

- Heritage Care; Monitoring and preventive conservation of historical and cultural heritage (Interreg-SUDOE),
- SHBuildings; Smart Heritage Buildings (InterregIVB-SUDOE) and
- MHS-EnerCon2 (Challenges-Collaboration2016, Spain).

MHS is focused on monitoring architectural heritage for preventive conservation and maintenance of historic buildings, but not on movable objects individually. Sensors are used to control the environment of buildings and the container of objects. In this case, CollectionCare follows the steps of previous projects enabling to provide specific control of each object, not only of the container.

4.2.3. Climate for Culture

Climate change is one of the most critical global challenges of our time affecting, among others, the conservation of our cultural heritage. The cultural heritage of Europe is particularly vulnerable to ambient factors making its safeguarding and conservation a high priority to all stakeholders.

Climate for Culture aims at effective sustainable adaptation and mitigation strategies in order to improve the long-term preservation of these invaluable cultural assets. More reliable assessments of the impact of climate change will lead to better prediction models, which in turn will enable preventive measures to be taken, thus reducing the consumption of energy and resources.

The main innovation of the project is to use simulation and modelling tools to better predict the influence of the changing outdoor climate on the indoor climate in historic buildings until 2100, and to assess the potential damage inflicted by these future climate conditions on art collections in various climate zones. For the first time regional climate models with a high resolution of 10x10 km are therefore being developed and coupled with whole building simulation tools to identify the most urgent risks for specific regions.

Buildings of outstanding significance are subject to in depth case studies providing knowledge on the state of preservation, interpretation of indoor climate conditions and requirements from a preventive conservation point of view. Various types of historic buildings located in different climate zones are investigated using two different climate scenarios. The aim is an improved assessment of the climatic function of historic buildings and their future energy demands using whole building simulation with regard to the dangers for the interior equipment or works of art and resulting measures to improve conditions. For these research tasks, the newest available technology from European projects (AMECP, LASERACT, Noah's Ark, Friendly Heating, EUROCARE EU-1383 PREVENT, OnSiteforMasonry, SMooHS) are applied.

CollectionCare can benefit from the experience from this an other projects relevant for the development of software for risk evaluation.

4.3 Partial solutions

4.3.1. Physics of Monuments

Physics of Monuments is a research team at TU Eindhoven devoted to give climate recommendations for monumental buildings and partners in the Climate for Culture EU project. The general mission is the conservation of the cultural heritage by giving specific climate recommendations. Their competences are:

- Monitoring the indoor climate, all results are available on the website
- Assessing indoor climate parameters, such as temperature, relative humidity, lighting level and carbon dioxide concentration
- Analysing buildings using infrared imaging
- Setting up simulation models of heat, air and moisture related issues.

They provide on-line software where user data can be uploaded to carry out climatic data analysis.

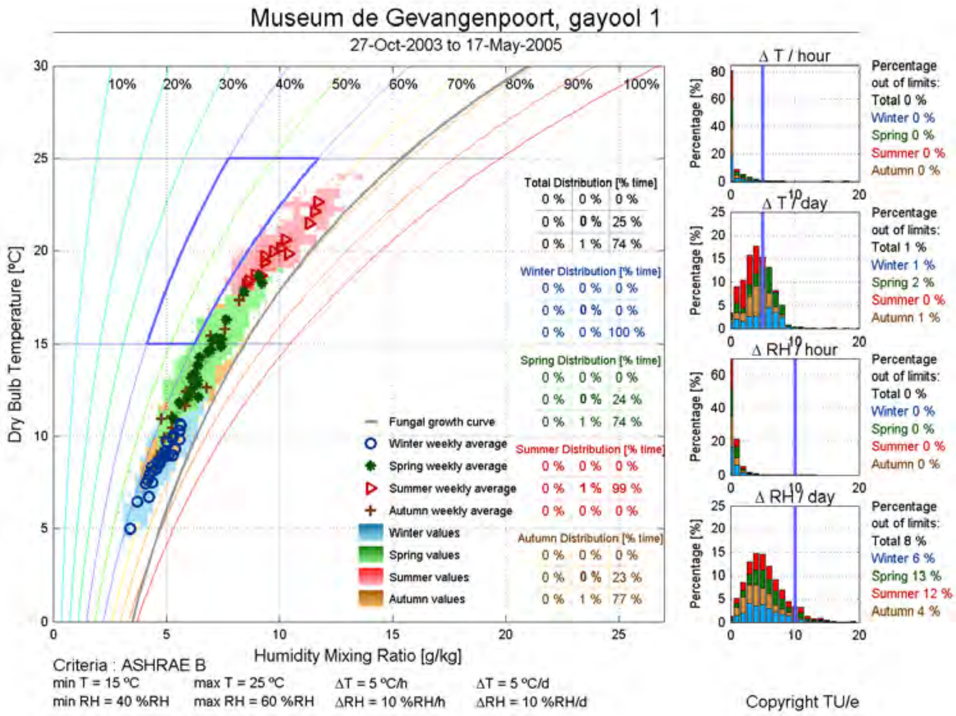

Fig. 4.3.1. Example of the product analysis by Physics for Monumenten team at TU/e: The psychrometric chart of Indoor climate is seasonally represented: blue (winter), green (spring), red (summer), and orange (autumn). The class B area is delimited by two horizontal blue lines (the T limits between 15°C and 25°C) and the vertical lines of RH (40% and 60%).

4.3.2. HERIe

HERIe is a web-based decision-supporting software tool to facilitate the management of collection environments by precise assessment of climate-induced risk of physical damage to vulnerable objects developed, among others, by the Jerzy Haber Institute of Catalysis and Surface Chemistry of Polish Academy of Sciences.

The software translates the relative humidity and temperature data recorded in the environment of the analysed object into a strain history experienced by it, and estimates the risk of physical damage using selected failure criteria. As all information is pre-calculated for the user, no engagement in complex and time-consuming numerical simulations is required. HERIe is available for testing at herie.mnk.pl.

As an example of capabilities, the software includes moisture-induced response of parchment to support managing environments in libraries and archives.

Data must be uploaded by the user in order to carry out the risk analysis.

4.4Wired solutions

Old-school solutions are based on wired sensors that exhibits very relevant characteristics: no energy limitations, very long life span and arbitrary sampling interval. Obviously, the main drawback is the complexity of installation in old buildings which house objects.

This solution has been included because some of the Collection Care partners have this type of wired sensors.

4.4.1. AKO-15740

AKO-15740 is part of a range of recorders for temperature and relative humidity devoted to temperature-controlled supply chain (cold chain) and utilized by the partner IVC/Culturarts to keep record of humidity and temperature in the climatic chambers where objects are stored. These devices are committed to regulatory compliance.

In this particular case, sensors are wired using RS-485 serial communications system and the Modbus protocol. Data register can be accessed by the provided software using local network infrastructure (Ethernet).

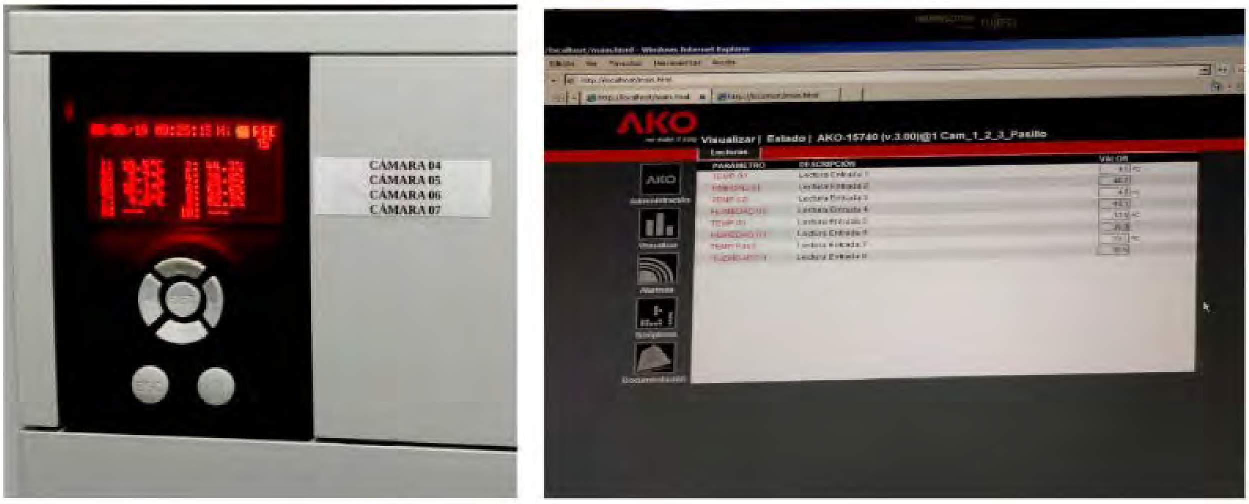

Fig. 4.4.1.AKO-15740 data recorder (left) and AKO data access software (right) (Source: IVC)

Following the latest trends in LPWAN technologies, AKO is providing NB-IoT enabled datalogging devices and cloud-based data storage and analysis.

4.5Wireless dataloggers

Datalogger-based solutions are the most widely used option for cultural heritage monitoring. In this section, we describe some key solutions of main manufacturers that, among others, include wireless connectivity.

4.5.1. Testo 160 and Testo Saveris H

Testo 160 and Testo Saveris H are Wi-Fi dataloggers system to monitor temperature, relative humidity, lux, UV radiation and CO_2 concentration in buildings, specific rooms or display cases. The system is well suited for museums, archives, galleries and libraries that can help in evaluating the risk of mould, bleaching, corrosion or deformation, thus protecting works of art.

Fig. 4.5.1. Testo series 160 (Source: Testo)

The measurement values are transmitted by wireless LAN to an online database called Testo Cloud where all values are stored. All data stored in the cloud can be called up on any device via an application or a browser.

Depending on the condition and material composition of the exhibited object, it is possible to set specific limit values for the stress caused by environmental conditions. Regarding the limit value violation, an alarm notification is available by either SMS or e-mail. For the radiation, an alarm can also be triggered if the accumulated light quantity within a day, a week or a month exceeds a limit value.

Wi-Fi-based communication benefits of low-cost common infrastructure but it is problematic dealing with long distances and thick walls. In addition, energy requirements are higher compared to other ISM-based solutions such as 868 MHz band.

4.5.2. SensMax® SensGuard

The SensMax® SensGuard is an automated temperature and relative humidity monitoring system.

The system consists of three components: wireless temperature and humidity sensors, LAN/Internet or 3G/Mobile Internet data gateway and an online temperature and humidity monitoring system. The wireless temperature and relative humidity sensors are battery powered with a guaranteed working time of 5+ years. The controlled temperature range is from -30 to +55°C and the relative humidity range is from 0-100%. The wireless sensors record T and RH parameters every 5 minutes and the data gateway automatically performs T and RH statistical analysis.

The automatic T and RH metering software is an online cloud-based reporting application, where one can see actual readings from the sensors, as well as a full history of events per each sensor or sensor groups.

It is possible to set up individual parameters of temperature and relative humidity in the allowed range for each sensor and get alarms via e-mail or SMS when temperature or relative humidity is out of the allowed range.

Wireless dataloggers use 868 MHz frequency for communication and have a range of up to 150 m.

4.5.3. Eltek Darca Heritage

Eltek is a classical provider of modular datalogger and specific software for microclimate conditions monitoring of cultural heritage.

From the point of view of ColletionCare approach, Eltek's devices such as GD-11 T and RH datalogger are a reference. For example GD-11 has both storage capability and telemetry to send data wirelessly following EN300-220-1 standard at 433 MHz ISM band.

Eltek also provides Darca Heritage software. According Eltek, Darca Heritage has been designed specifically for museum curators and conservators to monitor microclimate in case of large installations. The software allows sensors to be referred to according to their physical location. Sophisticated but simple-to-use, it provides powerful tools for:

- Configuring and metering sensors
- Changing logger settings
- Updating site data automatically to a datafile (version 1) or database (version 2)
- Warning if any channel inputs are outside of safe limits
- Sending alarms via email or text message
- Metering data graphically on user-defined floorplans which show each group's physical location
- Analysing data either graphically or statistically
- Generating reports for the presentation of data

In addition to standard measured values, calculated parameters may be added and analysed. Sensors may also be metered graphically on user-entered floor plans.

4.5.4. Onset Hobo ZW and MX series

Onset produces a renowned family of dataloggers well established in the area of collection management. In this sense, ZW and MX series are wireless dataloggers focused to different needs.

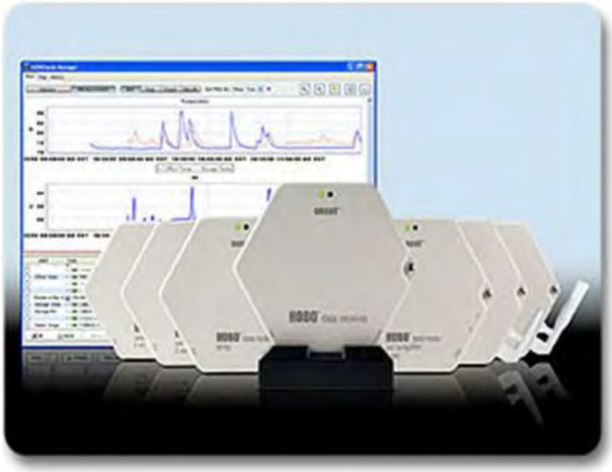

Fig. 4.5.4.a. Onset HOBO Zw series aspect (Source: Onset)

The HOBO ZW series wireless allows for a network of sensors that transmit data to a HOBO Data Receiver connected to a computer. To overcome issues related to building features, a set of intermediate HOBO data routers can be utilized.

According to Onset, the main features of this series are:

- Providing centralized building performance data collection
- Logging and wirelessly transmitting real-time data within a self-healing mesh network
- Notifying you of alarm conditions via email or text messages
- Preventing data loss by means of an Onboard buffer memory
- Having available a wide range of external sensors
- Organizing and viewing data by a powerful software
- AC powered with battery backup

HOBO sensors are battery-powered, so to preserve energy these have been built around IEEE 802.15.4 wireless standard at 2.4 GHz. This band has the drawback of poor performance dealing with obstacles (as Wi-Fi) so this is the reason for using HOBO data routers to organize a “mesh” that routes data to the central receiver. These data routers need mains to be powered.

Data is collected in a central computer using the HOBO Data Receiver and the HOBOware setup, which is the software that lets easy configuration of the complete range of Onset dataloggers and provides basic data collection, graphing and analysis. This software is sufficient to deal with basic alarms and automatic notification via e-mail or SMS.

Onset also provides the new MX series of wireless dataloggers based on Bluetooth Low Energy (BLE) wireless technology. Compared with other wireless technologies described in this section, BLE allows to design dataloggers with similar price to the classical ones (user intervention to download data using a serial/USB cable) but with the further advantage of not requiring cables to download data, reducing the need for manipulation of the object. Using a smartphone and the provided APP, data recorded by the MX series can be easily downloaded.

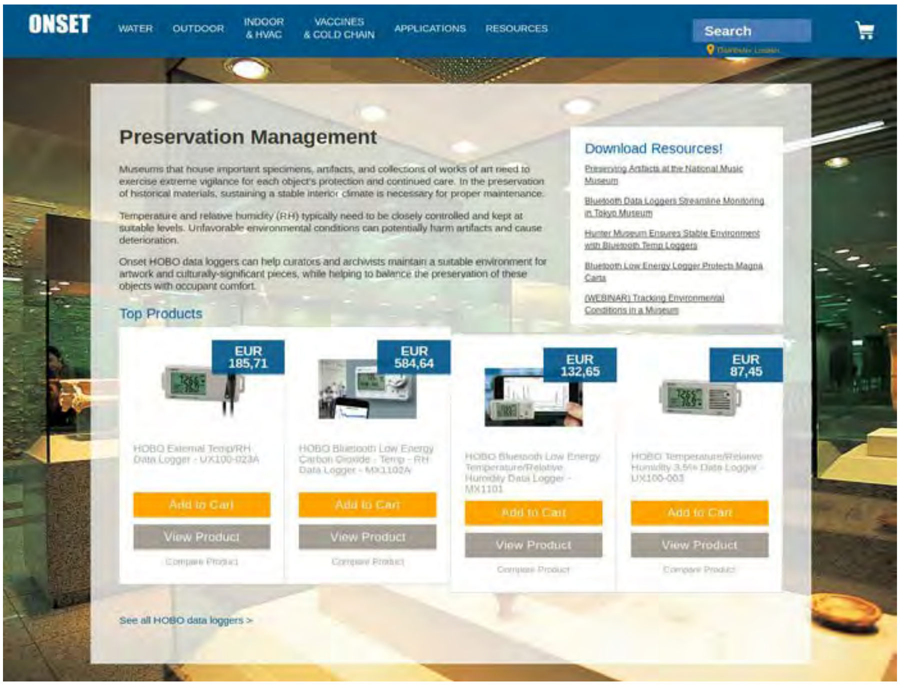

Fig. 4.5.4.b. Onset web page promoting ZX series for preservation management (Source: Onset)

4.6 Comparison

This section provides a representative range of technological solutions that helps in the monitoring and analysis of parameters that affect the preservation of objects. Table 4.6 summarizes key aspects of some of these solutions from the point of view of characteristics desired for CollectionCare.

Both eClimateNotebook and OCEAN should be a reference to how data should be analysed, manipulated and shown from the point of view of user interaction. These frameworks only concern T and RH analysis.

HEREi is a very interesting approach to individual canvas risk analysis, so it could be a reference to the individual objects approach proposed in CollectionCare.

From the point of view of wireless dataloggers, a set of different approaches to deal with data communications has been analysed. This diversity demonstrates that it is an open issue and no ideal solution is available. CollectionCare considers a different approach, the adaption of LPWAN technologies to the specifics of museum buildings, art display, storages and transport. This election is not exempt of risk.

	Sensor/datalogger	Wireless	Cloud-based	Automatic data analysis	Standards/normative automatic evaluation
eClimateNotebook	Yes (PEM2 t, RH)	No	Yes	Yes Only T and RH	No
OCEAN	Yes (Hanwell)	Yes. 433 MHz	No	Yes. T & RH	No
Physics of monuments	N.A.	N.A.	Yes	Yes	No
HERIe	N.A.	N.A.	Yes	Yes	No
Testo 160/Saveris H	Yes. T, RH, light, etc.	Wi-Fi	Yes	No. Only basics	No
SensMax SensGuard	Yes T, RH, etc.	Yes. 868 MHz	Yes	No. Only basics	No
Eltek Darca	Yes (Eltek)	Yes. 433 MHz	No	No. Only basics	No
Onset HOBO ZW, MX	Yes. T, RH, etc.	IEEE 802.15.4. Bluetooth Low Energy	No	No. Only basics	No

Table 4.6. Key aspects of some technical solutions for preservation monitoring

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5. Material types

This section introduces the selected material types for CollectionCare, their typical degradation, the type of objects that they represent in collections and the known standards for their preservation.

5.1 Description of canvas paintings

Basic structure and materials

Canvas paintings are constructed in numerous different ways over the centuries. The basic structure is a piece of fabric (the canvas) which is tensioned on a stretcher (an expandable frame) or strainer (a fixed frame) to provide a smooth surface to paint on. The stretcher/strainer is usually made from wood and the canvas is often made from flax, hemp, cotton or jute. Protein fibres like silk or wool are rare. In modern times synthetic fibres like polyester or polypropylene have been used but the natural fibres are still more common due to their greater absorbency and flexibility and for aesthetic reasons.

The canvas is in some cases covered by a layer of glue or starch in order to prevent that oil from ground and paint layers is absorbed by the canvas.

In most cases, a ground layer is then applied in order to get a smooth and uniform background to paint or draw on. Then the paint layer(s) is/are added. Ground and paint layers can consist of a number of materials. The binding media can be oil, pastel, acrylics, alkyds, house paint, or other types. Pigments can be natural or synthetic, organic or inorganic. Types of binders and pigments can have serious influence on the properties of the dry paint film (for example risks of fading, cracking and paint loss).

In traditional oil paintings a layer of varnish (a natural or synthetic resin) is usually applied after the oil paint has dried in order to protect the painting and to bring out the colours and contrasts in the composition. Furthermore, the varnish layers ensure a uniform gloss over the painting surface, which is desired in some traditions and times. Many modern paintings are not varnished by the artist. Dirt and degradation agents like oxygen and humidity therefore have free access to the exposed paint layer.

Examples of types of objects in collections

In the European tradition, canvas paintings of similar periods were often similar in materials and composition.

- Medieval canvas paintings
    - Tüchlein paintings (oil or glue based paint, no size and ground)
- Canvas paintings from 17th -18th Century
    - Usually oil paint on white or coloured ground, painted on flax/hemp.
- Canvas paintings from 19th Century
    - Usually oil paint on white ground painted on cotton or flax/hemp.
- Modern canvas paintings (20th Century)
    - Modern oil paintings
    - Acrylic paintings
    - House paint and other industrial products

Types of degradation

The layers of a painting can degrade due to physical (including mechanical) and/or chemical degradation. Usually it is a combination.

The paint layer can be weakened by oxidation and hydrolysis, by evaporation or removal of fatty acids (in the case of oil paint) or surfactants (in the case of acrylic paint) or by the formation of metal soaps due to a chemical reaction between fatty acids and metal ions. This can result in a higher risk of mechanical damage due to forces for example caused by impact, change of tension or vibrations.

Cracks, cupping or loss of paint and/or ground layers can be the result of impact during handling, changes in temperature or relative humidity, water damage and be due to the use of poor artist's materials. The canvas can have tears due to mechanical impact or water damage. Buckling/distortions can happen due to fluctuations in relative humidity or temperature.

Visual changes can also occur on the surface of the painting when dirt accumulates due to exhibition or storage conditions or due to colour change (often fading) usually due to oxidation through exposure to radiation.

Excessive conservation treatment (e.g. over paint, excessive cleaning, excessive use of heat, moisture or pressure) can also be a course for degradation.

Condition reporting

Condition reports are made to ensure that degradation phenomena are documented –either as a precaution before objects are lent out or acquired or as a documentation of state before conservation treatment. It can also be part of a larger survey. There are different kinds of condition reports depending on the purpose.

CCI proposes four types: 1. baseline condition report, 2. cursory inspection report, 3. purpose-based condition report, 4. cumulative condition report:

Canadian Conservation Institute (2019). Condition Reporting - Paintings. Part 1: Introduction - Canadian Conservation Institute (CCI) Notes 10/6. Government of Canada. https://www.canada.ca/en/conservation-institute/services/conservation-preservation-publications/canadian-conservation-institute-notes/condition-reporting-paintings-introduction.html (Accessed: 21.06.2019)

A good template for condition reporting can be found at the Canadian Conservation Institute's webpage:

Canadian Conservation Institute (2019). Appendix: sample report templates. Government of Canada. https://www.canada.ca/content/dam/cci-icc/documents/services/conservation-preservation-publications/canadian-conservation-institute-notes/Appendix-Note10-6-EN-20190123.pdf (Accessed: 21.06.2019)

Resources and glossary that in some cases provide photos of degradation phenomena can be found online:

The Fine Art Conservancy (2014). Glossary for paintings. http://www.art-conservation.org/?page_id=1170 (Accessed 21.06.2019)

Wikipedia (2019). The Free Encyclopedia. Conservation and restoration of paintings. https://en.wikipedia.org/wiki/Conservation_and_restoration_of_paintings (Accessed: 21.06.2019)

Rijksdienst voor het Cultureel Erfgoed (2019). Modern Paint Damage Atlas. http://paint.phpetra.nl/ (Accessed: 21.06.2019)

Canadian Conservation Institute (2017). Condition reporting - paintings. Part III: Glossary - Canadian Conservation Institute (CCI) Notes 10/11. https://www.canada.ca/en/conservation-institute/services/conservation-preservation-publications/canadian-conservation-institute-notes/condition-reporting-paintings-glossary.html (Accessed: 21.06.2019)

Climate recommendations for paintings on canvas

Climate recommendations for paintings on canvas are closely linked to the general recommendations for cultural and natural heritage, as discussed in chapter "2. Preventive conservation – standards and regulations for environmental parameters". The 10 standards or guidelines considered relevant for CollectionCare are presented in Table 2, followed by the detailed Table 2.1. (temperature and relative humidity), Table 2.2. (radiation), Table 2.3. (air pollutants), and Table 2.4. (vibrations).

Four sources or standards are especially relevant for canvas paintings concerning temperature and relative humidity. The recommendations concentrate on seasonal changes in the relative humidity with additional, recommended temperature set point in two publications.

Stolow, in the UNESCO publication "Conservation standards for works of art in transit and on exhibition" (1979), recommends seasonal changes kept within 40-55% RH while Mecklenburg (2007) consider 30-60% RH suitable for most [painting] materials, but with a tighter control for sensitive [painting] materials.

The ASHRAE handbook (2015, p. 23.13) recommends an average of 50% RH or a historic annual average for permanent collections, with the supplementary note that +/- 10% RH poses a tiny risk to most paintings.

The CCI (the Canadian Conservation Institute) in addition to the ASHRAE handbook recommends a temperature set point to be anywhere in the range of 16-25°C, while keeping the relative humidity within 40-60% RH. Paintings in permanent collections; the concept of a "proofed fluctuation" states that the risk is extremely small for further cracking or delamination of the paint due to fluctuations that are less severe than those already experienced by the painting.

The European Standard DS-CEN-TS 16163 (p.14) recommends light and radiation limits. Paintings are considered sensitive or moderately sensitive depending on their materials. Moderately sensitive oil paintings: 200 ± 50 lux (alternatively, an annual exposure of not more than 650000 lux*hour) while sensitive materials e.g. textiles [canvas not covered by paint]: 50 lux (alternatively, an annual exposure of not more than 200000 lux*hour).

Sunlight should be fully avoided and the proportion of UV radiation in the light source used is not to exceed 75 μW/lumen if it cannot be fully eliminated.

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Richard, M. (1994). The transport of paintings in microclimate display cases. Paper presented at the Preventive conservation: practice, theory and research. Preprints of the contributions to the Ottawa Congress, IIC, 12-16 September 1994.

5.2 Description of metals

Basic structure and materials

Metal objects are a very wide group of cultural heritage objects, which are made or created entirely or partly of metallic material. Among cultural heritage objects, the most commonly used metals and alloys are: gold, silver, bronze (copper alloys or copper and tin alloys with at least 80% of copper or copper and tin), brass (copper and zinc alloys), nickel, nickel silver (copper alloy with nickel and often zinc, usual with a rate of Cu:Ni:Zn: 60:20:20%, respectively), monel (nickel-copper alloy with 52-67% of nickel), chromium, iron, steel (alloy with iron and carbon as the major constituents), weathering steel, stainless steel (steel alloy, with a minimum of 10.5% chromium and a maximum of 1.2% carbon), titanium, tin, pewter (85-99% tin mixed with copper, antimony, bismuth and sometimes silver), lead, zinc and aluminium.

Metals are often used in combination with other materials, e.g. as a thin coating of metal/alloy on the surface of an object. Metals can also constitute the base of an object e.g. in case of jewellery it can be a basic material on which other materials (gem stones etc.) are fixed.

Examples of types of objects in collections

- Jewellery (beads, bracelets, rings, etc.)
- Armoury (e.g. swords, armour, arrowheads, cartridge, weapon, shotgun, guns, etc.)
- Coins, medals
- Everyday objects (cigarette case, mirrors, caskets, notebook covers, etc.)
- Furniture (tables, benches, etc.)
- Sculptures
- Architectural elements (slate, construction components, etc.)
- Enamels
- Musical instruments

Types of degradation

Corrosion

Corrosion is the most common form of deterioration affecting metal objects. Environmental factors such as exposure to moisture (water) and air pollution (air and different gases) can influence corrosion of metals and alloys. Salts, acids and alkalis are all corrosive agents for some metals and alloys. Depending on the material and the conditions, effects of corrosion can range from a minor surface and near-surface modifications that e.g. can cause a change in colour to a complete transformation or dissolution of the metallic material. Corrosion is not considered deterioration when it forms a 'patina' on the object.

There are two basic types of corrosion: chemical and electrochemical corrosion.

- Chemical corrosion is the destructive effect based on the direct reaction of the material with the aggressive substance (gas or liquid which is not an electrolyte). It is a result of chemical reactions at the metal/environment interface.
- Electrochemical corrosion is a process of destruction resulting from the electric current flow through the interface metal/electrolyte. The formation of galvanic cells can be caused by: heterogeneity of the material structure, non-uniform access of oxygen to the metal surface, temperature differences, or a combination of two different metals in contact with the electrolyte.

Depending on the course of the material deterioration, eight forms of corrosion can be classified:

- Uniform corrosion: uniform layer of corrosion covers the whole metal surface.
- Galvanic or two-metal: two different metals (with different electrochemical potentials) are in electric contact forming an electrochemical cell.
- Crevice: localized corrosion occurred in crevices or other areas, where the depletion of oxygen in the electrolyte occurs.
- Pitting: localized corrosion caused by the presence of localized galvanic cells forming between passive metal area (cathode) and local depassivated zone (anode).
- Intergranular: corrosion localized on grain boundaries.
- Selective leaching: selective dissolution of one of the alloy compounds resulting in formation of a porous structure.
- Erosion corrosion: a combination of corrosion, abrasion and mechanical wear.
- Stress corrosion cracking: a simultaneous interaction of corrosive agent and mechanical tensions.

Mechanical damage

Metals and alloys are characterized by plasticity and a certain strength and fracture toughness that can be changed under specific conditions (temperature, mechanical treatment, environmental conditions). Physical damage can be caused by abrasion, impact, or load stress. Possible mechanical causes of deterioration of metal objects include:

- Breakages
- Mishandling
- Dents or bends
- Scratches and gouges
- Cracks

- Losses
- Damage to patina
- Chips or losses to base
- Repairs
- Wear to gilding

The first four mentioned types of mechanical damage mechanisms are the most common causes of metal object deterioration. Scratches can cause flaws in the material that initiate cracks with high stress concentrations at the tip of the crack. Over-polishing of metals gradually grinds away surface layers while chemical cleaning breaks down plating, surface decoration, maker's marks and engravings. Such factors can activate and accelerate corrosion.

Inherent vice

Improper alloying, working flaws, and composite objects made of incompatible materials can be mentioned as examples of inherent vice that are considered deterioration of a metallic object.

Condition reporting

There are several different types of condition reports and many sorts of condition reporting forms, some of which form a component of a museum management system, others have been designed for specific uses or collections.

All condition reports should contain details about:

- Type of object – e.g. a coin, a sculpture, a medal, a sword etc.
- Date of examination and person who carried out the examination.
- Dimensions – in millimetres, for most objects dimensions like height, width and depth will be needed. A spherical item may use diameter in place of two of the measurements. Measurements need to be taken at the extremes of the item. Composite items can become confusing for measurement. The biggest dimensions should be considered involving all elements even if made from different materials.
- Description – including materials, how many components parts an object has, if there are any accessories (covers, cases, etc.), title, provenance, date and place of manufacture, artist/maker/manufacturer, inscriptions, stamps, imprints, whether it relates to other items in the collection. For complicated objects, a diagram or a photograph should be included.
- Condition – it is usually a single word or number at the beginning of the section that describing the object's condition. Limited vocabulary within enclosed glossary should be provided for this section, as terms can be subjective. For example: Excellent (as new condition with little or no sign of use), Good (some signs of wear but physically sound), Fair (minor damage, some losses/deterioration more aesthetic than physical), Poor (wear, damage, deterioration and loss to a large proportion of the item), Very poor (extremely deteriorated, weakened condition with very extensive loss/damage which greatly impacts the integrity of the object).

Examples of condition reports for metals, and guidelines for preparation of condition reports:

Canadian Conservation Institute (2018). Caring for metal objects - Glossary. https://www.canada.ca/en/conservation-institute/services/preventive-conservation/guidelines-collections/metal-objects.html#a7 (Accessed: 21.06.2019)

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Museums & Galleries of NSW (2019). Condition reports: a 'how-to' guide. https://mgnsw.org.au/sector/resources/online-resources/collection-care/condition-reports-how-guide/ (Accessed: 21.06.2019)

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South West Fed (2019), Together for Heritage. https://www.swfed.org.uk/wp-content/uploads/2013/02/Condition-Report-Example.pdf (Accessed: 21.06.2019)

Examples of glossaries and photographs of degradation phenomena:

The Australian Institute for the Conservation of Cultural Material (AICCM) (2019). Visual Glossary. https://aiccm.org.au/conservation/visual-glossary (Accessed: 21.06.2019)

reCollections (2019). Collection Surveys and Condition Reporting. Managing collections. http://culturalmaterials.net/wp/28-2/managing-collections/collection-surveys-and-condition-reporting-2/ (Accessed: 21.06.2019)

Climate recommendations for metals

Climate recommendations for metals are closely linked to the general recommendations for cultural and natural heritage, as discussed in chapter "2. Preventive conservation – standards and regulations for environmental parameters". The 10 standards or guidelines considered relevant for CollectionCare are presented in Table 2, followed by the detailed Table 2.1. (temperature and relative humidity), Table 2.2. (radiation), Table 2.3. (air pollutants), and Table 2.4. (vibrations).

Four sources or standards are especially relevant for metals (metal objects) concerning temperature and relative humidity. The recommendations concentrate on long term averages in the relative humidity, in all instances recommending a low RH level.

Two sources recommends a long-term average of 15-40% RH (Stolow, 1979, and The Handbook for Museum, 2003), the latter with a note that a relative humidity level > 15% RH tarnish polished metals. The ASHRAE Handbook, 2015 (p. 23.13) recommends a lower long-term average of 0-30% RH for special metals collections, and dry room storage. The CCI (the Canadian Conservation Institute) recommends a slightly higher long-term average of 35-55% RH, with some specific considerations, including that unstable, actively corroding metals be stored at < 35% RH.

Limitations or recommended levels concerning light and radiation in itself is generally know not to be needed, since these factors do not affect metals. One source, G. Pavlogeorgatos, 2003, is referred to endorse this fact.

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5.3 Description of paper

Basic structure and materials

Paper is a hygroscopic, man-made material mainly consisting of plant fibres. These plant fibres consist of cellulose, lignin and hemicellulose, of which cellulose (a non-branched polymer of glucose) is the main component. Besides cellulose (or fibres), paper usually consists of a mixture of minerals (e.g. kaolin), organic sizing agents and chemical additives of different natures.

Lignin is covalently bound to cellulose and hemicellulose in the plant fibres. All chemical pulping processes (manufacturing of fibres) are designed to remove the lignin component and hereby release the fibres. The lignin that may remain in the fibres gives a brownish colour to paper made from unbleached pulps.

Different pulping processes yield pulps for different types of paper. The pulping techniques can be grouped into mechanical, chemical and semi-chemical techniques. Hereafter, the pulp can be whitened through a bleaching process, to manufacture white paper. Chemical additives can be added to the fibrous stock to extend the usefulness of the paper manufactured from wood. Sizing agents can be added to make the paper less absorbent, while mineral filler pigments can enhance the paper's appearance and its printing characteristics.

Examples of types of objects in collections

- Books
- Documents
- Engravings/prints
- Lithographs
- Maps
- Newspapers and magazines
- Lithographs
- Boxes
- Posters
- Globes
- Etc.

Types of degradation

During ageing, paper can experience loss of strength, which endangers the physical integrity of a paper. This is due to the weakening of the fibres, rather than of the bonds between them. Paper fibres loses strength when the cellulose chains are broken and thereby shortened in length. This process is a form of cellulose chemical degradation.

When the cellulose in paper degrades, in terms of cellulose chain breakage, it will not only cause physical property changes, but will also result in new chemicals being created in the paper, e.g. small chain fragments and sugars (degradation products). The creation of these small degradation products is a significant process in the ageing of paper, because they will accumulate in the paper and can undergo further reactions. Some will form acidic substances, thus the paper will become more acidic and will lose strength and flexibility in time.

Several synergic biological and chemical processes (or reactions) during manufacturing and ageing cause the cellulose chains to break and hereby affect the mechanical performance of paper. These are biodegradation, photodegradation, oxidation and hydrolysis.

There are two issues that promote biodeterioration: the removal of lignin during manufacturing (and therefore the loss of its inhibiting effect against microorganisms) and the presence of organic sizings (e.g. starch, glue, etc.), and fillers (e.g. chalk, clays, etc.) which increase paper vulnerability to biodeterioration. The action mode is to a great extent governed by the enzymic action of excreted metabolic products of fungi on the different elements present in paper artefacts, that leads to the hydrolysis and accelerated depolymerization of cellulose, decomposition of paper additives, etc. among others. Regarding the chemical degradation of paper, oxidation (and photooxidation) and hydrolysis reactions take usually place simultaneously. On the one hand, most oxidation reactions (many of them induced or enhanced by photoxidation) of cellulose are random processes that lead to the transformation of alcohol groups into carbonyl and carboxyl ones at various positions in the glucose-units of the cellulose. The formation of carbonyl and carboxyl groups increases acidity and induces depolymerisation, which is also reducing the physical and mechanical strength of the material. Furthermore, these groups are able to absorb visible radiation; they are chromophores and, as such, they are responsible for the yellowing of paper. On the other hand, hydrolysis is a reaction that breaks chains by adding a molecule of water to the structure. Acid hydrolysis is a type of hydrolysis that refers to cleavage at the glycosidic linkage between the carbon and oxygen by an acid. Acid hydrolysis can proceed with strong acids, which dissolve the substrate, or with weaker acids, where the cellulose maintains its fibrous structure. The loss of strength of paper upon ageing, particularly when the pH of the paper is low, is an effect of acid degradation.

All these processes together contribute to a significant gradual loss of mechanical resistance in paper objects.

Finally, paper may experience moisture induced deformations that are critical for the visual appearance of the objects.

Condition reporting

The most significant effort in compiling the information existing for condition reporting of paper artefacts has been done by the Book and Paper Group of the American Institute for Conservation (https://www.conservation-wiki.com/wiki/BP_Chapter_5_-).

In the Paper Conservation Catalog (wiki version), 2 types of written documentation reports are presented: examination reports and treatment reports. In 2016 (and again in 2018), Book and Paper Group members, and in particular, the Library Collections Conservation Discussion Group, submitted examples of written documentation and electronic documentation systems. These can be found as PDFs at: https://www.conservation-wiki.com/wiki/BP_Chapter_5_-_Written_Documentation#Examples_of_Examination_and_Treatment_Reports

Glossary and photos for paper degradation phenomena and paper conservation

There have recently been several initiatives to guide the description of paper features and condition.

The on-line book Descriptive Terminology for Works of Art on Paper (https://www.philamuseum.org/conservation/22.html) is a guideline for the accurate and consistent description of the materials and techniques of drawings, prints and collages published in 2015 as a result of a project led by the Philadelphia Museum of Art. The project was intended to address the need for more accurate and consistent documentation of the materials and techniques used to create works of art on paper and to provide conservators, curators, registrars, cataloguers and others charged with describing art on paper with a step by step approach for describing all aspects of the manufacture of these works.

The Archives Damage Atlas-A tool for assessing damage Library and the Damage Atlas-A tool for assessing damage are the result of Metamorfoze (https://www.metamorfoze.nl/english), the Netherlands' National Programme for the Preservation of Paper Heritage supported by the Ministry of Education, Culture and Science to engage in the struggle against acidification and other forms of intrinsic paper decay, such as ink corrosion and copper corrosion.

The book Damage Atlas (http://paber.ut.ee/EN/kalkulaator) is another initiative based on the methodology developed for the project "THULE-The State of Cultural Heritage in Major Estonian Libraries". It is a tool which enables to recognize damage and determine its extent. The Atlas presents the description of types and categories of damage with illustrative photos and it is meant to be used by all establishments and specialists in the field of conservation and also all interested amateurs. No previous knowledge or special skills are required to use it. The damage to books is assessed visually. The book condition calculator enables to summarize different types of damage easily and receive a general assessment of object condition.

As a result of the terms compiled by conservators all over Australia, the Australian Institute for the Conservation of Cultural Materials (AICCM) created a visual glossary (https://aiccm.org.au/conservation/visual-glossary) to identify damage and deterioration and to help describe an object's condition. The definitions used in this glossary are informed by those used in reCollections, a six-volume Australian publication launched in 1998 about caring for a wide range of collection materials, developed by Artlab and Australian conservators for the Heritage Collections Council and supported by the Ministry for the Arts, Attorney-General's Department.

Finally, AIC's Book and Paper Group compiled a Documentation Terminology consisting of a glossary and a wiki lexicon

- A glossary of terms written "for paper conservators, related professionals, and other persons who read written documentation created by paper conservators and intended to define specialized terminology used in condition and treatment reports which is not defined in general dictionaries, either adequately or at all. While a completely standardized vocabulary does not yet exist in the field, this glossary is an attempt to gather terms in general use and their meanings. Some terms are more widely used than others, and usage may vary according to individual conservators. Not included in the glossary are terms describing artist's techniques and media which have been well covered in a growing body of literature".
- A lexicon grouped by: condition terms and treatments terms https://www.conservation-wiki.com/wiki/Lexicon_Terms

Climate recommendations for paper artefacts

Climate recommendations for paper artefacts are closely linked to the general recommendations for cultural and natural heritage, as discussed in chapter "2. Preventive conservation – standards and regulations for environmental parameters". The 10 standards or guidelines considered relevant for CollectionCare are presented in Table 2, followed by the detailed Table 2.1. (temperature and relative humidity), Table 2.2. (radiation), Table 2.3. (air pollutants), and Table 2.4. (vibrations).

Two sources or standards carry specific recommendations regarding temperature and RH and paper artefacts. In UNESCO (now online) publication on "Museum collection storage", 1979, a temperature range of 15-22° C is recommended and a seasonal accepted cycle of 45-60% RH. The ASHRAE Handbook,1999 (p. 20.1 -20.13), recommends a temperature range of 15-25° C and 50% RH or a historic annual average for storage of paper in permanent collections.

Further three sources or standards carry recommendations for temperature and RH, as well as for light and UV-radiation. Concerning temperature and RH, CCI (the Canadian Conservation Institute,1995, online, notes 11.2) recommends <21°C and <50% RH. UNI10586 ("Condizioni climatiche per ambienti di conservazione di documenti grafici e caratteristiche degli alloggiamenti", 1997) recommends a temperature range of 14-20° C (±2° /day) and 50-60% RH (±5%) for paper artefacts in storage and 18-23ºC (±4º/day) and 50-60% (±5%) for paper artefacts in loan/exhibition conditions. IFLA (International Federation of Library Associations and Institutions, 1998) specifically cover paper artefacts in storage, recommending 16-21° C and 40-60% RH.

CCI, UNI10586, and IFLA carry recommendations on light and UV-radiation. Paper artefacts are generally considered sensitive or moderately sensitive to light and UV-radiation depending on their materials. They all recommend that the proportion of UV radiation in the light source used is not to exceed 75 μW/lumen if it cannot be fully eliminated. Concerning light CCI recommends restriction of exposure time in general and a maximum of 50 lux or as low as possible for sensitive paper artefacts (including watercolours and poor quality paper), while recommending a maximum of 150 lux for artefacts with stable inks on good quality paper. In the UNI10586 document 75 lux is recommended for storage conditions and 50 lux in case of loans and/or exhibitions. IFLA recommend 50 lux for storage (or 50.000 lux*hours/year).

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5.4 Description of wood

Basic structure and materials

Wood, in contrast to man-made materials, is a fully natural polymer formed as a secondary xylem by cell division in trees. Due to its availability and easy workability, wood is one of the oldest materials used by people for making buildings, vehicles, household items as well as art objects. In general, wood is characterized by diversity of both anatomical structure and chemical composition depending on its origin (softwood or hardwood, species, growing conditions of a tree, and location in tree trunk). However, regardless of species-specific variations, the chemical bases of all woods consists of two major chemical polymeric components: lignin (18–35%) and carbohydrates (65– 75%), and extraneous materials of minor amounts. Moreover, common characteristics of wood include anisotropy in three anatomical directions – longitudinal, radial and tangential, and dimensional instability in changing humidity due to its sorption characteristics.

Examples of types of objects in collections

A large diversity of wooden objects exists including individual items made completely of wood or wood used for making some part of another object (picture frame, icon base, handle). Moreover, different ways exist for joining separate wood pieces in one object such as gluing, using wooden or other material fasteners, finger-jointing etc. In addition, wooden objects can be covered with some kind of protecting or decorative coating or be treated with waxes, oils etc.

Types of wooden objects can be:

- Furniture
- Household items
- Musical instruments
- Art objects
- Other

Types of degradation

The main wood degrading abiotic factors are UV and shorter wavelength of visible light causing surface chemical degradation and discolouration, humidity alteration causing crack formation through dimensional changes, and oxygen causing auto-oxidation reactions resulting in wood ageing with the passage of time.

Wood biodeterioration is caused by different microorganisms, including wood discolouring fungi. Fungal growth is one of the main deterioration processes in museums across the world. Discolouring fungi (moulds and blue stain fungi) mainly deteriorate decorative properties of wood rather than affect strength, and increase wood permeability. Mould makes the surface grey and infected with spores and acts as a precursor of wood decay. Mould growth can also negatively influence the health of museum staff and visitors. The critical factors of mould development indoors are relative humidity, temperature, substrate surface, wood moisture content and time.

Long-term high RH near surfaces is the cause for fungi to appear. According to Sedlbauer (2001) the substrate material plays an important role in determining fungal growth conditions. By strategically lowering relative humidity and associated moisture contents, deterioration mechanisms can be slowed down or even stopped. The upper RH limit of 65% was adopted primarily as a threshold for mould growth. Much of the scientific literature suggests that the threshold for most moulds is about 70 to 80% RH, but the limit of 65% was found to work well in historic houses. This allows the difference between the measurement of the bulk room environment and of the cooler microclimates close to external walls in showrooms, as well as sensor inaccuracies. By maintaining room RH below 65%, one aspires to keep the coolest parts of a room below the more widely recognised 70 to 80% RH mould threshold.

Condition reporting

Glossaries and photographs of degradation phenomena:

Ashley-Smith, J., Burmester, A. & Eibl, M. (2012). Climate for Collections – Standards and Uncertainties. Postprints of the Munich Climate Conference 7 to 9 November 2012. P. 452.

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Matsuo, M., Yokoyama, M., Umemura, K., Sugiyama, J., Kawai, S. (2011). Aging of wood - Analysis of color changing during natural aging and heat treatment. Holzforschung, De Gruyter, 65 (3), pp.361-368. https://hal.archives-ouvertes.fr/hal-00702706/document (Accessed: 21.06.2019)

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https://www.dora.lib4ri.ch/empa/islandora/object/empa%3A8283/datastream/PDF/Turkulin-2004-SEM_Research_on_surfaces_of-%28published_version%29.pdf (Accessed: 21.06.2019)

Vereecken, E., Vanoirbeek, K. & Roels, S. (2015). Towards a more thoughtful use of mould prediction models: A critical view on experimental mould growth research. Journal of Building Physics, 39(2), pp. 102-123. https://journals.sagepub.com/doi/abs/10.1177/1744259115588718 (Accessed: 21.06.2019)

Douglas B. Murphy (2001). Fundamentals of light microscopy and electronic imaging.(2001), Wiley-Liss,ISBN 0-471-25391-X, pp. 357. http://www.biology.uoc.gr/courses/BIOL493/documents/book.pdf (Accessed:

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Climate recommendations for wood

Climate recommendations for wood are closely linked to the general recommendations for cultural and natural heritage, as discussed in chapter "2. Preventive conservation – standards and regulations for environmental parameters". The 10 standards or guidelines considered relevant for CollectionCare are presented in Table 2, followed by the detailed Table 2.1. (temperature and relative humidity), Table 2.2. (radiation), Table 2.3. (air pollutants), and Table 2.4. (vibrations).

Eight sources or standards carry specific recommendations regarding temperature and RH and wood.

Garry Thomson, 1978, divide the recommendations into two classes. Regarding class 1 - national museums and important new museum buildings - the recommendations are from 19° C (winter) to 24° C (summer) and 50% or 55% (±5% RH) as long term average. Regarding class 2 - e.g. historic houses and churches - the recommendation is a relatively constant temperature (to stabilize temperature and a long term average of 40-70% RH.

CCI recommended (1979) 21° C (allowing seasonal variation from 20° C to 25° C), a long term average of 47-53% RH and a seasonal cycle between 38% RH and 55% RH (5% variations can be tolerated exceptionally).

National Trust recommended (1994) temperature range within 5°-22° C, and a long term average of 58% RH, with 50-65% RH constituting alarm level 1, and 40-75% RH constituting alarm level 2.

ASHRAE (1999) recommended 15°-25° C, 50% RH (or a historic annual average), accepting no seasonal cycles of relative humidity, and accepting short term fluctuations only within 5% RH or 10% RH, depending on the accepted level of control. In case of less or non-vulnerable wood, seasonal cycles can be accepted in ranges such as ±10% RH and up to 25-75% RH. Classes of control: AA, A, B, and C.

National Trust recommended (2006) temperature range within 5°-22° C, and a long term average of a target level of 50-65% RH. National Trust recommended individual set points in each room, depending on object conditions and proofed acclimatization.

Smithsonian Institution (2007) recommended 21° C, and a long term average of 45% RH (±8%).

The National Museum directors Conference (UK, 2009) recommended 16-25° C and a long term average of 40-60% RH. This being general recommendations of objects of organic, hygroscopic nature, the conference recommended specific and tighter control for sensitive panel paintings, e.g.)

The European Standard (EN15757, 2010) only carries recommendations for maximum short term fluctuations, constituting 10% RH (or calculated from a historic climate).

CEN TS 16163 (2014) and Latvian Rules for National Museums collections (2006) carry recommendations on light and UV-radiation. Both documents recommend that the proportion of UV radiation in the light source used is not to exceed 75 μW/lumen if it cannot be fully eliminated. Concerning light, CEN TS 16163 recommends a maximum illuminance of 200 lux and the Latvia document limits the illumination to 150 lux.

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6. Degradation models

Museums and collections generally store a large variety of art objects, which may be extremely different in their nature (i.e. materials they are composed of) and in the environmental conditions they experience. As a consequence, different types of degradation mechanisms occur. Focusing on the analysis of paper objects, wooden objects, paintings on canvas and metal objects as in the goals of CollectionCare, the most relevant degradation agents (e.g. temperature, relative humidity, radiation, pollutants and vibrations) and the associated degradation mechanisms are summarized in Table 6.

MATERIAL	DEGRADATION AGENT	VULNERABILITY	TYPE OF DAMAGE INDUCED
Paper	Relative Humidity and Temperature	+++++	Dimensional changes Chemical degradation: oxidation/ acidity Mechanical damage (brittleness, weakening, tears, etc.) Bio-deterioration Corrosion (iron gall inks)
	Radiation	++++	Yellowing Chemical degradation: oxidation/acidity Brittleness Discolouration of inks (watercolours, etc.)
	Pollutants	++++	Chemical degradation: oxidation/acidity Bio-deterioration
	Vibration	+++	Failure of dry techniques (charcoal, pastel, etc)
Wood	Relative Humidity and Temperature	+++++	Dimensional changes Mechanical damage (fissures, cracks, separation of joints, etc.) Chemical degradation: oxidation/ acidity Biodeterioration (mould, etc)
	Radiation	+++	Discolouration of pigments Darkening of wood

	Pollutants	+++	Bio-deterioration Rotting
	Vibration	++++	Mechanical damage (fissures, cracks, separation of joints, etc.)
Paintings on canvas	Relative Humidity and Temperature	++++++	Chemical degradation of painting materials Dimensional changes of fabrics Internal stresses Oxidation of cellulose (darkening and weakening of the fabric) Corrosion of nails (and oxidation of the surrounding fabric) Dimensional changes of the wooden stretcher
	Radiation	++++	Discolouration of pigments Yellowing and polimerization of binding media and varnishes
	Pollutants	++++	Bio-deterioration
	Vibration	+++++	Internal stresses
Metals	RH and temperature	+++++	Corrosion Thermal degradation (thermal cycling): phase formation and transformation, interdiffusion for materials/contacts
	Radiation	+	Laser (?)
	Pollutants	++++	Chemical degradation (Steinberg model)
	Vibration (e.g. during transport)	+	Vibration fatigue Strain energy models for solders (Coffin-Manson model)

Table 6. Overview on degradation agents and mechanisms associated to different types of art objects

6.1 Canvas paintings

The most critical degradation agents for canvas paintings are the relative humidity and the temperature, which cause moisture induced dimensional changes both of the paint layers and the support, consequently introducing internal stresses in the system and promoting the onset of mechanical damage. Chemical degradation may be also associated to these degradation agents.

6.1.1. Details on the degradation models

Modelling relative humidity and differential temperature induced stresses and mechanical damage in multi layered canvas paintings

A single painting generally consists of numerous layers of different materials (e.g. canvas, ground, glue, paint and varnish), which exhibit a different mechanical response when exposed to dynamic environmental conditions, as a function of both the location in the paint and the time. Degradation of historical paintings is particularly triggered by the effect of relative humidity and temperature. These can, on the one hand, cause the change of mechanical properties of the paint material (which generally decrease as RH and T increase) and on the other hand promote differential shrinkage/swelling of the layers, introducing internal stresses in the system (Mecklenburg & Tumosa, 1993; Mecklenburg, 2007). The combination of these phenomena can lead to cracking in paintings and further delamination of the paint layers, which may eventually risk falling off.

The reference degradation model refers to the computational method based on finite elements (FE), applied by Mecklenburg & Tumosa (1993) to compute the stress development in paintings (Figure 6.1.1). This method will be extended to achieve a better representation of the physical reality. For example, the geometry of the layered system will be described in a more accurate way, by modelling explicitly the cross-sectional profile of the textile support, which was previously idealized as regular rectangular layer. In addition, the analysis will assume inhomogeneous material properties in the plane and will characterize the interface response between the layers, by referring to experimental data extracted from peel-off and shear tests.

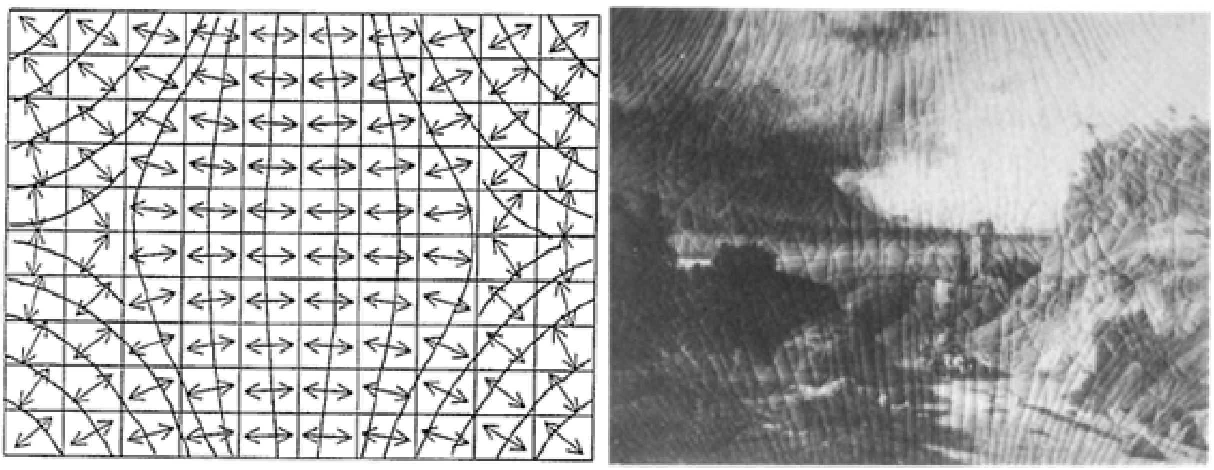

Fig. 6.1.1. The computed paint stress directions and crack prediction from cooling a model painting (Mecklenburg et al., 1993).

6.1.2. Experimental data

An overview of existing mechanical test results on paints, glues and canvases is needed along with an assessment of the need for additional experiments for the numerical models in order to give a widely facetted characterization of paintings behaviour with a worst-case approach based on conservation experience. These may include the measure of hygro-expansive strains upon moisture cycles and the measure of mechanical properties as a function of time and of the relative humidity.

6.2 Metal objects

Considering Table 6, the most critical degradation agents for metallic art objects appear to be relative humidity, chemical compounds and pollutants as well as temperature. Therefore, the selected degradation models are related to these degradation agents and focus on the prediction of chemical degradation of surfaces and near-surface regions, particularly corrosion (Robbiola et al, 1998), and on thermal degradation caused by phase formation and phase transition and – in the case of materials couples – interdiffusion.

6.2.1. Details on the degradation models

Modelling chemical degradation and corrosion

To evaluate the vulnerability to corrosion of archaeological metal objects, simple corrosiveness tests were introduced into museums by Andrew Oddy in the 1970's. They rely on accelerated ageing of metal test coupons which are placed in a sealed environment at elevated temperature and humidity together with possible hazardous materials. Severity of corrosion on the indicators is evaluated regularly being the base for final conclusions. Departing from this reference methodology, corrosion of metal alloys will be assessed by analysing the effect of airborne particles of variable composition deposited on the surface of model samples. These data will allow to formulate heuristic criteria to predict corrosion of the metal alloy as a function of several parameters, such as the type of alloy (particularly copper, iron, lead, tin and zinc, which are sensitive to corrosion processes), the composition of the airborne particles, temperature, relative humidity, time.

In case of materials couples (e.g. welded parts or solder connections, but also mechanically connected parts, using no additions or using fasteners, rivets, etc.), additional solid-state physical and chemical processes such as contact corrosion caused by different electrochemical potentials and interdiffusion caused by gradients in the element concentration have to be considered. These processes are thermally activated processes, i.e. temperature-dependent degradation mechanisms are expected (Arrhenius-type of atomic transport mechanisms).

In addition, radiation is an agent to be considered in case the energy is concentrated on a small area or volume (e.g. lasers). Vibrations and related fatigue processes in metallic materials.

Generally, all technical metallic materials exist in a non-equilibrium state. That means in the case of precipitation-hardened alloys that the precipitation kinetics is ongoing in art objects. Whether these kinetic processes result in real degradation in relevant periods of time, depends on the material (e.g. melting temperature) and the temperature in the environment of the object. In most of the cases, these kinetic processes can be neglected.

6.2.2. Experimental data

Experiments to assess corrosion of metal alloys needs to be performed by depositing variable airborne particles, collected from the museums participating to the CollectionCare project, on the surface of the metallic samples and by performing corrosiveness tests simulating artificial ageing.

In addition to surface-related studies, it is planned to characterize the materials microstructure with diffraction and metallographic (imaging) techniques.

6.3 Paper objects

Considering Table 6, the most critical degradation agents for paper art objects appear to be relative humidity, radiation and pollutants. The selected degradation models are therefore related to these degradation agents and focus on the prediction of moisture induced dimensional changes, mechanical damage and chemical degradation.

6.3.1. Details on the degradation models

Modelling moisture induced dimensional changes and mechanical damage

Paper is a complex multi-scale material mainly consisting of cellulose fibres bonded to each other to form a discrete network. Paper fibres are extremely sensitive to moisture content variations. This affects the effective hygro-expansive response at the sheet level, which is generally manifested through complex in-plane, and especially out-of-plane deformations. The reference degradation model is based on a random network model, characterized by an anisotropic orientation probability density function – see Figure 6.3.1 (Bosco et al., 2017). Referring to a finite element solution scheme, the fibres are modelled as two dimensional transversely isotropic elements. This allows to describe the coupling occurring in the bonding regions between the longitudinal and transverse hygro-mechanical properties of the fibres that strongly influence the overall response of the material. A dedicated constitutive model allows to represent the main features of paper deformation, including moisture dependency of the mechanical properties, creep and ageing effects (Bosco et al., 2015). The mechanical behaviour of the network is finally coupled with moisture diffusion.

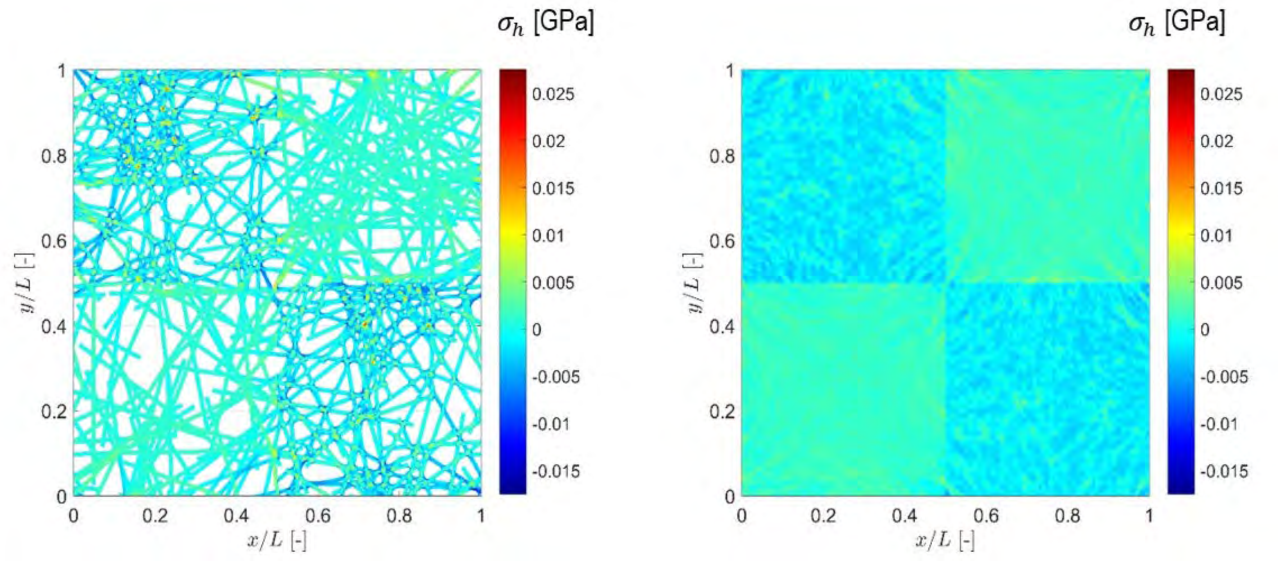

Fig. 6.3.1. Distribution of the hydrostatic stress (in GPa) in two paper networks of different density corresponding to a moisture content variation.

The fibrous network is subjected to moisture cycles, yielding inhomogeneous moisture distributions in the system. The moisture induced strains and stresses are firstly quantified in order to identify the regions that are characterized by higher stress levels and in which damage can potentially initiate.

Further, the effective material response of the network is calculated by using the asymptotic homogenization method. This allows to obtain the effective mechanical (e.g. elastic modulus, strength) and hygro-expansive properties of the paper network as a function of the evolution of moisture content in time. This tool can provide an estimate of the extent of the degradation of paper art objects.

Modelling chemical degradation

The fibrous network model discussed in the paragraph above can be extended to incorporate chemical degradation. This can be done by formulating an appropriate constitutive model for the paper fibres that describes the degradation of cellulose in terms of the loss of degree of polymerization, along the lines of Ding et al. (2007).

Input parameters: The input parameters for the numerical analysis, such as the hygro-mechanical properties at the fibre level, are initially taken from different sources in the literature (Bergander & Salmén, 2002; Niskanen, 1998; Schulgasser & Page, 1988).

6.3.2. Experimental data

An overview of experimental data in the literature on ageing of paper due to hygro-mechanical loadings and to chemical degradation will be provided. Additional experiments on mock-ups will be planned both to provide input parameters and to validate the model. These may include the measure of hygro-expansive strains upon moisture cycles and the measure of mechanical properties as a function of time and of the relative humidity.

6.4Wooden objects

The most critical degradation agents for wood materials are the relative humidity and the temperature. These may be the cause of different types of degradation mechanisms such as biodeterioration, chemical and mechanical damage. Radiation is another critical degradation agent, which promotes photodegradation of wooden objects.

6.4.1. Details on the degradation models

Modelling radiation induced photodegradation

Wood photodegradation depends upon the incident radiation intensity and wavelength composition, duration of exposure and wood characteristics such as species, origin (growing site and trunk zone – sapwood/heartwood), and density. Temperature and humidity are also factors affecting wood photodegradation. For simulation of solar radiation effect on wood, artificial weathering by applying irradiation with fluorescent UVA-340 type lamps or xenon arc lamps with adjusted filters is common practice. For simulation of sun through glazing, UVA-351 type lamps are used. More detailed wood photodegradation analyses depending on the incident radiation wavelength are based on exposing wood to irradiation under cut-off filters transmitting only radiation of definite wavelength. The data collected from these analyses will allow to formulate heuristic criteria to predict wood photodegradation.

Modelling biodeterioration inducing factors

Ambient RH above 75 - 80% is a critical limit for the development of mould fungi on the surface of wood and other wood based building materials (Viitanen, 2014). The temperature range required for mould growth is mostly between 0 and +50°C. The mould fungi grow rapidly at higher humidity (RH > 95%) at temperatures between 20 and 40°C. At low temperatures (below 5 °C), the growth of mould fungi is slower even at high RH. Some fungi species can grow at low temperatures, around 0 and - 5°C and some species prefer high temperatures, around 45 - 50°C (Viitanen, 2014). In Figure 6.4.1., the critical temperature and humidity limits for risk of mould growth on wood is shown (Viitanen & Ojanen, 2007).

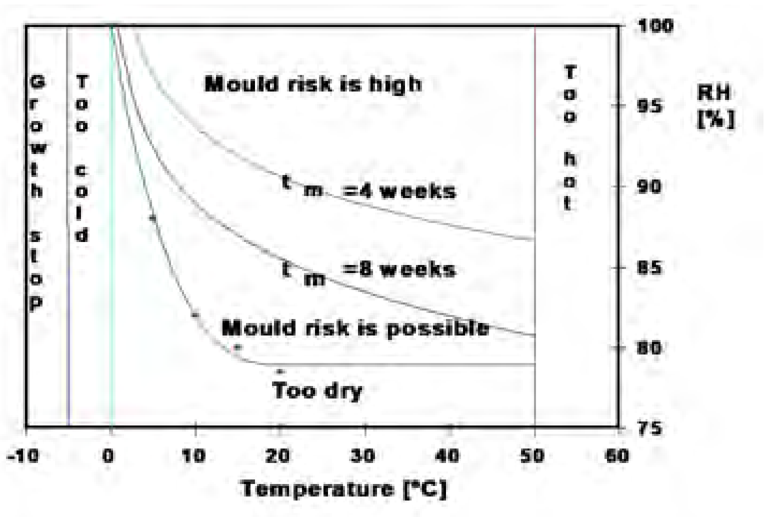

Fig. 6.4.1. An overview model on the critical temperature and humidity limits for the risk of mould growth (Viitanen & Ojanen, 2007).

Modelling of the development of mould growth is a tool for evaluating the eventual risk of ambient humidity or material moisture conditions for biodeterioration (Viitanen, 2011). Moisture availability is the primary factor controlling mould growth development, but the characteristics of the substrate and environmental conditions determine the dynamics of the growth. The models make it possible to evaluate the critical conditions needed for the start of growth of fungi. A systematic literature review on mould prediction models is provided in Gradeci et al. (2017). Consistent experiments will be performed to assess the reliability of these models as described in the paragraph below.

6.4.2. Experimental data

Experiments to assess photo degradation of wood materials needs to be performed. Discolouration and chemical changes will be measured for wood specimens subjected to irradiation with different radiation wavelength composition. Radiation sources such as fluorescent UVA-340 and UVA-351 type lamps, and solar radiation through three cut-off filters can be used. Discolouration should be quantitatively traced by regular spectrophotometric reflectance spectra measurements and data conversion into the CIELAB colour model parameters L*, a*, b* from which discolouration, expressed as a distance between the coordinates of two colours (initial and resulting) in the three-dimensional CIELAB colour space, will be computed.

Bio deterioration should also be assessed by measuring the growth of mould as a function of several parameters, such as the ambient relative humidity, temperature and initial wood moisture content.

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7. Sensors

In this, and the following sections technological options and considerations relevant to the CollectionCare project are described. In this chapter different options for choosing appropriate sensors are discussed.

7.1 Sensors for measuring temperature

7.1.1 Air temperature

As mentioned in chapter 3, air temperature (T) is the temperature read on a thermometer, which is exposed to air in a position sheltered from direct solar radiation or other energy sources. Many types of sensors measuring T are available, but not all are suitable for microclimate monitoring.

Mercury or spirit -in glass thermometers (usually named liquid-in glass thermometers) are the most popular sensors used to measure T, also in some old not automatic weather stations. The operating principle of this type of sensor is based on volume changes when air is heated or cooled. As the liquid level changes, a corresponding temperature scale can be read to indicate the current temperature. Continuously recording temperature readings are not possible. The use of liquid-in glass thermometers in the field of microclimate is not recommended.

Bimetallic thermographs are in use today both in old not automatic weather stations and in museums. This type of sensor is often associated with hair hygrometer and called thermohygrograph. The bimetallic strip is constructed by bonding together the two thin strips of different metals having different thermal expansion property. Therefore, the difference in thermal expansion rates is used to produce deflections that are proportional to changes in temperature. This type of sensor requires frequent controls and at least monthly maintenance which in practice are not often followed. This sensor is not included in the list of instruments recommended by EN 15758: 2010.

Metal resistance sensors are based on the characteristic that the electric resistance value of metal linearly changes with temperature. Platinum resistance thermometers are used most widely in many fields. Platinum resistance sensors are very small and their features are in accordance with the metrological characteristics issued by EN 15758:2010.

A thermistor is a resistance thermometer using semiconductors as sensitive elements. The thermistor has a high temperature coefficient of electric resistance, which usually decreases when temperature increases, but with nonlinear relationship, differently from resistance sensors. This sensor is also small like the resistance sensor but it is more sensitive than the latter. The features are in accordance with the metrological characteristics issued by EN 15758:2010.

Thermocouples consists of at least two metals put into contact at their ends to form two junctions. One is connected to the body whose temperature is to be measured. The other junction is connected to a body of known temperature. The working principle of the temperature measure is based on the generation of electromotive force between the two junctions, which is a function of the temperature difference between the two junctions.

All T sensors are installed in tailored screen devices in order to avoid to be reached by direct solar beams or artificial light, but at the same time well ventilated.

7.1.2 Surface temperature of objects

The same sensors for measuring air temperature can be used for measuring the surface temperature (Ts), but only three methodologies can be used in accordance with European standard EN 15758:2010, depending on the material of the object, its vulnerability, size and its location. The Standard recommends to measure Ts with contact sensors using platinum resistance sensors, thermistors, thermocouples when it is strictly necessary and upon the consultation of conservators. Quasi-contact thermometers are indeed installed close to the surface but not in contact with the surface. Remote thermometers which are located at safe distance from the surface and based on measuring the IR from the body.

Instruments	Symbol	Measuring range	Uncertainty	Repeatability	Resolution	Response time	Stability
Thermometer for air temperature	T	Outdoors -40°C to 60°C Indoors -20°C to 60°C	Required: 0.5°C Desirable: 0.2°C	0.1°C	0.1°C	The shortest possible; not longer than 60 s	±0.2°C/year
Surface temperature (contact or proximity sensors)	Ts	Outdoors -40°C to 100°C Indoors -20°C to 80°C	Required: 1°C+0.01|T-Ts| Desirable: 0.5°C+0.01|T-Ts|	0.2°C	0.1°C	The shortest possible; not longer than 200 s	±0.2°C/year
Surface temperature (remote sensors)	Ts	Outdoors -40°C to 100°C Indoors -20°C to 80°C	Required: 1°C+0.01|T-Ts| Desirable: 0.5°C+0.01|T-Ts|	0.5°C	0.1°C	The shortest possible; not longer than 60 s	±0.2°C/year

Table 7.1. Metrological features of sensors for measuring temperature. This table has been extracted from the European standard EN 15758:2010.

7.2 Sensors for measuring relative humidity

Several sensors have been developed for measuring relative humidity. In this section, an overview of hygrometers that can be used in the field of preventive conservation is given. Hygrometers can be classified as follows:

Dew-point meter: based on detecting temperature of a cooled mirror at the point where condensation forms (high-quality, accurate, calibration purpose);

Electronic fan psychrometer: based on matching temperature readings of two thermometers (one detects dry-bulb temperature and other detects wet-bulb temperature) both ventilated with a forced air flow (field measurements, accurate, calibration purpose);

Thin-film capacitive hygrometer: based on the capacitive effect of a thin-film of a hydrophilic material (a dielectric material) surrounded by electrodes to vary according to moisture content changes in ambient air (long-term monitoring on-site);

Thin-film resistive hygrometer: based on the impedance effect of solution resistance cells or polystyrene film cells made of hydrophilic material to vary according to moisture content changes in ambient air (long-term monitoring on-site);

Hair hygrometer: based on the elongation of hair or synthetic fibres (large hysteresis, departing from linearity, continuous maintenance and frequent calibration). This sensor is not included in the list of instruments recommended by EN 15758: 2010.

	Dew-point meter	**Electronic fan psychrometer**	**Thin-film capacitive hygrometer**	**Thin-film resistive hygrometer**	**Hair hygrometer**
Accuracy level	1: very high	2: high	3: medium	3: medium	4: low
Measuring range	-20°C to 50°C	5-95% 10°C to 50°C	5-95% -10°C to 50°C	5-95% -10°C to 50°C	35-95% -10°C to 50°C
Uncertainty	0.5°C	2%	3%	3%	10%
Repeatability	0.2°C	1%	2%	2%	5%
Resolution	0.1°C	1%	1%	1%	2.5%
Instrument time constant (63%) in still air	not relevant	required: ≤2 min desirable [c]: ≤1 min	required: ≤5 min desirable: ≤2 min	required: ≤5 min desirable: ≤2 min	10 min
Stability	≤0.2°C/year	≤2%/year	≤2%/year	≤2%/year	5%/month
Periodic checking and maintenance	6 months	calibration: 1 year; Wick: daily, or when the instrument is used	1 year	1 year	3 months
Recommended use	laboratory calibration	1) checking calibration of other hygrometers 2) spot field measurements	spot or routine measurements; data collection for statistical analysis	spot or routine measurements; data collection for statistical analysis	only for exceptional circumstances for visual inspection

Table 7.2. Metrological features of sensors for measuring relative humidity. This table has been extracted from the European standard EN 16242:2012

7.3 Sampling frequency

As specified in section 3 sampling frequency should be chosen in order to be able to detect the shortest variation of phenomenon of interest.

This means that when RH and T fluctuations are very fast (for example a numerous group of visitors in a small room) it should be evaluated whether they may affect the state of the object housed in the room before setting the sampling frequency.

In fact according to the response time of the material, very fast RH cycles may not be noticed by the bulk of the object, so there could be not a response to these cycles.

Increasing the frequency seems to be important in microclimatic characterization, but there are a couple of problems with increasing this sampling frequency. Namely, increasing in data amounts implies a database so large that it could be difficult to manage and interpret and increase in the energy expenditure of the probes.

It is necessary to reach a compromise between energy expenditure, minimum data to characterize the microclimate and ease of handling and interpretability.

Among the studies of microclimates in art works, is usual to take a frequency of one data per hour if the microclimate assessment is based on the calculation of running moving averages.

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EN 15758 Conservation of Cultural Property – Procedures and instruments for measuring temperatures of the air and the surfaces of objects. European Committee for Standardization, Brussels, 2010.

EN 16242 Conservation of Cultural Property – Procedures and instruments for measuring humidity in the air and moisture exchanges between air and cultural property. European Committee for Standardization, Brussels, 2012.

8. Wireless technology

CollectionCare will use battery-powered wireless sensor nodes to collect and transfer environmental information wirelessly using electromagnetic waves.

Wireless technology excels in this project because it can provide a flexible, scalable, easy to install and cost-effective solution compared to its wired counterparts. Moreover, a well-conceived installation procedure combined with its wireless nature can minimize the visual impact on the object on display.

This section attempts to describe the basic principles of wireless communications, the associated issues, and the limitations imposed by the specific technologies selected for CollectionCare. Knowing these limitations in the early stages of the project will allow us to concentrate on viable solutions and discard those that are not viable today.

8.1 Electromagnetic waves and radio spectrum

Wireless transmission in CollectionCare is based on electromagnetic waves. In classical physics, an electromagnetic wave is a synchronized oscillation of magnetic and electric fields, that is, a changing magnetic field induces a perpendicular electric field which in turn induces another magnetic field and so on. These fields propagate at the speed of light in the vacuum.

The rhythm at which the fields change is named *frequency* (measured in cycles per second or Hz) and the distance over which the wave's shape repeats is named *wavelength*. Visible light is a mixture of different wavelength electromagnetic waves, so it is ideal to illustrate how electromagnetic waves behave from an artist's point of view. Figure 8.1.a shows a beautiful piece with nice blue decorations, it is blue because it reflects a wavelength of 450-495 nm (nanometers or billionths of a meter) and the rest of wavelengths that our eyes can “see” are absorbed.

The electromagnetic waves used in CollectionCare’s sensor nodes behave in the same way: they cross some materials with more or less difficulty, they are absorbed by other materials or, perhaps, they are reflected. The “only” difference is the frequency/wavelength of this signal and, therefore, its behaviour (blue and red light do not behave in the same way).

Fig. 8.1.a. Ceramic piece by Charles Catteau (Source: KMKG)

The radio spectrum is the part of the electromagnetic spectrum or range of frequencies used for radio communications. This range goes from 30 Hz to 300 GHz (GHz = 1,000,000,000 Hz) and are known as *radio frequency* (RF). For simplicity, they are divided in radio bands, that is, a contiguous range of frequencies with similar properties that are normalized by different international cores. Figure 8.1.b shows the names of the bands for different international institutions.

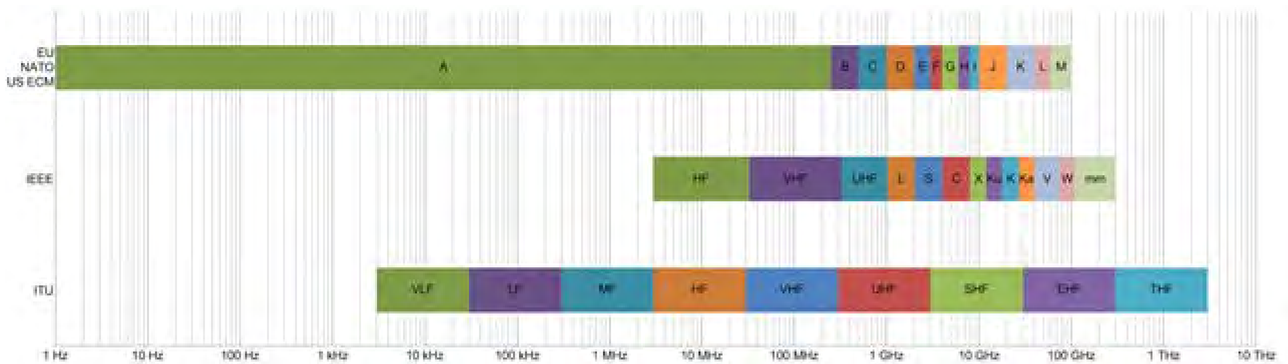

Fig. 8.1.b. Comparison of frequency band designation (Source: Wikipedia)

For example, to listen to your favourite radio station in the car, the radio receives a VHF signal of a hundred MHz (1 MHz = 1,000,000 Hz) in a licensed band using FM modulation and a transmission power of 1 kW (1,000 W).

CollectionCare wireless technology must select a given radio band and deal with associated behaviour and regulatory limitations. Each radio band has their advantages and disadvantages, so the selection must be focused on the problem to be faced. How these radio bands are utilized is also critical because each modulation technique is affected in a different way by other radio signals, radio interference, reflections and fading.

Each country has different RF regulations. In Europe, we are considering that the most appropriate radio band for collection care are the 433 and 868 MHz ISM (Industrial, scientific, medical) bands. The ISM bands were initially reserved for non-communications uses of RF energy, such as microwave ovens. In recent years, these bands have mostly been used by short-range low-power communications systems, since users do not have to hold a radio operator's license. WiFi connections, Bluetooth devices, cordless telephones and garage door openers use these bands. A main drawback of ISM bands that they do not have an adequate regulatory protection against interference from other users of the band. This is the reason why they are called *unlicensed bands* compared to the bands utilised by the mobile operators named *licensed bands* (Bands that users pay for).

Specifically, CollectionCare will use the 868 MHz radio band because it has a convenient trade-off between antenna size, object penetration and reached distance. Considering that wireless installation will be indoors, the recommendation ITU-R P.1238-7 (2012) indoor propagation model is adequate to estimate the path loss inside a room or a closed area inside a building delimited by walls of any form. Deliverable D1.4 is a good example of typical scenarios.

Any wall, window, object, etc. will attenuate and/or reflect the RF signal between transmitter and receiver. Table 8.1 classifies typical blockers in museums and objects storages based on the RF attenuation level. Deliverable D1.4 provides quantitative values of different types of materials.

Attenuation	Materials
Low	Wood, curtains, transparent glass, paper, plastic.
Medium	Walls of bricks or plasterboard, animals, plants.
High	Ceramic tiles, concrete walls, stone walls, bulletproof glass, floor separation.
Very high	Reinforced concrete, metal walls, elevator cage, mirrors, golden wood

Table 8.1. Classification of materials based on RF attenuation at 900 MHz

8.2 Digital wireless communications

Most modern devices with wireless communication capability employ digital transmission techniques. This includes wireless phones, mobile phones (including voice), laptops, etc. Like digital computers, these data are 0s and 1s that are transmitted by modulating the signal. For example, using the FM analog radio technique in digital systems is called frequency-shift keying (FSK), and in AM it is called amplitude-shift keying (ASK). The demo site in Santo Tomás Church in Valencia (Spain) uses FSK at 868 MHz for transmitting data. Figure 8.2.a. illustrates an FSK modulation.

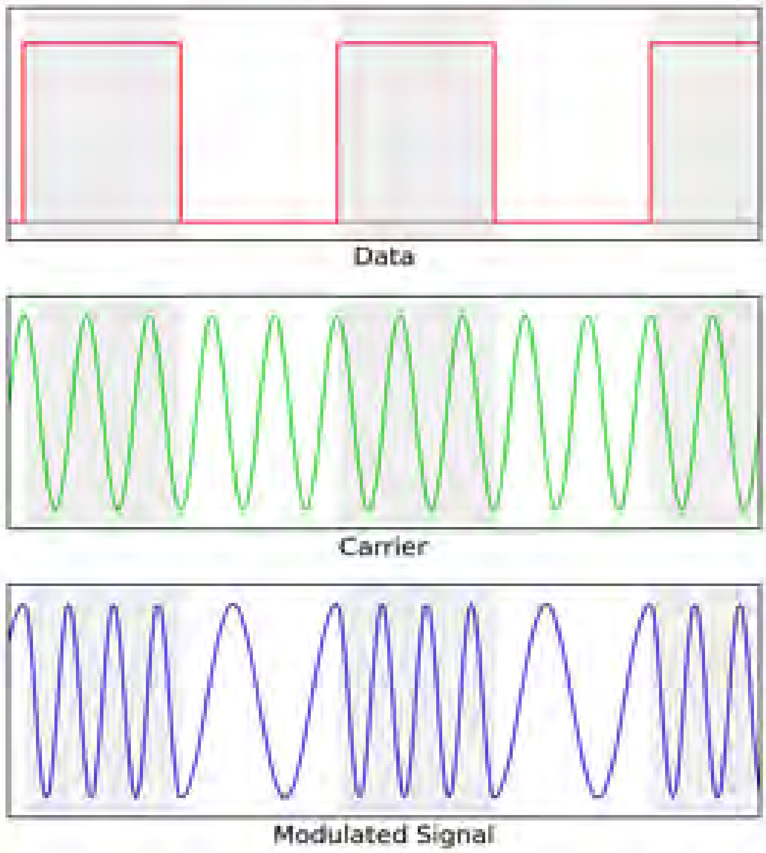

Fig. 8.2.a. FSK principle of operation (Source: Wikipedia)

There are many different RF modulation techniques and each one has advantages and disadvantages. Complex modulations are able to provide more bandwidth (data transmitted per time unit) or/and are more robust to interferences. Higher frequencies also provide higher bandwidth but lower communications range.

From a practical point of view, our choice should be focused on the characteristics that each solution provides. Some of these key pragmatic concepts are:

- Coverage: defines the range of communications, that is, the reached distance.
- Dependability: wireless communications are extremely susceptible to interference. Radio signals, radiation and any other similar type of interference may cause a wireless network to malfunction.
- Bandwidth: measured as the quantity of data transmitted per time unit.
- Security: Wireless networks can be received by any computer within the range of the network's signal, so information transmitted through the air may be intercepted by unauthorized users. Encryption techniques are fundamental
- Energy: Wireless transmissions need to generate energy in the form of electromagnetic waves. Receiving wireless communications is also an energy consuming task.

Figure 8.2.b tries to summarize the available commercial solutions from the point of view of bandwidth and coverage. An ideal solution should provide high bandwidth and large communications range.

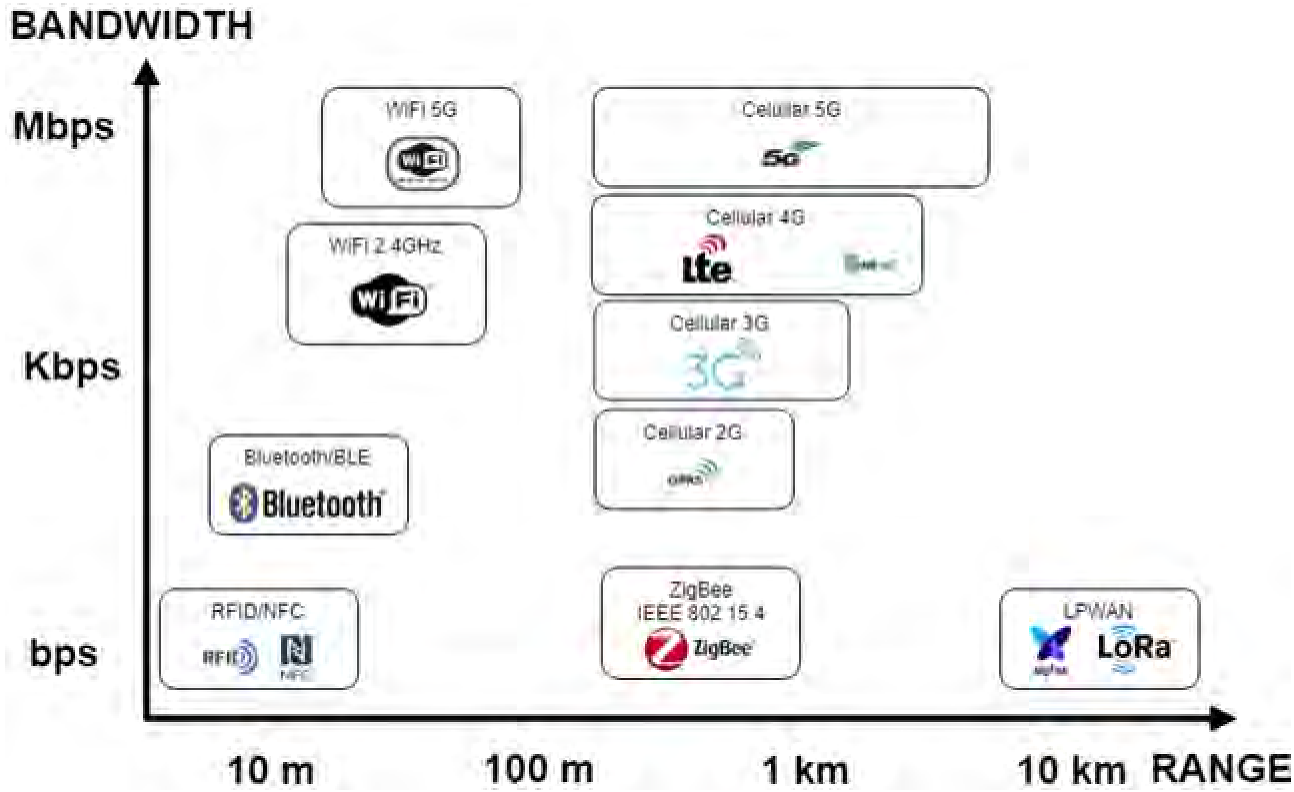

Fig. 8.2.b. Common wireless digital communications technologies available today (Source: own)

Wi-Fi is a popular technology currently working on the unlicensed bands of 2.4 GHz and 5 GHz providing an excellent bandwidth. It has a coverage of around 100 meters in open spaces but is not well suited to deal with obstacles. Using the appropriate encryption techniques (e.g. WPA2 enterprise) it could be considered a secure approach. Due to its popularity, there are several products focused on preventive conservation that use this technology (see sec. 4.5). The main disadvantages for CollectionCare would be the difficulty in handling the obstacles and the energy required by the nodes that would limit the lifespan.

Bluetooth shares the same 2.4 GHz with WiFi, so it shares similar drawbacks with WiFi. It is focused to shorter distances and is more energy friendly so it is possible to develop products that are able to communicate for many years. It is not feasible for CollectionCare because of its distance limitation. Bluetooth is focused on replacing connecting cables and therefore presents interesting data logger solutions for preventive conservation (see sec. 4.5). However, it is not feasible for CollectionCare because its short range limitations.

RFID (Radio Frequency Identification) is a short range wireless technology that uses electronic tags placed on objects, people, or animals to relay identifying information to an electronic reader. Near Field Communication (NFC) could be considered an evolved RFID technology devoted to secure very short range communications and widely implemented in smartphones. Both RFID and NFC are not adequate for CollectionCare but could be a complement in object tagging tasks.

IEEE 802.15.4 is focused to low-rate wireless personal area networks (LP-WPAN) and deals with low data rate but very long battery life and low implementation complexity. It is based on the creation of "mesh" networks where intermediate nodes act as routers of information. There a very interesting commercial implementations such as Thread, 6lowWPAN, WirelessHART, Zigbee and ISA100.11a. In general, these implementations use the unlicensed band of 2.4 GHz, so important drawbacks apply related to signal coverage inside museums. This option was discarded, since it was considered that mesh-based implementations are prone to faults when any node fails and tend to exhaust batteries of routing nodes. Some data loggers used in preventive conservation use this standard (see sec. 4.5).

Cellular communications is another must when designing wireless devices. Thanks to the global coverage of this technology and to the fact that they work through licensed bands, its universal accessibility can be guaranteed. The main drawback of this approach are the economic cost of connectivity and the energy needed in the nodes, which makes it unfeasible if battery life of years is intended. With the exception of the NB-IoT (commented later as part of the LPWAN section) specification, the rest of the cellular communication proposal is unsuitable for CollectionCare.

Finally, low-power wide-area networks (LPWAN) is a new category of wireless technologies focused on solving the needs of Internet of Things (IoT) in the context of Smartcities. Next section is devoted to this type of digital wireless communications.

8.3 Low-power wide-area networks (LPWAN)

Due to the development of the IoT on the last decade, new wireless communication technologies have been launched in order to fulfill the needs of these new connected devices.

Low-power wide-area networks (LPWAN) are the ones oriented to low power devices with a long range coverage, but with a very low limited bandwidth. This is the ideal case for simple wireless sensors operated on battery.

They operate on sub-gigahertz RF bands so they have better figures penetrating objects than equivalent technologies using 2.4 GHz band. For example they operate in the unlicensed 868 MHz ISM band in Europe (Sigfox, LoRa) or in the 800 MHz licensed band in the case of cellular-based implementations (NB-IoT).

The operating range of this kind of networks varies from a few kilometers in urban areas to over 10 km in rural areas.

From our point of view, three LPWAN technologies meet the requirements of CollectionCare: Sigfox, LoRa and NB-IoT.

8.3.1. Sigfox

Sigfox is a global provider of IoT connectivity for low-power objects present in 50 countries. Its proprietary technology employs the unlicensed ISM band of 868 MHz in Europe, using a robust modulation technique and an “ultra-narrow band” (UNB) approach, allowing thousands of objects working in the same area of each Sigfox cell. Figure 8.3.1. shows the operation principle of Sigfox.

The band that is used, the modulation technique and the UNB approach allow a coverage range of about 10 km and good object penetration, being ideal for smartcity scenarios.

The main limitations of Sigfox are a maximum “uplink” payload (data transfer from one node to one cell) of 12 bytes and a maximum “downlink” payload (data transfer from cell to node) of 8 bytes. Due to European regulations, a maximum of 140 uplink messages per day is allowed at a data rate of about 100 bytes per second.

In the context of CollectionCare, these limitations impose a minimum of 10 minutes between transmissions and 3 or 4 measurements of physical magnitudes per message.

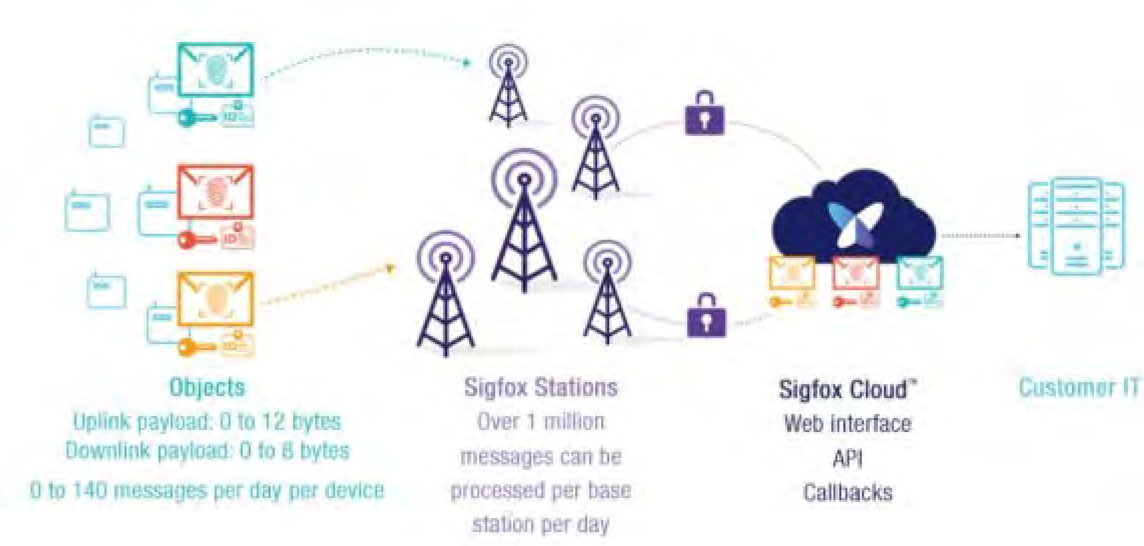

Fig. 8.3.1. Sigfox operation principle (Source: Sigfox)

8.3.2. LoRa

LoRa (Long Range) is a type of LPWAN modulation developed by Semtech that operates on the same ISM unlicensed band as Sigfox (868MHz). It defines the physical layer of the LoRa based network.

LoRaWAN is the Low Power Wide Area Network based on LoRa modulation. It is a open-source cloud-based network protocol that manages communications between gateways and end devices suchs a sensors and serves the data to the end application.

It is a star topology, meaning that the sensors transmit messages using LoRa modulation, which is received from one or more gateways. The gateways are connected to the network server through the Internet that receives the messages and perform all the decoding and decrypting, before it finally sends the information to the final application or database. Figure 8.3.2.

Due to the open-sourceness of this network stack, the development of a custom private network using LoRa wireless technology is relatively easy.

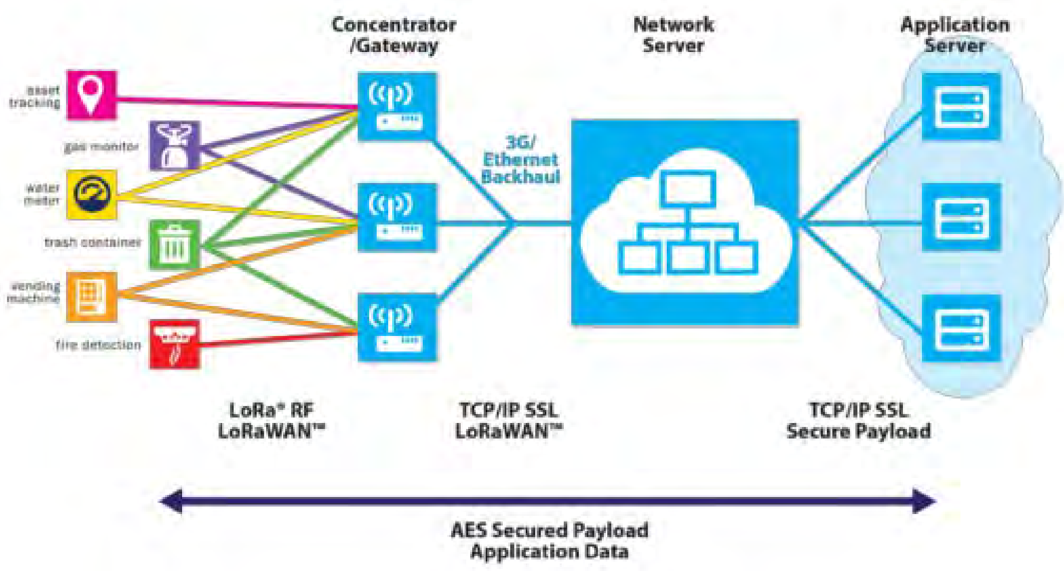

Fig. 8.3.2. LoRaWAN operation principle (Source: LoRa alliance)

8.3.3. Narrowband Internet of Things (NB-IoT)

NB-IoT is a standard LPWAN radio technology developed by 3GPP, i.e. those responsible for standards such as GSM, GPRS, etc., to enable a wide range of devices and cellular services as an update of the actual deployment of the mobile operator's infrastructure. This technology could be considered the mobile operators' response to competing technologies such as Sigfox and those based on LoRa.

NB-IoT focuses specifically on indoor coverage, low cost, long battery life and high connection density. NB-IoT uses a subset of the LTE standard, but limits bandwidth to a single narrow band of 200 kHz.

In the context of CollectionCare, this is a viable option, but implementations require more power (reduced battery life), a subscription using a SIM card, and an unclear subscription cost.

8.4Wireless solutions for CollectionCare

CollectionCare has decided to use Sigfox and LoRA's LPWAN technologies to face the complex scenarios imposed by museum spaces.

Sigfox would be the ideal solution for the monitoring of a few objects and LoRA would be ideal when many objects are monitored or when Sigfox coverage is not available. In the deliverable D1.4 a first analysis is made of how each technology adapts to the spaces of the different partners.

In any case, the choice leads to the following restrictions:

- Battery lifespan is reduced by increasing the number of measurements and the number of transmissions.
- The messages are very short, allowing a payload of few measures.

- It is not possible to collect and transmit complex information such as images or continuous reading of vibrations.

References

Recommendation ITU-R P. 1238-7 (2012). Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 MHz to 100 GHz. Geneva

9. Cloud computing

Digitalization is the process where information is converted to a bits based format for computers. Historically, the initial steps towards digitalization meant that Internet giants such as Google, Facebook and Twitter generated the necessary technologies that caused a data explosion. This facilitated the emergence of two major technology trends: Big Data and Cloud computing.

Provision of Big Data analytics features by means Cloud delivery models has simplified adoption for many organizations and has brought relevant cost savings by enabling organizations of all sizes to develop useful insights out of generated data from operational processes, which in many cases has driven to competitive advantages and transformational business value.

Today, after this initial wave, the emergence of IoT and Artificial intelligence is bringing a new wave of evolution. Connected IoT devices are expected to grow up to 75b by 2025 (Statista 2019). This will generate an unprecedented growth in the data that is available today, being the fuel that is expected to enable AI growth.

CollectionCare explores these technologies for the benefit of cultural heritage conservation, being a very innovative usage scenario that brings novel requirements and capabilities. These are detailed in the next sections.

9.1 Cloud technology

Cloud computing advanced previous developments on Utility Computing by entrance on the IT market in 2006 of AWS EC2 Service. This pioneering Infrastructure as a Service (IaaS) service offered an on-demand and pay-per-use virtualized computing infrastructure. The evolution of Cloud computing means that nowadays Cloud computing is considered both a business and delivery model. Cloud today makes it possible for users to acquire a wide diversity of IT capabilities extending from computing environments, to data analytics and storage services, security features and a wide variety of different final user applications. This way, Cloud computing is realising the idea of IT as a utility service, in which IT features are offered as an infinite all-purpose elastic IT service in which everything is open to be consumed by anyone and from anywhere "as-a-Service".

The US National Institute of Standards and Technology (NIST) has provided the following definitions layers of Cloud Stack (NIST 2009)":

- *Software as a Service (SaaS).* The service offered to the customer is the possibility to make use of provider's software applications executing on the provider's physical infrastructure. In order to do so, applications are typically accessible from diverse thin client interfaces, such as web browsers. The main identified benefit is that any technical aspect of the application is completely hidden to users, only focusing on the application delivered functionality. On the other hand, drawbacks are often identified in relation to vendor lock in and lack of features available to final customers to data portability.
- *Platform as a Service (PaaS).* As defined by NIST PaaS offers "The capability provided to the consumer is to deploy onto the cloud infrastructure consumer-created or acquired applications created using programming languages and tools supported by the provider." (NIST 2009). Similarly than for SaaS, the user of PaaS does not handle the underlying execution environment of the application (network, storage, os, …).
- *Infrastructure as a Service (IaaS).* In IaaS the services offered rely on the provisioning of virtualized

computing, storage, network and security capabilities in a managed service approach in which the user can install and configure its software applications. At this level, the user "does not manage or control the underlying cloud infrastructure but has control over operating systems, storage, deployed applications, and possibly limited control of select networking components (e.g., host firewalls)." (NIST 2009)

Another classification is provided also based on the type of Cloud development and the scope of use of the cloud installation (NIST 2009):

- Private cloud. The cloud infrastructure owned and managed by one organization.
- Community cloud. In this model a cloud infrastructure is collectively used by some organizations.
- Public cloud. The cloud infrastructure is open to be used to any user in pay-per-use model.
- Hybrid cloud. A hybrid cloud model consists in the combination of more than one of the previous introduced models, private, community, or public.

9.2 Required resources

Due to the nature of the problem addressed in this project, cloud computing has been identified as a solution that might fit the requirements to resolve some key tasks in the technological side of this project: data storage and processing. As this project aims to collect a significant amount of data, a big data cloud based approach has been proposed to face these two tasks, looking for the scalability and consistency some cloud providers, such as Amazon Web Services, offer nowadays. In the following subsections, a small introduction to those two main topics is presented in order to ease the comprehension of the choices performed regarding the data storage and processing side of the project.

9.2.1 Data storage

In this project, a significant amount of data is going to be generated. Each one of the sensing nodes to be used in the project is expected to measure different environmental magnitudes (such as temperature, relative humidity, etc.) that might help to detect possible unfavourable conditions for the preventive conservation of the objects. As the data is collected, the first step to be taken is to properly store it so it can be accessed when needed. Due to the data requirements in this project, some characteristics of the data storage to be chosen have to be taken into account such as integrity (data should be stored as it is, avoiding changes in the data), availability (data should be easily available for its use) or concurrency (different actors might be accessing or adding data at the same time).

Since their introduction in the 70s, relational databases have been traditionally the most adopted approach to store data. Relational databases require a design in order not only to store the data but also to define the relations between them. Following that approach, data is traditionally stored in form of tables, which are structured in columns. Each table has a given number of columns and each column stores a certain type of data. In order to draw relations between different data rows (in different tables or in the same table), rows are usually given an identifier, which can be referenced by other rows. When working with relational databases, the use of a Relational Database Management System (RDBMS) is the most common approach, as this kind of software systems provides the tools required to create, maintain and access the data. It is in the data access part that one of the most critical points reside, as there are many situations where the access to the data needs to be as fast as possible, something optimized in this kind of systems by mean of indexing and structuring in different ways the files where the data is stored. Regarding the way to interact with these RDBMSs, the SQL (Structured Query Language) is the most common language that implements all the required operations to handle a relational database.

Nevertheless, due to the increase in data volume, some disadvantages in RDBMSs use are being spotted. When dealing with very high volumes of data, RDBMSs show some limitations, as they are not very good at some scalability levels (as relational databases are traditionally run in a single server which contains all the data). Additionally, the restrictions on the data structure design, force the data to be stored in the database following the database design.

In order to deal with those issues (and others), during the last years, NoSQL ("Non SQL" or "Not Only SQL" as some of them still support SQL-like languages) database systems have appeared, allowing new approaches for database management. Some of their main advantages include the possibility to handle big data volumes (allowing a better scalability for the databases), even allowing their use in distributed servers, the capability to handle different types of data, including images, videos, etc. and their flexibility on the database schemas, that can be dynamically modified (allowing to store change the database after its creation). The NoSQL databases are commonly divided in four different categories:

1. *Key-Value databases*: databases where the data is stored as key-value pairs, being the key a sort of identifier that will be used in order to retrieve the data assigned to it. This kind of databases offer a significant improvement in performance compared to relational databases.

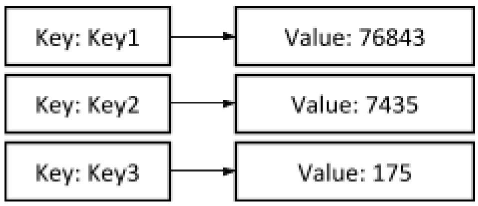

Fig. 9.2.1.a. Graphical representation of a Key-Value database approach

2. *Document databases*: key value similar databases allowing the storage of complex types of data, arrays or documents.

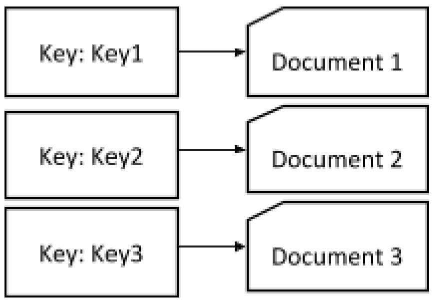

Fig. 9.2.1.b. Graphical representation of a document database approach

3. *Graph databases*: databases where the data is stored following a graph design, defining the relations between each node of data in the database.

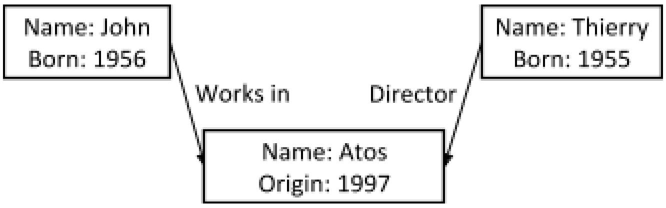

Fig. 9.2.1.c. Graphical representation of a graph database approach

4. *Wide-column store*: databases where the data is stored in related columns, where each data element might have different columns.

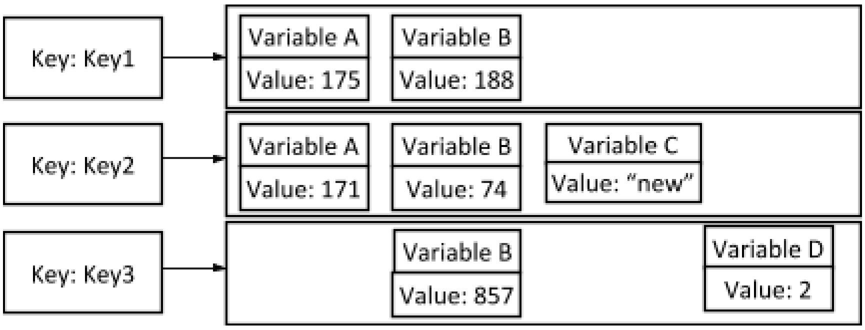

Fig. 9.2.1.d. Graphical representation of a wide-column store database approach

Also, the appearance of new trends in computing such as IoT or Smartcities, which involve a lot of data interactions (as there are many sensors sending data streams at the same time) have contributed to the popularity of NoSQL databases, thanks to their scalability and flexibility. During the last years, there has been an increase in the use of NoSQL solutions, becoming more and more used (see Figure 9.2.1.e), and with many NoSQL databases becoming popular as we can see in Table 9.2.1.

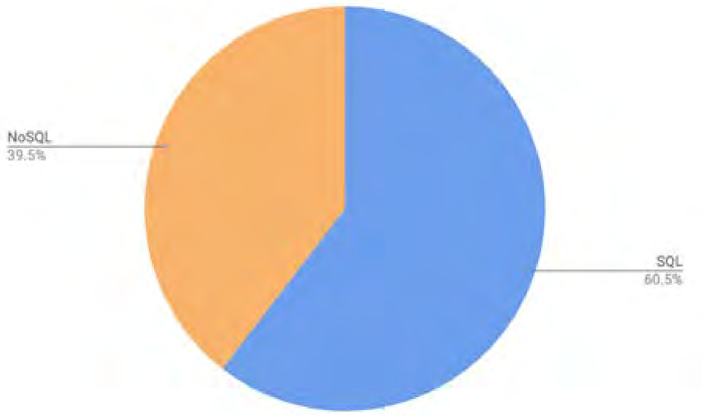

Fig. 9.2.1.e. SQL vs. NoSQL Databases use in 2019 according to a chart from Scalegrid 2019. (Scalegrid 2019)

Rank June 2019	Rank June 2018	DBMS	Database Model	Score June 2019	Score June 2018
1.	1.	Oracle	Relational, Multi-model	1299.21	-12.04
2.	2.	MySQL	Relational, Multi-model	1223.63	-10.06
3.	3.	Microsoft SQL Server	Relational, Multi-model	1087.76	+0.03
4.	4.	PostgreSQL	Relational, Multi-model	476.62	+65.95
5.	5.	MongoDB	Document	403.90	+60.12
6.	6.	IBM Db2	Relational, Multi-model	172.20	-13.44
7.	8.	Elasticsearch	Search engine, Multi-model	148.82	+17.78
8.	7.	Redis	Key-value, Multi-model	146.13	+9.83
9.	9.	Microsoft Access	Relational	141.01	+10.02
10.	10.	Cassandra	Wide column	125.18	+5.97
11.	11.	SQLite	Relational	124.89	+10.63
12.	13.	MariaDB	Relational, Multi-model	85.20	+19.35
13.	14.	Splunk	Search engine	84.62	+18.84
14.	18.	Hive	Relational	79.06	+21.73
15.	12.	Teradata	Relational	76.64	+0.87
16.	15.	Solr	Search engine	60.48	-1.58
17.	17.	HBase	Wide column	58.04	-1.67
18.	19.	FileMaker	Relational	57.80	+1.62
19.	20.	SAP HANA	Relational, Multi-model	56.38	+7.04
20.	21.	Amazon DynamoDB	Multi-model	55.26	+9.47

Table 9.2.1. Top 20 2019 DB-Engines by popularity according to DB-Engines 2019 (DB-Engines 2019)

9.2.1.1. Data storage in the cloud

Traditionally, databases were stored in servers hosted by database owner. That implied that the database owner should to take care of the database as well and resources had to be dedicated in order to host that database (i.e. a running server if 24/7 service was required, etc.). To avoid those maintenance task (and others), there is nowadays a wide variety of cloud-based storage solutions. By means of adopting one of those solutions, many aspects of the maintenance of the database can be carried out by the solution provider, such regular backups of the database, easy deployment and automatic installation of database systems, etc. Additionally, some aspects as the scalability of the solutions deployed in these data storage providers is usually transparent for the clients, which makes the maintenance of big data databases easier. This is very useful in initial states of big data related database deployments as, in case of a conservative estimation of the required resources, it is easy to provide more resources to the database (without buying hardware and setting it up).

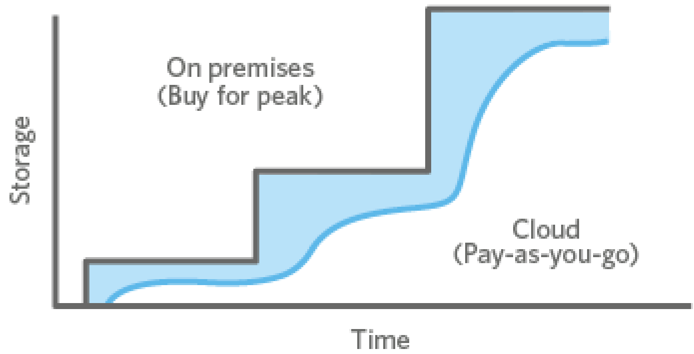

Fig. 9.2.1.1. Resource assignation on demand representation by AWS (AWS 2019a)

Nevertheless, these solutions are not free, and many costs apply. Nowadays solutions, such as those provided by Amazon Web Services (AWS) are very fine tailored to the requirements of their users and the costs are calculated (in most cases) per resource consumption, which makes them very competitive. Another point to be aware of when deciding to use a cloud-based storage solution is the location the data is going to be stored in. As you are uploading it to the internet, the data will be stored in external servers. According to AWS data privacy FAQ (AWS 2019b), as customer you "maintain full control of your content and responsibility for configuring access to AWS services and resources" (AWS 2019a). Additionally, AWS provides the possibility to choose the region the servers to be used are going to be located.

AWS offers a wide range of solutions regarding data storage, covering the approaches described in the previous section, including:

- Simple Storage Service (Amazon S3) can be used as data lake solution to store raw data.
- Relational databases through the RDS service including implementations of popular RDBMS engines such as MySQL, PostgreSQL, ORACLE, etc. as well as their own MySQL and PostgreSQL-compatible engine Amazon Aurora.
- Data warehouse solutions at petabyte levels with Amazon RedShift.
- Key-Value database implemented in the Amazon DynamoDB service, offering great performance.
- Document databases are also available in AWS, providing mongoDB compatibility through DocumentDB.
- Graph databases can be also deployed in AWS thank to their solution Amazon Neptune.

9.2.2 Data processing

Data processing can be described as the process for transforming any data into valuable data, with meaningful information in the scope where this data is transformed.

All the process could be split into different phases and compose as a cycle, as is shown in Figure 9.2.2.a, and with more details in Figure 9.2.2.b.

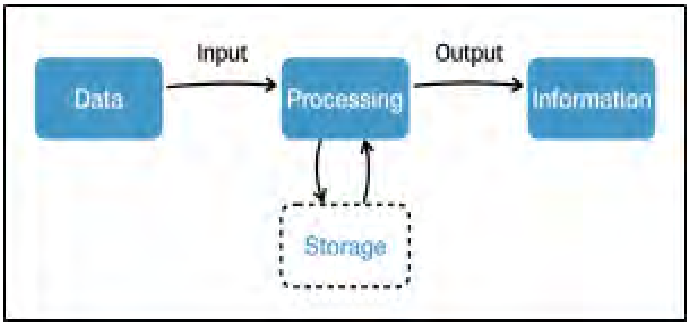

Fig. 9.2.2.a. Data processing cycle (Trackinno 2019)

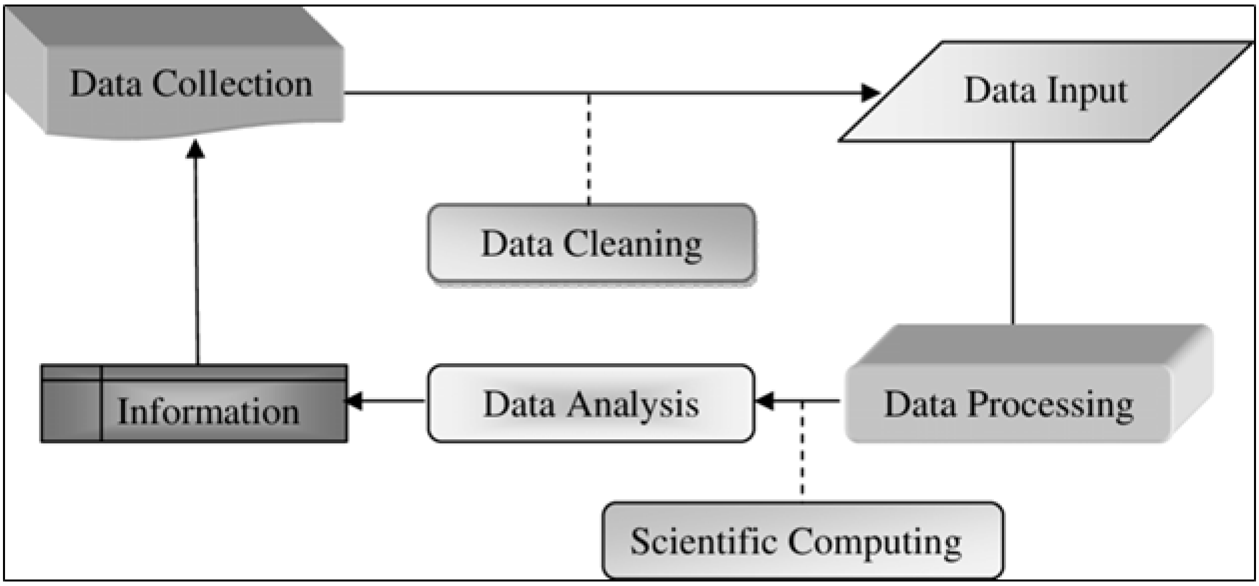

Fig. 9.2.2.b. Data processing cycle in details (ResearchGate 2019)

The main phases are data collection, data storage, data pre-processing, data analysis, and data visualization.

In the project, those phases are related to the next actions:

- All the data is collected from the sensors distributed in the museums and getting raw information about the objects.
- Once you have this data collected, a first processing step can be applied to do some cleaning, aggregations, analytics, etc.
- Raw data or pre-processed data is stored to be accessible for future analysis performed in batch mode, or could be sent to different components and execute algorithms in real-time.

- In this step, the different models developed in the project could be designed to compute degradation risk of objects, and other techniques based on the specific composition of the objects. The data is fed to the models by getting to concrete data stored in the project, as shown in Section 3.4.3.1.
- After the execution of the models, the output data is valuable information for the project and is stored again to be used by the visualization component, and/or to be processed again.

9.2.2.1 Data processing in the cloud

The cycle described in the data processing introduction will be deployed using a cloud-based approach, and it will be performed by cloud services.

The description of cloud computing is explained in the introduction, and the pros of using the cloud for data processing are related to that it could be executed wherever you are, and the costs are usually lower than keeping the environment and the services in one or more private servers. In this case, providers as Amazon Web Services (AWS 2019c), has flexible payment plans and only the resources used are charged for the time they have been running. Even they provide maintenance methods with the services without an extra payment.

In the cloud-based approach, the resources can be scaled if necessary following a few steps or configuring the behaviour in the configuration where the cloud environment is created. If you are working on premise, this would not be so easy, because this change requires extra effort and money to replicate the environment and configure all the services.

Next is listed the cloud services that provides AWS and the potential solutions to be used in the project:

- *Data collection*: the data to be collected will come from the edge, the sensors distributed in the museums, and then be stored or processed. AWS IoT Greengrass (AWS 2019d) is a potential tool to be used to execute transformations and analysis at the edge.
- *Data storage*: follow Section 9.2.1.1 for more information.
- *Data processing:* to perform this step, the common way is using ETL (Extract, Transform, Load) tools. With the correct connectors to the databases described in the data storage section, many transformations can be applied and then stored again or sent to a visualization component. The main tool provided by AWS for ETL is AWS Glue (AWS 2019e).
- *Data analysis:* in this step is necessary to provide an environment and tools for executing the models developed in the project and different useful algorithms. AWS provided a bunch of tools that could be used for machine learning, the main ones are:
    - Amazon EMR (AWS 2019f) is a managed Hadoop framework to process big amount of data. Other popular frameworks can be used as Apache Spark or Apache Flink, and different connectors are available to access the data stored, for example, in Amazon S3 or Amazon DynamoDB.
    - Amazon Sagemaker (AWS 2019g) covers the machine learning workflow to build, train and deploy models. Different optimized frameworks can be chosen as TensorFlow, Scikit-learn, SparkML, and more. And a large variety of pre-built algorithms are accessible. But this is not restricted to only those frameworks or algorithms, because own algorithms and models can be deployed using this tool.
- *Data visualization*: follow Section 10 for more information.

More technical information about data processing will be provided in D1.9.

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10. User interfaces

Gartner (2019a) has stated that the simplification of big data platforms is a primary objective for almost all data analysis application. This is largely to cater for what Gartner calls "citizen analysts", the number of which is expected to grow at the rate of 400%, faster than that of formally qualified data scientists.

For this reason, CollectionCare should adopt an analytical approach that will be readily adopted, factoring in a lot of design efforts for user interface (UI) and making sure it provides the best possible user experience (UX). End users should find the experience effortless, allowing them to interact with data in ways that they find intuitive. To create such an experience, the CollectionCare UI design should follow certain key principles and best practices. Some of these are common to any UX project while others relate purely to the presentation and visualisation of big data insights in environmental data. The following recommendations fall into the latter category of big data visualisation.

10.1 Definition of users and their needs

In order to design user interfaces it is necessary to identify and understand users and their needs. When dealing with big data analytics, research should be directed towards providing an understanding of what data (and in what quantities) users want or need to see. Of special importance is the need to avoid overloading user dashboards with data. This is a common mistake made when designers or developers fixate on demonstrating the richness of a solution's analytic capabilities. CollectionCare users will be aware that there is a large quantity of data behind their tables, graphs and charts. However, the majority of users do not want to see any more than is necessary to meet their objectives.

For the CollectionCare project it is expected that users will not have the budget to hire specialised conservators to interpret the data they see and, in any case, there are probably not enough skilled analysts in the preventive conservation field to go around. This was highlighted in a more generalist study into insight-driven enterprise by Capgemini, in which 39% of executives mentioned a shortage of specialists is a major barrier to the use of big data.

With the need to make big data more accessible to the lay person then, the sweet spot to strive for in big data UX is one in which each user has an immediate view of the data that they need to monitor or interact with the most. This, of course, differs from user to user, so a winning UI will be one that can be customised to suit personal preferences, ideally by the users themselves.

In seeking UX insights into the needs for a product, it is necessary to carry out a user analysis as some essential questions should be answered. These include:

- Which key metrics should be visualised to help users make decisions?
- How will different client stakeholders use the data?
- How will software integrations be received and how will the data be handled?
- Will the available data be displayed primarily on desktop monitors or on mobile devices?
- Which users need to monitor data in real-time?
- To what extent will users need to interact with the data presented?

Regardless of how well users are identified, assumptions should not be made about the answers to these questions. If any assumptions have to be made, a false-consensus effect should be avoided by validating these assumptions with CollectionCare target users before beginning UI development.

Neither software developers nor preventive conservation specialists are guaranteed to know what users' real requirements are for a big data UI and it is essential to spend time "observing" how CollectionCare target users work, rather than simply asking for their views.

10.2 Prioritization structure for dashboards

While a lot of valuable design guidance can be gained from observing and talking to users, a project will inevitably make certain decisions based purely on design principles and a modicum of common sense. For example, once target users have provided an initial understanding of which data is of most use to them, data presentation will need to be prioritised in some way.

In dashboard design, it is often an advantage to use tabs to separate different reporting elements and to order those tabs in a structured way from left to right. The sequence of tabs should be structured to tell a story, which unfolds as the user navigates from tab to tab.

It also makes sense to prioritise the data displayed in each tab, with the most important metrics or results nearest to the top of the screen, preferably highlighted with colour or a tile to help them stand out. This is one way to achieve the "sweet spot", enabling users to access their most important insights with little more than a mouse click or a single screen tap.

10.3 Visualisation

It can be tempting to think that for non-technical users data analytics is a dry and dull topic and that, therefore, data displays need to be vibrant and flashy. However, going this way will only result in confusion, making data harder to interpret. For instance, using a wide array of colours can seem like a good idea to enliven graphs and charts, but based on past working experience a single colour gradient is actually much more effective in helping users to comprehend their data.

The same principle applies to selecting the types of visualisations to incorporate into the CollectionCare data analytics UI. A dashboard with a thoughtfully minimalistic layout, plenty of white space and consistent visualisations will be more helpful and welcoming to CollectionCare users than the one with a garish mix of multicoloured pie charts and 3D graphs.

10.4 Levels of usability

Naturally, CollectionCare will need to have some variety in its dashboards, as some chart types will not be suitable to display environmental data in the most helpful way for users. The important thing is to put necessity, rather than creative ego, into the driving seat and strive for consistency as much as possible.

As people from different disciplines will use CollectionCare, a more complex UI might be needed in some cases. If so, the best approach will be to design two or three levels of usability.

For example, non-technical CollectionCare users will probably fare best with straightforward, easy-to-digest dashboard visualisations. Management users are more likely to need access to menu-based reports and table selection. For preventive conservation analysts and data scientists, the third level of usability might include a combination of menus and keyboard commands, providing access to advanced features.

10.5 APIs to improve the approachability of big data

Big data will always be complex, but that doesn't mean user experience must be complex too. In addition to the above guidelines, another way to make big data approachable for the CollectionCare targeted user base and maximise the number of people reached, is to integrate with the tools they already use, such as museum collection management software.

Museum collection management software interfaces are designed to be graphically appealing and inspire confidence in first-time, as well as experienced users. They provide an ergonomic screen design for everyday use, with an overview of the most important information and functions related to collections work. They offer intuitive, user-friendly navigation and intelligent full-text search, resulting in that crucial "easy-to-use" experience.

Furthermore, museum collection management software support dynamic reporting capabilities, allowing users to further process and evaluate information easily and efficiently, even outside of the software.

Unlike legacy technologies, it is now much easier to integrate with other software, especially in the cloud. APIs are built with cloud computing in mind. "We live in an API economy, a set of business models and channels based on secure access of functionality and exchange of data" (Gartner analyst Christy Pettey, Gartner 2019b). "APIs make it easier to integrate and connect people, places, systems, data, things and algorithms, create new user experiences, share data and information, authenticate people and things, enable transactions and algorithms, leverage third-party algorithms and create new product/services and business models".

Through API-based integrations, CollectionCare data in JSON format will be added to existing museum data contained in museum collection management software, providing users with a clear view of all collections-related activities across their entire organisation, as well as a robust, customisable toolkit to manage the essential details of their collection and associated tasks, including preventive conservation-specific tasks.

CollectionCare data will thus be added to the core documentation data in museum collection management software, which covers object data, shipping data, loans data, exhibitions data and artist/makers data, as well as advanced information such as item locations, accessioning information, values, documents, exhibition history and literature references.

The API-based integrations will enable the contribution of historical and real-time data on conservation activity to the relevant museum collection management software conservation module, leading to the generation of actionable reporting, with in-depth object condition documentation that also supports images, videos and sound as supporting evidence.

Storage and transportation information in the relevant museum collection management software movement/transport module can also be updated in detail from CollectionCare data. This will enable the contribution of data on object movement, either within the museum exhibition spaces, in storage or in transit, with further documentation that also supports linked media for shipments, mode of transportation and relevant details for shippers, lenders, borrowers or couriers.

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11. Conclusion

This report constitutes D1.1 of the CollectionCare project. It provides to the partners of the project a common understanding about the different fields involved in such a cross disciplinary project. The deliverable therefore serves as a starting point for the work to be done in the CollectionCare project but also points to the future direction of the project.

The deliverable reports on international standards and state of the art for preventive conservation, environmental parameters, microclimate field monitoring, object/collection monitoring systems, material types, and degradation models. Following that, the chapters on sensors, wireless technology, cloud computing, and user interfaces report on technological solutions and provide a first approach to the implementation of the CollectionCare product.

When possible, the CollectionCare project will aim for an integration of the international standards. For some standards updated versions are presently in preparation. As these standards become available, we will include possible changes, if relevant.

This and other reports from WP1 will be discussed during the partnership workshop in Copenhagen 30-31 July 2019 and possible changes and/or additions will be mentioned in D1.5 to be delivered by the end of August 2019 by KADK.

The work with D1.1 has led to extensive communication between CollectionCare partners and this written result will feed information into all WP's during the CollectionCare project.