Getty Conservation Institute

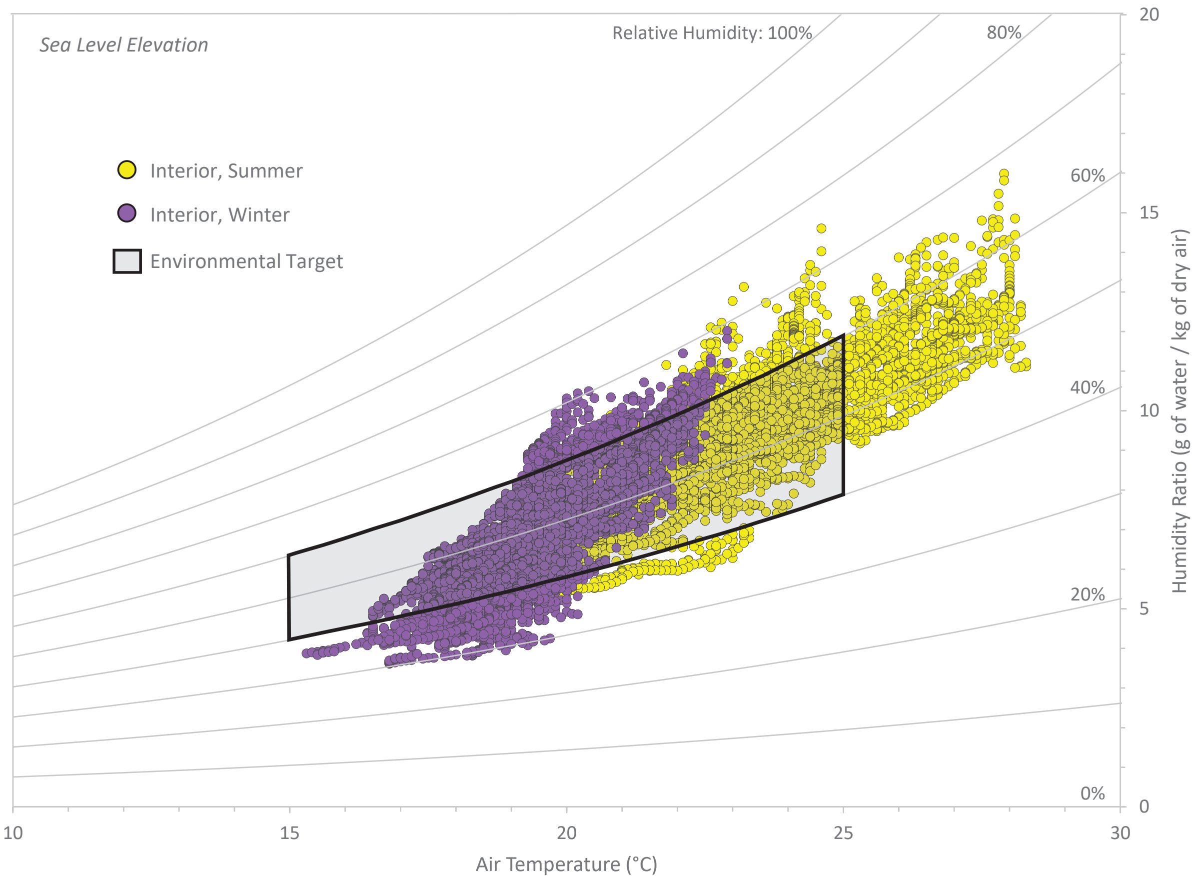
Annelies Cosaert, Vincent Laudato Beltran, Geert Bauwens, Melissa King, Rebecca Napolitano, Bhavesh Shah, and Joelle Wickens

Edited by Annelies Cosaert and Vincent Laudato Beltran

Tools for the Analysis of Collection Environments

Lessons Learned and Future Development

Research Report



Tools for the Analysis of Collection Environments

Lessons Learned and Future Development

Research Report

Annelies Cosaert,
Vincent Laudato Beltran,
Geert Bauwens,
Melissa King,
Rebecca Napolitano,
Bhavesh Shah,
and Joelle Wickens

Edited by Annelies Cosaert
and Vincent Laudato Beltran

Getty Conservation Institute
Los Angeles

1200 Getty Center Drive, Suite 700
Los Angeles, CA 90049-1684
United States
Telephone 310 440-7325
Fax 310 440-7702
E-mail gciweb@getty.edu
www.getty.edu/conservation

ISBN: 978-1-937433-96-3 (online resource)

The Getty Conservation Institute (GCI) works internationally to advance conservation practice in the visual arts—broadly interpreted to include objects, collections, architecture, and sites. It serves the conservation community through scientific research, education and training, field projects, and the dissemination of information. In all its endeavors, the GCI creates and delivers knowledge that contributes to the conservation of the world's cultural heritage.

Conservation
Research
Foundation
Museum

CONTENTS

Acknowledgements 6

CHAPTER 1

Introduction

Perspectives 8

Educators by Joelle Wickens 8

Engineers by Geert Bauwens 9

Computer Scientists by Rebecca Napolitano 10

References 10

CHAPTER 2

Analysis and Visualization by Vincent Laudato Beltran and Geert Bauwens

Numerical Analysis 12

Data Visualization 13

Conclusion 19

References 19

CHAPTER 3

Tool Definition and Attributes by Annelies Cosaert and Bhavesh Shah

Institution-Specific Motivation for Development 20

Efficiency and Post-Processing Data 21

Comparison with Guidelines 22

Comparison with Exterior Climate 22

Assessment of Risk 23

Define Mechanical Strategies and Reduce Energy Use 24

Facilitate Stakeholder Communication 24

Conclusion 24

References 25

CHAPTER 4

Integration with Other Datasets by Bhavesh Shah, Geert Bauwens, and Melissa King

Climate Control Systems 26
Archival/Collection Management Systems 27
Staff Observations 27
Exterior Climate 28
Building Envelope/Health 28
Light 28
Gaseous Pollution 29
Pests 29
Vibration 29
Dust Deposition 30
Occupancy 30
Conclusion 31
References 31

CHAPTER 5

Dissemination, Education, and Collaboration

by Joelle Wickens, Melissa King, and Rebecca Napolitano

Online Tools for Learning Purposes 32
Connecting Preventive Conservation Tools 33
Transparency Encourages Further Learning and Collaboration 34
Imperative of Collaborative Development 35
Data Sharing Encourages Tool Development and Analysis 36
Next Steps for Tool Development and Education 36
Conclusion 37
References 37

CHAPTER 6

Future Tool Development by Rebecca Napolitano, Geert Bauwens, and Bhavesh Shah

What Developers Need from Conservators 39
Development of Online Modular Tools 39
Connect to Data Management 40
Application of Machine Learning 41
Connection to Other Preventive Conservation Tools 41
Guidelines for More Efficient Creation and Compatibility 42
Mechanism for User Feedback 42
Mechanism for Dissemination to Field 43
Conclusion 43
References 43

CHAPTER 7

Conclusion 45

Appendix 1. Meeting Participants 46

Appendix 2. Glossary 49

Appendix 3. Tool Descriptions 56

ACKNOWLEDGMENTS

The authors would like to extend their sincere gratitude to the following individuals: Michael C. Henry and Rebecca A. Kaczkowski for graciously sharing their insights and experiences during the 2019 meeting at the Winterthur Museum; Maddie Cooper and Marie Desrochers for capturing the meeting discourse; and Chris Arkins, Josep Grau-Bove, and Simon Lambert for their comprehensive critique and invaluable suggestions as our external reviewers. We would also like to thank deeply our colleagues at the Getty Conservation Institute who provided support and encouragement throughout this project: Reem Baroody, Chelsea Bingham, Kathy Dardes, Cynthia Godlewski, Tom Learner, Michał Łukomski, Gary Mattison, Savannah Novencido, and Joel Taylor.

CHAPTER 1

INTRODUCTION

The collection of environmental data such as temperature (T) and relative humidity (RH) is a fundamental aspect of collection management for many cultural heritage institutions. While other "agents of deterioration" (CCI 2017) may be equally impactful, if not more so, in causing damage to cultural heritage artifacts, T and RH have been important considerations when deciding upon environmental management strategies that can have an extended effect upon both the collection and the institution. The analysis and interpretation of environmental data supports decision making for a range of museum activities, including collection and risk assessments, loan considerations, and the development of passive and/or mechanical environmental management strategies. The influence of T and RH on the mechanical, chemical, and biological deterioration of objects has motivated the development of environmental guidance, including BSI 2018 (*Conservation of Cultural Heritage: Specifications for Location, Construction and Modification of Buildings or Rooms Intended for the Storage or Use of Heritage Collections;* AFNOR / BSI / DIN 2018) and the 2019 ASHRAE chapter "Museums, Galleries, Archives, and Libraries." The issue of museum sustainability has recently become of greater importance as standards and guidelines embrace T and RH ranges that reflect the performance of the building envelope and the climate zone to which the building and collection are exposed (e.g., NMDC 2015 and IIC/ICOM-CC 2014, AICCM 2019).

Due to the importance of the collection environment, a number of analysis tools have been developed or are forthcoming to improve understanding of T and RH data. While there exist a wide variety of tool categories, including those that provide step-by-step decision-making guidance, a tool is defined in this publication by its reception of data inputs and return of actionable outputs. Chapter 3 will further outline the tool selection criteria. Use of these tools can supplement the more limited analysis typically available in commercial data logger software. Developed by various institutions to meet specific needs, the use of complementary tools can provide a more holistic view of the data and improve communication with stakeholders involved in defining and implementing environmental management strategies.

Users of these environmental analysis tools will typically support collection or building management, but there are a number of factors that limit their effective use. Users may possess a broad range of backgrounds, skills, and experience, and can include scientists, engineers, architects, facilities staff, conservators, registrars, curators, and volunteers. A lack of training in environmental data analysis can hinder data exploration, as knowledge of a range of analysis and visualization options is needed to clearly and effectively convey results to audiences with varying levels of expertise. The institutions in which the users reside can also vary widely based on type, size, staffing, and funding; for small- to medium-sized institutions, staff may need to assume multiple roles. With an already brimming list of tasks and responsibilities, it can be daunting for users to devote the time necessary to gain familiarity and proficiency with the specific features of each tool.

Research on the topic of preventive conservation tools (Cosaert and Beltran 2021), conducted as part of the Managing Collection Environments (MCE) Initiative at the Getty Conservation Institute (GCI), highlighted persons and institutions active in both the use and development of tools. This research also underscored a tendency for siloed activity that might benefit from a broader discussion with a community of tool users and developers.

In December 2019, the GCI convened a meeting at the Winterthur Museum to discuss T and RH analysis tools and the potential for creating a framework to support their use and development for collection preservation needs. Meeting participants represented users and/or developers of tools from various disciplines, including conservation, engineering, architecture, data science, and building physics (appendix 1).

This publication aims to summarize the interdisciplinary discussion of T and RH tools at the Winterthur meeting and promote further discourse of tools for preventive conservation analysis in general. The next two chapters provide brief overviews of data analysis and visualization techniques (chapter 2) and the state of the field with respect to T and RH tools (chapter 3). This is followed by examinations of the utility of integration with complementary datasets (chapter 4), the importance of effective dissemination, education, and collaboration (chapter 5), and possible paths of tool development (chapter 6). Also included are appendices introducing the meeting participants (appendix 1), defining glossary terms (appendix 2), and briefly describing select T and RH analysis tools (appendix 3).

By merging discussion of the current landscape of T and RH analysis tools with recommendations for collectively advancing the field, it is hoped that this will promote more effective data analysis that transcends standards, improves communication with stakeholders, encourages transparency among the various tools, and promotes new and continued tool development for environmental data analysis.

Perspectives

Collection care professionals are a primary audience for the use and development of preventive conservation tools. The viewpoint of this group was touched upon in the preceding section and represents a through line in this document. To further advance discussion of environmental tool use and development, it is essential to consider the perspectives of allied groups, such as educators, engineers, and computer scientists. The interests and motivations of these colleagues are specific to their role, and the following section highlights the nature and importance of their contributions.

Educators by Joelle Wickens

Preventive conservation educators work with students to help them see the care of collections as a variable task. It is variable because institutions have budgets of different sizes, diverse missions and staffing levels, and are located in different climates, while the collections for which they are responsible are composed of different materials and used in different ways. At the intersection of these variables, we find the path to sustainable preventive conservation. This intersection is distinct for every institution, and the specific elements of the sustainable preventive conservation solution will often be different. Consistency is found in the goal of balancing risks to people, planet, and profit, while preserving collections.

Currently, we use available tools to quantify and analyze many individual preventive conservation factors: temperature, relative humidity, pests, ultraviolet, visible light, infrared, dust, pollutants, and vibration. We collect data and generally find simple trends in siloed categories. We focus on teaching skills of use that will allow students to apply this approach to all hardware and software platforms.

However, these tools are not particularly dynamic or didactic. They produce results such as determining a light level at a particular moment in time or cumulative light exposure for a particular object. Although the result seems definitive and straightforward, it may overlook the potential influence of related factors. We need tools that will help teach relationships and interconnectivity, and that a museum and its collections are a system with many overlapping and interconnected layers and paths.

The process of risk assessment helps teach the reality of multiple factors, competing priorities, and prioritization of tasks and resources. A set of tools that could help highlight significant relationships between the siloed preventive conservation factors discussed above, combined with existing or modified risk assessment methods, could empower the preventive conservation educator to teach students to develop situation-appropriate and sustainable preventive conservation approaches.

Engineers by Geert Bauwens

Monitoring tools can facilitate communication between internal and external stakeholders responsible for environmental management. While conservators need to communicate clearly about the value of the collection and the necessary climate specifications for its preservation, engineers must understand and communicate the impact of active and passive control strategies, possible mitigating measures and alerts, and their impact on investment and operational costs.

A number of sector-specific guidelines and standards highlight the need to manage T and, particularly, RH in buildings that house collections. There are several notions that we need to track: human comfort, energy use, and collection lifetime. In addition to sensors used to control the HVAC system, mobile sensors should be employed to define conditions at the zone and object level. Stakeholders should agree on how these sensors are maintained (e.g., regular calibration), how the data is pre-processed and interpreted, and how this informs management decisions related to the appropriate level of environmental control and the resulting cost.

Engineers need to understand the opportunities and limitations of the building infrastructure. Deep renovation steps such as facade insulation and heating and ventilation system upgrades are often not feasible in historic heritage buildings, and passive control strategies should be explored. It is crucial that we can accurately predict the building’s hygrothermal response based on reliable input parameters, using Building Energy Simulation (BES) or simplified hygrothermal models. The latter can employ low-cost sensors that generate energy use and indoor climate data. This data informs the relationship between the indoor and outdoor climate, and the dynamic hygrothermal behavior of the building and the moisture-buffering potential of the collection spaces. Thus, we can better assess potential benefits and risks associated with mitigation measures.

Engineers can foster strong institution-wide ambitions with regard to environmental management. Extended T and RH analysis tools can prove invaluable in educating both the client (e.g., conservators, facility managers, and management) and stakeholders from the external design and build teams on the process, opportunities, and risks.

Computer Scientists by Rebecca Napolitano

Since T and RH measurements are accessible concepts to a broad audience, they are ideal discussion topics to facilitate collaborations between conservators and developers. The conversation can encompass the questions conservators are asking of their data, what problems their current methods are facing, and what types of analysis are possible from the developer side. The development of this foundational relationship and common language about a tool can ensure more productive development time. This foundation is critical because the process of developing a tool is both bi-directional and iterative.

From this starting point, developers can begin to develop prototype tools and user interfaces for the conservators to test and provide feedback on. If a tool is intended for broad use, this should be reflected in the range of partner institutions and datasets used during the prototype stages. This will ensure compatibility with various data types and flexibility with the analysis and visualization, and will accommodate different definitions of "allowable behavior" and "risk" due to variances such as climate zone, funding, and the collection.

These iterative conversations rely on clear communication of needs and goals. Discussions regarding descriptive and predictive statistics require input from a conservator and a building engineer. The computer scientist needs the context provided by a conservator and an engineer to understand what the trends mean with respect to collection care and building performance. Further discussions will focus on interface design and accessibility, and the balance between complexity and usability of the output.

The creation of this common language among disciplines is not a trivial pursuit. Since complete transfer of knowledge is not possible, it must be determined how far each discipline needs to "step" toward the middle to make a common language feasible. Any stakeholders beyond computer scientists, conservators, and engineers must also be identified; this may include material scientists, registrars, facilities staff, and docents.

References

AFNOR. 2018. N*F EN 16893 Conservation du Patrimoine Culturel – Spécifications pour l'emplacement, la construction et la modification des bâtiments et des salles destinés au stockage ou à l'utilisation de collections – Conservation du Patrimoine Culturel – Nouveaux sites et bâtiments destinés au stockage et à l'utilisation de collections.* La Plaine Saint-Denis, France: Association Française de Normalisation.

AICCM. 2019. E*nvironmental Guidelines.* Canberra: Australian Institute for the Conservation of Cultural Material. https://aiccm.org.au/conservation/environmental-guidelines/.

ASHRAE. 2019. "A24—Museums, Galleries, Archives, and Libraries." Chap. 24 in *ASHRAE Handbook—HVAC Applications.* Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers. Also issued as IP edition, 2019.

BSI. 2018. *BS EN 16893:2018 Conservation of Cultural Heritage: Specifications for Location, Construction and Modification of Buildings or Rooms Intended for the Storage or Use of Heritage Collections*. London: British Standards Institution.

Canadian Conservation Institute (CCI). 2017. "Agents of Deterioration." Government of Canada. https://www.canada.ca/en/conservation-institute/services/agents-deterioration.html.

Cosaert, Annelies, and Vincent Beltran. 2021. "Comparison of Temperature and Relative Humidity Analysis Tools to Address Practitioner Needs and Improve Decision-Making." In *ICOM-CC 19th Triennial Conference Preprints, Beijing, 17–21 May 2021* (forthcoming), edited by Janet Bridgland. Paris: International Council of Museums.

DIN. 2018. *DIN EN 16893 Erhaltung des kulturellen Erbes – Festlegungen für Standort, Errichtung und Änderung von Gebäuden oder Räumlichkeiten für die Lagerung oder Nutzung von Sammlungen des kulturellen Erbes*. Berlin: Deutsches Institut für Normung. doi: https://dx.doi.org/10.31030/2695151.

IIC and ICOM-CC. 2014. "Environmental Guidelines – IIC and ICOM-CC Declaration." London: International Institute for Conservation of Historic and Artistic Works; Paris: International Council of Museums – Committee for Conservation. https://www.iiconservation.org/sites/default/files/news/attachments/5681-2014_declaration_on_environmental_guidelines.pdf.

NMDC. 2015. "Bizot Green Protocol." In *Environmental Sustainability: Reducing Museums' Carbon Footprint*. London: National Museum Directors' Council.

CHAPTER 2

ANALYSIS AND VISUALIZATION

By Vincent Laudato Beltran and Geert Bauwens

The collection of environmental data is integral to the practice of collection management. In addition to air temperature (T) and relative humidity (RH), variables may include light, vibration, pollution, and occupancy. While data collection fulfills the criteria for monitoring, it is meaningless without subsequent analysis and interpretation. The purpose of data collection can include:

- Characterization of current environmental conditions, including temporal and spatial relationships
- Comparison to environmental guidance and/or loan specifications
- Performance assessment of building and environmental management systems with respect to moderation of thermal and moisture loads
- Assessment of non-mechanical and mechanical environmental management strategies

Numerical and visual exploratory analysis of this data improves our understanding of the collection environment by highlighting relationships and trends. Equally important is the communication of these results to stakeholders responsible for environmental management, an interdisciplinary group that can include directors, curators, conservators, facilities and maintenance staff, conservation scientists, engineers, and architects. The use of clear and precise visualizations tailored to audiences with varying levels of expertise will establish awareness of environmental issues and support the decision-making process.

This chapter provides the reader with a brief overview of various techniques that can be employed in the analysis and visualization of environmental data. While the numerical metrics and visualizations presented are by no means exhaustive, they provide a possible template for expanding typical environmental data analysis. With the exception of the floor plan overlay, the visualizations shown in this chapter were created by a suite of Excel analysis tools developed at the Getty Conservation Institute (GCI Excel Tools) and thus do not require use of additional third-party software. The authors encourage readers who seek to apply these techniques to consult available resources that discuss data analysis and visualization (e.g., Cassar and Hutchings 2000; Tufte 2001; Maekawa, Beltran, and Henry 2015; National Park Service 2016); it is expected that additional didactic material on this topic will be produced in the near future.

Numerical Analysis

Quantitative analysis of data provides a framework by which it can be organized, analyzed, interpreted, and presented. The raw environmental data taken from the data logger should first be inspected to identify and remove erroneous values, after which it can be combined with clean datasets for analysis.

T and RH are part of a suite of interconnected thermodynamic properties that describe a parcel of air. Given a specific elevation or barometric pressure, concurrent values of T and RH can be used to calculate other variables. Of particular interest are humidity ratio and dew point temperature, both of which relate to the moisture content of air.

Various numerical indices can statistically characterize a dataset. The central region of a dataset is described by an average or median value, while the spread of data is depicted by measures such as standard deviation (square root of the variance), range (difference between maximum and minimum values), and interquartile range (IQR, difference between the 25th and 75th percentiles). The latter measure is anchored by the concept of probability distribution, which describes how likely a value is to occur in a dataset. For example, if the 90th percentile of RH data is 65% RH, then 90% of the dataset falls below this RH value.

While statistics can describe an overall dataset, their application to specific subsets can be informative. Quantitative comparisons of seasonal environmental data, which necessitates data collection over an extended period (typically at least one year), can illuminate transitory risks to a collection. Other subsets of note are alternating periods of HVAC system operation and shutdown, before and after strategy implementation, or during specific occupancy or climatic events.

Data analysis can also focus on specific time windows, such as a month, week, or day. Statistics can be calculated within these discrete windows, which can then be shifted forward over the entire dataset. For example, a weekly moving average would calculate the average value for all one-week periods (note that each period is shifted forward by one data point); this results in a smoothing out of short-term variability in the raw data, which may be particularly relevant for massive objects that respond slowly to changes in ambient RH. Similarly, fluctuations in T and RH can be quantified by calculating their moving range (maximum minus minimum) over relevant time windows (e.g., 24 hours).

Environmental data can be used as a forecasting tool. When paired with models of object response, preservation metrics or indices can assess the biological, chemical, and mechanical risk to a collection, and may be useful in informing decision-making regarding environmental management. It should be noted that the calculations behind each index will vary and can evolve with new research, and it is important that users have a general understanding of the rationale informing the calculations. Knowledge of building envelope performance and exterior climate may also allow predictions of the resulting interior environment and energy use.

Data Visualization

The graphical representation of numerical data and associated metrics can often facilitate an improved understanding of complex concepts. Edward R. Tufte, a statistician and noted expert on informational graphics, espouses the following visualization principles (Tufte 2001):

- Show data without distortion.
- Present many numbers in a small space.
- Encourage comparison of different pieces of data.
- Reveal data at several levels of detail.
- Serve a clear purpose.

The collection of environmental data over time naturally lends itself to visualization by time series plots, which show time on the horizontal axis and variables of interest on the vertical axis. Presentation of multiple locations or variables can be helpful in discerning trends in the dataset. For example, overlapping plots of RH, air temperature, and dew point temperature at one location can highlight temperature- or moisture-driven shifts in RH (fig. 2.1). Time series plots of indices of biological (mold), chemical, and mechanical risk can emphasize periods when the collection is exposed to environmental conditions that may be more harmful. The examination of narrower time windows offers an opportunity to explore diurnal cycles, as well as relationships to parameters such as operating hours, space occupancy, and HVAC operation.

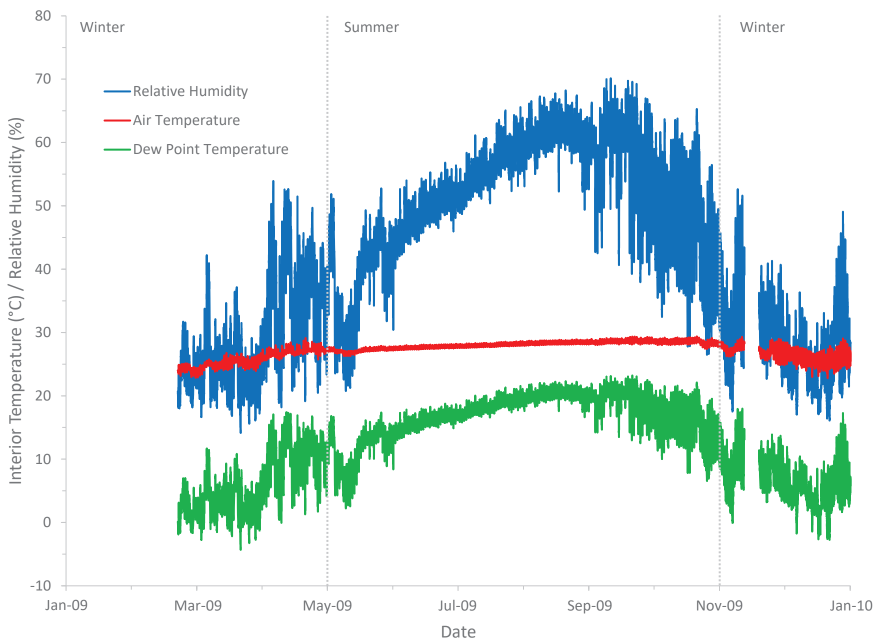


FIGURE 2.1

Time series plot showing interior environmental conditions (created with the GCI Excel Tools). The increased summer RH is driven largely by a rise in dew point temperature, while air temperature remains relatively stable.

Time series plots can also present multiple levels of detail for individual variables. Figure 2.2 shows interior raw RH data collected at 15-minute intervals, and calculations from this dataset in the form of a 7-day moving RH average and a 24-hour moving RH range. While the 15-minute data depicts the frequency of short-term fluctuations, the 24-hour range highlights the magnitude of these variations. The 7-day average smooths out the rapid fluctuations observed in the raw data and emphasizes longer-term shifts that may be more relevant for slow-responding objects. The addition of target zones draws attention to periods when conditions are outside of specification.

Visualizations of probability provide insight into the spread of the data, and can be shown as cumulative relative frequency (CRF) plots and box plots. CRF is a descriptor from 0 to 1 for each data point indicating the proportion of observations that are less than or equal to that specific

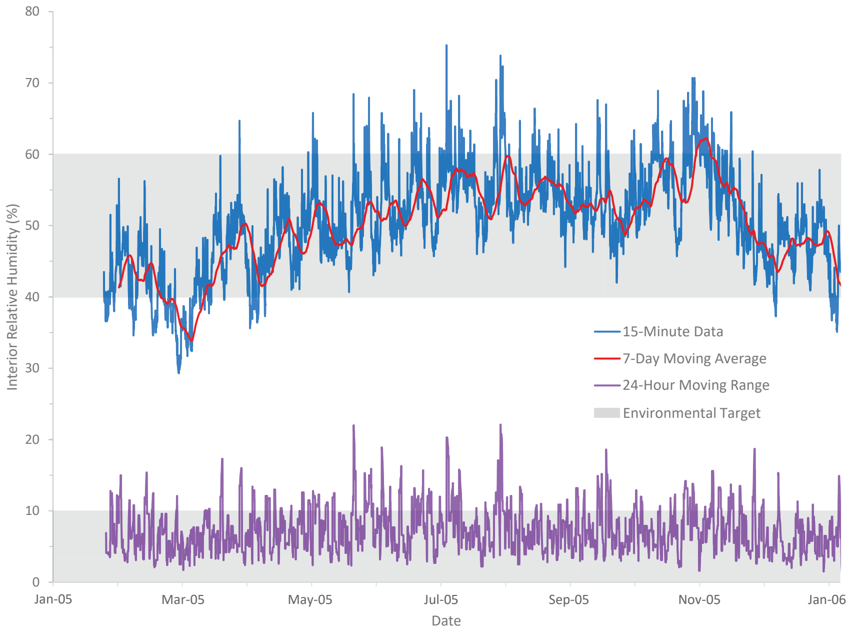


FIGURE 2.2

Time series showing 15-minute interior raw RH data, the calculated 7-day moving RH average, and 24-hour moving RH range (created with the GCI Excel Tools). The semitransparent gray boxes indicate target conditions from 40%–60%RH (for raw data and moving average) and 0%–10%RH (for moving range).

value; if the CRF of 22°C is 0.42, this indicates that 42% of the dataset is equal to or less than 22°C. CRF plots display the variable of interest on the horizontal axis and its CRF on the vertical axis. Using RH data displayed as a time series in figure 2.3a, figure 2.3b shows the cumulative relative frequency of RH for interior and exterior locations. Note that the IQR of each location is denoted by the RH values corresponding to CRFs of 0.75 (75th percentile) and 0.25 (25th percentile). If the dataset is relatively complete, a CRF plot can determine the percentage of time that the data resides within a target zone. For example, the interior data in figure 2.3b has CRF values of 0.103 and 0.935 at 40% and 60% RH, respectively; thus, the interior dataset is within the 40%–60% RH range during ~83% (0.935 minus 0.103) of the period.

Box plots (or box and whisker plots) provide a complementary means of visualizing probability. Box plots depict the variable of interest on the vertical axis and data groupings on the horizontal axis (fig. 2.3c). These plots use line markers connected as a box: the top and bottom borders always indicate the IQR, while the line within the box specifies the median value. This graphical organization facilitates comparison of the vertical position (higher or lower) and height (narrow or wide) of the IQR for different locations. The definition of the whiskers extending beyond the box can vary, though they often denote maximum/minimum values (as in fig. 2.3c) or percentile pairs (e.g., 90th/10th percentiles). The positioning of the box with respect to the whiskers gives an indication of the skew or asymmetry in the dataset.

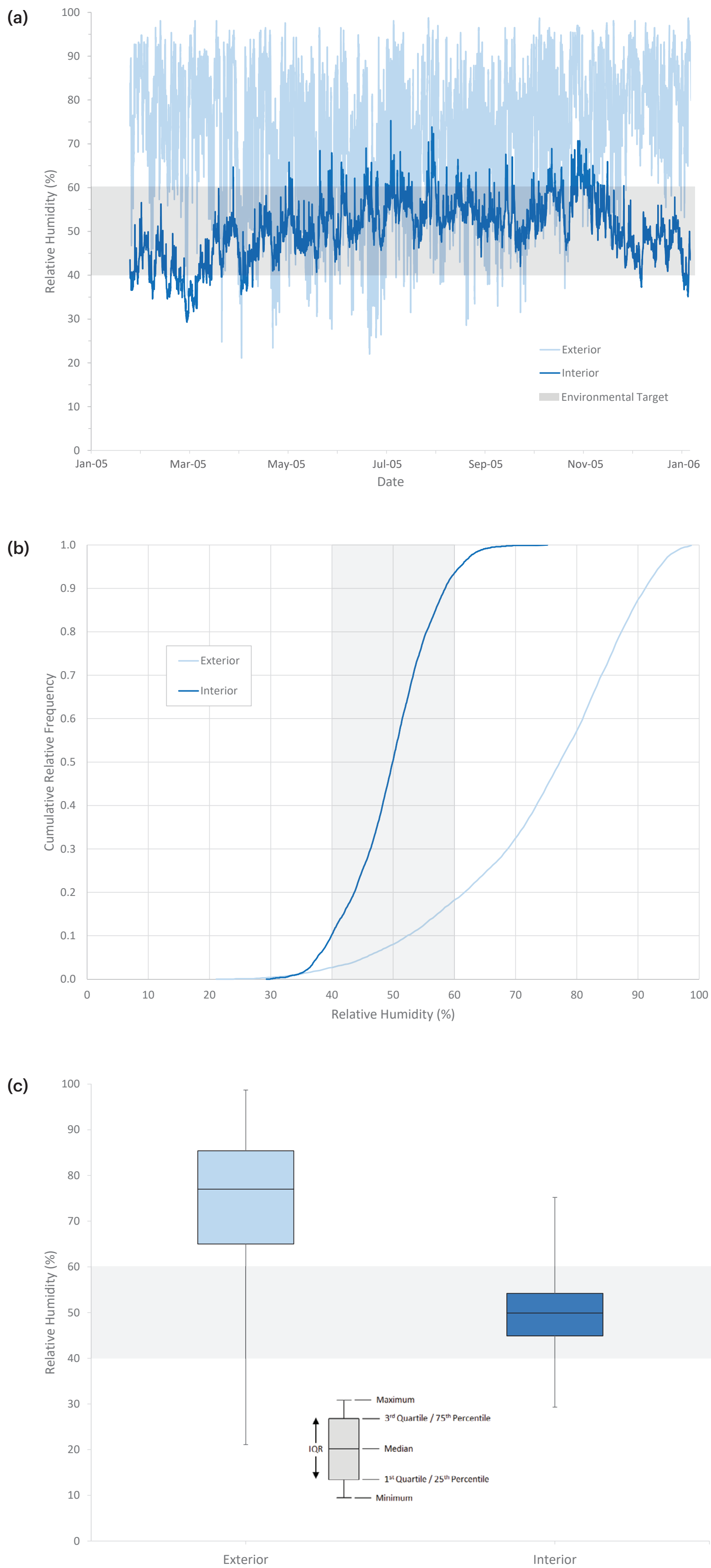


FIGURE 2.3

Exterior (light blue) and interior (dark blue) RH visualized as (a) a time series plot and by its probability distribution via (b) a cumulative relative frequency plot and (c) a box plot (all were created with the GCI Excel Tools). The semitransparent gray regions indicate target conditions from 40%–60%RH.

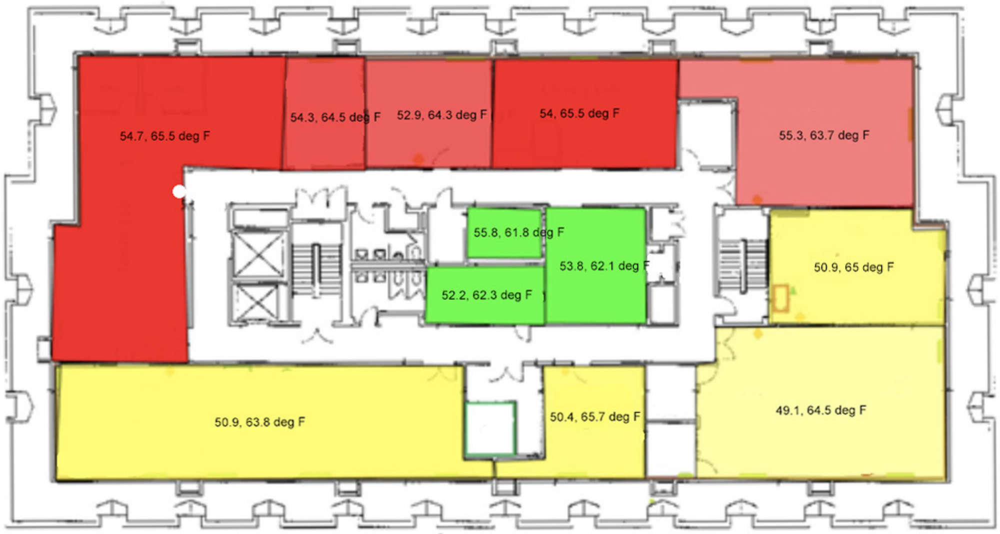


FIGURE 2.4

An overlay of dew point temperature on a museum floor plan. Relative to a target range, the red, green, and yellow regions indicate that it is above, within, and both above and below, respectively. This visualization was created with a tool developed by Rebecca Napolitano, Melissa King, Joelle Wickens, Marie Desrochers, Maddie Cooper, and Michael C. Henry for the Winterthur/University of Delaware Program in Art Conservation (WUDPAC).

The spatial relationships of environmental data can be directly visualized on museum floor plans of gallery and storage spaces. Figure 2.4 shows dew point temperature represented across a floor plan, with the magnitude at each location indicated by a scaled color. While an overlay represents a moment in time, sequential data overlays can merge the spatial and temporal domains. By overlaying environmental data onto a floor plan, one can better understand relationships between rooms and the building envelope, as well as their possible causative factors.

While prior examples focused on independent visualizations of variables, the psychrometric chart graphically illustrates the interdependence of T and RH with other thermodynamic properties. Commonly employed by HVAC engineers and facilities staff, psychrometric charts show T on the x-axis and humidity ratio on the y-axis, with RH depicted by isohume lines curving upward from left to right (figs. 2.5a and b). Though not shown on this iteration of the psychrometric chart, additional chart parameters can include dew point temperature, wet bulb temperature, enthalpy, specific volume, and sensible heat ratio. The psychrometric chart is also elevation dependent—sea level charts are typically used for elevations below 600 m above sea level.

Multiple environmental datasets and subsets can be plotted on the psychrometric chart, with each point thermodynamically describing a parcel of air at a specific time. Figure 2.5a depicts exterior and interior data, while figure 2.5b focuses on the display of seasonal interior data. Figure 2.5b also overlays a target zone defined by both T and RH conditions. Comparison of the relative positioning of "out-of-spec" interior data with the target zone can inform the psychrometric strategies

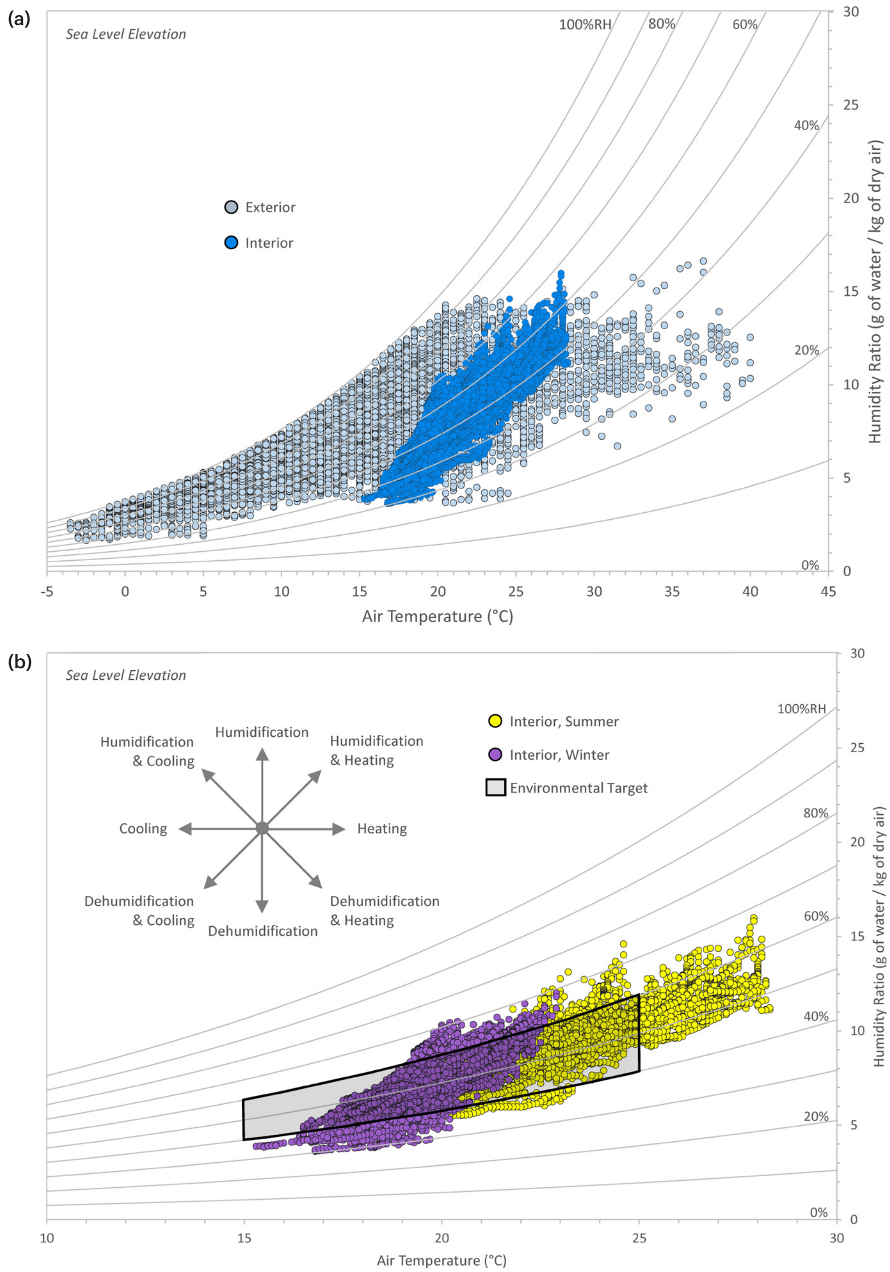


FIGURE 2.5

Psychrometric charts showing (a) exterior/interior data, and (b) seasonal interior data (created with the GCI Excel Tools). Also depicted in (b) are target conditions based on T and RH, and a compass connecting directionality on the plot with psychrometric processes.

needed to shift the air parcel closer to or within the target, or determine if a modified target is more appropriate. The net direction on the psychrometric chart provides a visual depiction of the path of the psychrometric process—heating, cooling, humidification, and dehumidification—between initial and final state points or environmental conditions. (It should be noted that the actual path in modifying the environment may not be linear.)

Conclusion

The use of a range of numerical analyses and visualizations with complementary objectives provides the user with a more holistic view of the museum environment than has been typically available via individual data logger software. While the methods discussed here have proved helpful in understanding the heritage environment, additional analysis and visualization techniques may prove equally illuminating. For example, the use of real-time dashboards displaying a suite of numerical and graphical aids can provide an efficient overview of current trends.

To effectively apply one or more data analysis tools, the user must have awareness of and access to the tool, and an understanding of how it is employed; the latter may be particularly challenging given the myriad of responsibilities for many collection care professionals. However, it is hoped that broad dissemination of didactic material on analysis fundamentals and practical tool use, continued development of tools that are user friendly and collection focused, and open dialogue among tool users and developers can support improved environmental management within the cultural heritage field.

References

Cassar, May and Jeremy Hutchings. 2000. *Relative Humidity and Temperature Pattern Book: A Guide to Understanding and Using Data on the Museum Environment.* London: Museums & Galleries Commission. https://collectionstrust.org.uk/resource/relative-humidity-and-temperature-pattern-book/.

Maekawa, Shin, Vincent L. Beltran, and Michael C. Henry. 2015. *Environmental Management for Collections: Alternative Conservation Strategies for Hot and Humid Climates*. Los Angeles: Getty Conservation Institute. http://www.getty.edu/conservation/publications_resources/books/environmental.html.

National Park Service. 2016. "Museum Collections Environment." Chap. 4 in *The Museum Handbook, Part 1: Museum Collections*. Washington, D.C.: National Park Service. https://www.nps.gov/museum/publications/MHI/mushbkI.html.

Tufte, Edward R. 2001. *The Visual Display of Quantitative Information.* Cheshire, CT: Graphics Press.

CHAPTER 3

TOOL DEFINITION AND ATTRIBUTES

By Annelies Cosaert and Bhavesh Shah

Data analysis tools can play an important role in advancing the conservation of cultural heritage objects, both in historical buildings and purpose-built structures. These tools help efficiently gather data for documentation, communication, investigation, and diagnosis; shape decisions related to risk assessment and management; aid in identifying, evaluating, and selecting conservation options; and assist in planning and budgeting for new and upgraded environmental control systems (BSI 2017).

This chapter aims to define tools and their ideal attributes based on recent explorations of the topic. This effort includes formal interviews with twelve conservation colleagues versed in environmental data analysis. This cohort was comprised of consultants/researchers, museum staff, and independent conservators. Most were employed by large (50+ employees) museums or research institutions, but their work was often done in collaboration with clients or partners from small and mid-size heritage institutions in Europe, Australia, and the Americas. This chapter is also informed by discussions on the state of tool use and development during the 2019 Winterthur meeting, and an analysis of existing temperature (T) and relative humidity (RH) tools (Cosaert and Beltran 2021).

A series of preferred tool attributes was identified based on user needs not sufficiently addressed by current tools, or needs that are addressed by the use of multiple tools. These attributes may guide further development of preventive conservation tools. Based on the previously mentioned interviews and discussions, and taking into account the 2018 work by Lambert and Katrakazis, an ideal tool was defined by the following qualities:

- Carries out a clearly defined function
- Oriented toward practice and implementation
- Intuitive, user friendly, and results in a good staff/time benefit ratio
- Assists in the decision-making process
- Free or inexpensive (less than US$100/year)
- Accessible online or through download

Institution-Specific Motivation for Development

Research institutions, universities, and individuals have created tools to analyze their collected T and RH data. These tools can vary in motivation (e.g., archives, building performance, and mechanical response), form, and function; the latter includes performing simple calculations, modeling complex interactions, visualizing data, and/or calculating object and collection risk. Increasingly sophisticated tools are being developed using new technology and incorporating an improved understanding of how objects change. There has been a growing comprehension of how materials respond to T and RH fluctuations, as well as the impact of the climate zone and building envelope performance on the interior environment.

A selection of relevant numerical data is displayed or translated to preservation metrics (which are based on varying assumptions) that can be, from a user perspective, challenging to compare across tools. The variety of tools for T and RH analysis and the differences between them allow for comparison of not only what they offer users visually and numerically, but also how they work technically, how these choices were made, and how this impacts the management of museum environments. This might be supported by efficient dissemination and an interdisciplinary effort between tool users and developers for self-learning on open-source platforms and workshops requiring active participation.

Efficiency and Post-Processing Data

Interviewees perceive advantages in using different tools, but the unique data requirements of each tool with respect to import and format is an obstacle for their effective use. To facilitate more user-friendly platforms, we need to evolve toward:

- Standardized data (e.g., ISO date-time, SI and I-P units, Fahrenheit and Celsius)
- Accommodation of different file formats (e.g., decimal, comma, and point)
- Management of datasets with variable time intervals and missing data
- Global compatibility (e.g., applicability in northern and southern hemispheres, elevation correction)

Figure 3.1 visualizes the flow of data collection, analysis, and communication. Typically, a dataset is accessed using logger software. This can be complicated by the use of different types of data

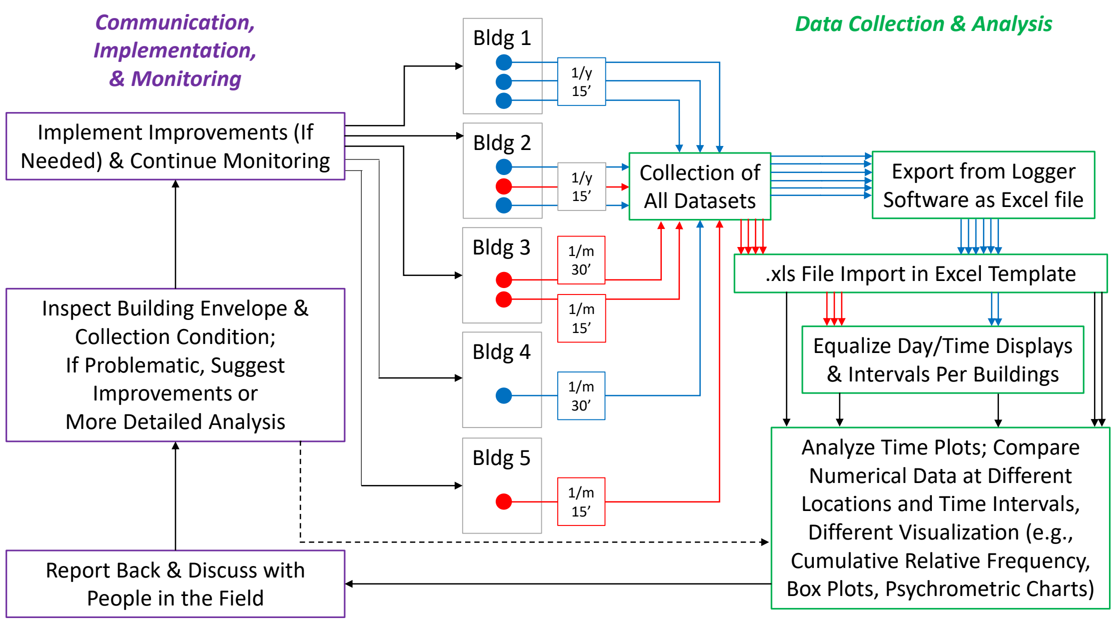


FIGURE 3.1

An example of a complex dataflow based on interviewee testimony. This dataflow represents a situation in which an institution conducts environmental analysis for a set of buildings using multiple data loggers and time intervals. The activities highlighted in green indicate the extent of manual labor needed (each arrow is representative of a single dataset) to format datasets for analysis.

loggers, for which access requires their native software, and different time intervals of data collection. If analyzing with alternate software, the data is exported from the logger software, reformatted to match the format requirements of the tool, and then uploaded to the tool. Most tools save data on their local server so it is easily accessible in the future. In an effort to reduce time, interviewees emphasized their reliance on their IT department to facilitate automated data import capabilities from systems such as a Building Management System (BMS).

Furthermore, there is a general desire to link T and RH data to both locations and events. While interviewees feel this information is essential to contextualize their analysis, they often have to rely on colleagues in other departments, volunteers, or other stakeholders to provide this information. While one can connect events to each location's dataset in the form of comments, in most cases this information must be extracted from written records and manually transferred to an electronic data file.

Comparison with Guidelines

While interviewees were familiar with environmental guidelines (e.g., NMDC 2015; IIC/ICOM-CC 2014; AFNOR / BSI / DIN 2018; AICCM 2019; and ASHRAE 2019) and recognize their importance, each institution considers them in the context of its own specific circumstances (loan and exhibition agreements are exceptions). These "institutional standards" can be a more relaxed (or tightened, in rarer cases) version of existing guidelines in which people take into account the quality of the building envelope, the function and occupancy of the room, the capacity of existing mechanical systems, and the material composition of the objects in that room. They are, in other words, often a reflection of what is feasible, avoiding rapid fluctuation or worse due to malfunctioning equipment, rather than the theoretical ideal.

Subsequently, the option of comparing an environmental dataset to institutionally determined T and RH limits is considered valuable. These results can be integrated into environmental performance reviews, support research aimed at improving sustainability, and visualize environmental conditions for loans.

Comparison with Exterior Climate

Comparison of the interior environment with the outdoor climate is considered valuable. This helps conservators gain insight into the performance of their building, determine seasonal periods based on data rather than date, and implement set point adjustments to reduce demands on environmental control systems and promote sustainable operations. When collaborating with architects and building engineers, historical data is often sought out.

Despite these benefits and their relatively low installation cost, most museums do not have access to an onsite weather station or outdoor T and RH logger. While outdoor data collected elsewhere in the region may be available (for example, via .EPW files [NREL 2019]), these files may not be geographically representative for the site in question. Further, climate change can impact the relevance of historic climate data and may promote the use of near-term regional projections.

Assessment of Risk

Interviewees see T and RH analysis as one of a number of contributing factors for risk analysis. Tools can link T and RH data to the development of mold (germination), chemical decay, and mechanical response (fig. 3.2). Some tools allow for a comparison of generalized collections, while others permit the user to define object-specific characteristics (e.g., type of object, thickness, restrained or non-restrained). Both visual and numerical translations of these risks vary between tools; note that the use of traffic light systems can mask nuance in the data interpretation. The interviewees typically used risk calculations to aid in their selection of threshold values to establish preservation specifications, explore more sustainable climate system operations, and discuss desired environments for loan agreements.

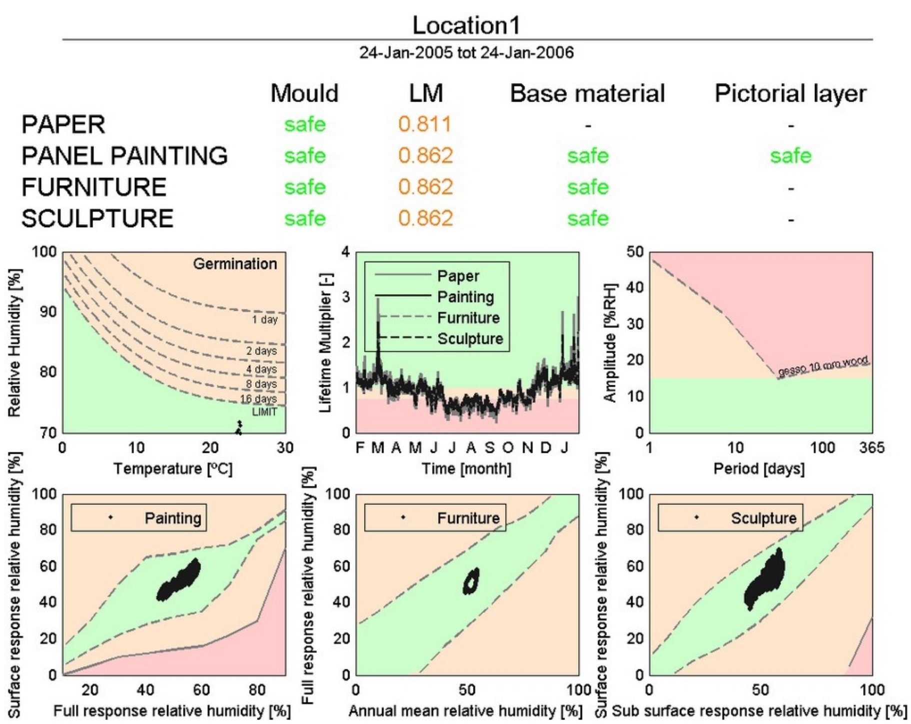


FIGURE 3.2A
TU/e – Building Physics for Monuments tool (2019): The Specific Risk plot is a collection of different types of plots and quantitative data about the risk associated with biological damage such as mold, chemical aging represented by the lifetime multiplier (LM), and physical/mechanical damage of the "base material" (support) and the "pictorial layer." © 2014 TU/e – Harrie Smulders & Marco Martens

Preservation Environment Evaluation

Type of Decay	Risks & Metrics	Evaluation & General Comments
Natural Aging Chemical decay of organic materials	RISK TWPI = 15	Accelerated rate of chemical decay in all organic materials due to the cumulative effects of temperature and humidity, with especially high risk for fast decaying organic materials such as acidic paper, color photographs and cellulosic plastics.
Mechanical Damage Physical damage to hygroscopic materials	OK % DC = 1 % EMC min = 7.7 % EMC max = 11.3	Generally OK, but sensitive or fast responding hygroscopic materials such as paintings, rare books, vellum manuscripts or musical instruments will be at elevated risk of physical damage due to fluctuations of humidity.
Mold Risk Mold growth in area or on collection objects	GOOD MRF = 0	Minimal risk of mold growth.
Metal Corrosion Corrosion of metal components or objects	RISK % EMC max = 11.3	Heightened risk of metal corrosion due to extended periods of high levels of humidity.

FIGURE 3.2B
RIT/IPI – eClimateNotebook (2019): The "Preservation Environment Evaluation" is a translation of a quantified set of risks that can be visualized by a time plot. Biological decay is represented as "mold," chemical decay is divided into "natural aging" and "metal corrosion," and physical and "mechanical damage" are defined by % Dimensional Change (DC) and % Equilibrium Moisture Content (EMC). © 2019 Image Permanence Institute (IPI)

The application of risk calculations for cultural heritage objects should be considered carefully. The respective definitions of risk for each tool can vary and are based on results from a finite experimental dataset. Additionally, as a tool delves into data interpretation, more assumptions are required (e.g., collection type, mold-growth type) to carry out the calculation. It is also worth mentioning that the different risk types (chemical, mechanical, and biological) are not assessed together (e.g., presence of mold can lead to destabilization of an artwork and subsequent mechanical damage), and thus can exaggerate or underestimate the risk. Interviewees were aware of the limitations of these risk analyses, and therefore chose to use the results as indicators, combine them with visual inspections, or not apply them.

Define Mechanical Strategies and Reduce Energy Use

Museum environments are impacted by various factors, including climate change, aging HVAC systems, the renovation of existing structures, and the construction of new storage facilities and/or exhibition spaces. Simultaneously, environmental guidelines (e.g., IIC/ICOM-CC 2014; NMDC 2015; AICCM 2019; ASHRAE 2019) are promoting a shift from traditional prescriptive narrow ranges to wider bands based on collection vulnerability (linked to proofed fluctuation) and sustainable practice.

Interviewees analyze current and historical data (if available) to explore questions from internal and external stakeholders about current and future environmental management strategies. Included in this dialogue are investigations of non-mechanical and mechanical environmental approaches and their sustainability, particularly with respect to energy consumption. This discussion can be supported by the analysis of seasonal and annual data, and comparisons of exterior/interior conditions and data from pre-/post-strategy implementation.

Facilitate Stakeholder Communication

Effective communication is crucial for defining and achieving sustainable environmental goals. Both internal and external stakeholders must understand the narrative defined by the data. These results can be used to obtain grants or funding from governing agencies, facilitate internal discussion, and communicate with lending institutions.

While T and RH analysis tools facilitate the export of data, visualizations, and automated reports, interviewees rarely mentioned utilizing the reporting function. Instead they relied on bespoke report templates based on the purpose of the analysis and the stakeholders to be addressed.

Conclusion

The range of T and RH tools available to the cultural heritage field are valuable because they show us an array of possibilities for data analysis and visualization and help tool users define their environmental needs. Using a suite of tools as a "toolbox," in which different tools can serve different purposes, allows for a more nuanced analysis of the environment. However, this requires the various tools to be identified, their functionalities understood, and their learning curves navigated; all are practical issues that prevent the effective use of potentially complementary tools.

Overall, users are in general agreement that the desired short-term improvements in T and RH analysis tools involve maximizing flexibility (predominantly in visual and numerical display of results) and improving efficiency in dealing with different data formats. Further, users expressed a desire that future tool development integrate complementary datasets—pollutants, light, pests, vibration, occupancy, corresponding events—as a means of improving their understanding of the overall museum environment.

References

AFNOR. 2018. *NF EN 16893 Conservation du Patrimoine Culturel – Spécifications pour l'emplacement, la construction et la modification des bâtiments et des salles destinés au stockage ou à l'utilisation de collections – Conservation du Patrimoine Culturel – Nouveaux sites et bâtiments destinés au stockage et à l'utilisation de collections*. La Plaine Saint-Denis, France: Association Française de Normalisation.

AICCM. 2019. *Environmental Guidelines*. Canberra: Australian Institute for the Conservation of Cultural Material. https://aiccm.org.au/conservation/environmental-guidelines/.

ASHRAE. 2019. "A24—Museums, Galleries, Archives, and Libraries." Chap. 24 in *ASHRAE Handbook—HVAC Applications*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers. Also issued as IP edition, 2019.

BSI. 2017. *BS EN 16853:2017 Conservation of Cultural Heritage: Conservation Process: Decision Making, Planning and Implementation*. London: British Standards Institution.

BSI. 2018. *BS EN 16893:2018 Conservation of Cultural Heritage: Specifications for Location, Construction and Modification of Buildings or Rooms Intended for the Storage or Use of Heritage Collections*. London: British Standards Institution.

Cosaert, Annelies, and Vincent Beltran. 2021. "Comparison of Temperature and Relative Humidity Analysis Tools to Address Practitioner Needs and Improve Decision-Making." In *ICOM-CC 19th Triennial Conference Preprints, Beijing, 17–21 May 2021* (forthcoming), edited by Janet Bridgland. Paris: International Council of Museums.

DIN. 2018. *DIN EN 16893 Erhaltung des kulturellen Erbes – Festlegungen für Standort, Errichtung und Änderung von Gebäuden oder Räumlichkeiten für die Lagerung oder Nutzung von Sammlungen des kulturellen Erbes*. Berlin: Deutsches Institut für Normung. doi: https://dx.doi.org/10.31030/2695151.

IIC and ICOM-CC. 2014. "Environmental Guidelines – IIC and ICOM-CC Declaration." London: International Institute for Conservation of Historic and Artistic Works; Paris: International Council of Museums – Committee for Conservation. https://www.iiconservation.org/sites/default/files/news/attachments/5681-2014_declaration_on_environmental_guidelines.pdf.

Lambert, Simon, and Theocharis Katrakazis. 2018. "Survey of Preventive Conservation Tool and Resource Users: Summary of Findings." Rome: International Centre for the Study of the Preservation and Restoration of Cultural Property; Ottawa: Canadian Conservation Institute. https://www.iccrom.org/sites/default/files/2018-07/iccrom_precon_tools-resources_eng.pdf.

National Renewable Energy Laboratory (NREL). 2019. "Weather Data." EnergyPlus. Washington, D.C.: National Renewable Energy Laboratory. https://energyplus.net/weather.

NMDC. 2015. "Bizot Green Protocol." In Environmental Sustainability: Reducing Museums' Carbon Footprint. London: National Museum Directors' Council. http://www.nationalmuseums.org.uk/what-we-do/contributing-sector/environmental-conditions/.

CHAPTER 4

INTEGRATION WITH OTHER DATASETS

By Bhavesh Shah, Geert Bauwens, and Melissa King

Mitigating risks to ensure the preservation of cultural heritage requires monitoring of a number of variables that inherently involves the collection of large amounts of data. Statistical analyses ranging from basic calculations (e.g., percentiles, moving averages, fluctuations) to more complex processes (e.g., cross-correlation, machine-learning techniques) might offer insight into interconnected systems that affect these variables. While this paper has thus far largely addressed temperature (T) and relative humidity (RH) data, this chapter acknowledges the value of integrating other forms of data to inform our understanding of the preservation environment. This chapter discusses three types of data integration: those that are possible and commonly done, those that are possible and should be utilized more, and those that are currently not known to be utilized and warrant more research.

Climate Control Systems

Climate control systems manage environmental conditions in spaces for a combination of object protection and visitor/staff comfort. The management of such systems is normally undertaken by in-house facility managers or knowledgeable staff members who must also consider costs and energy consumption. These systems include sensors as part of the Building Management System (BMS) to monitor temperature, humidity, chilled/heated water temperature and flow, pressure, airflow rates, fan speeds, on/off coil temperatures, and more. The position of these sensors is driven by equipment needs rather than monitoring of museum objects, so they are often fixed and located in hard-to-access areas, such as ducting and pipes. Unless incorporated into the system-maintenance plan, this may mean that the calibration of sensors associated with the climate control system occurs less often than that of sensors used to monitor moveable collections. It should also be noted that placement of these climate control system sensors might affect the ability of the logged data to represent the true conditions of the space if they are placed too close to windows, entry points, heat sources, and other impactful variables.

The data collected from the BMS is commonly used to support short-term temporary actions, such as adjusting equipment settings or operational parameters; as a result, long-term data is not always saved and available for analysis. When the climate control system is managed by an external contractor, it can become challenging to gain access to the data recorded by system sensors. Specific actions undertaken by facility teams to manage the climate control system can be stored digitally or manually, including handwritten records.

The integration of T and RH tools with data collected by climate control systems is important to support various objectives:

- Improvements in collections care, visitor experience, and staff comfort.

- Reduction in energy consumption and costs.
- Alerts to out-of-spec environmental conditions, allowing for more timely assessments and interventions if needed.
- Understanding of patterns and trends in climate data to support decision making.
- Prediction of future equipment and budget needs.
- Reduction in energy consumption and costs by correlating energy costs and carbon budgets with environmental data.
- Facilitation of communication with clients and stakeholders.
- Calibration of T and RH sensors employed for monitoring the collection environment.

Archival/Collection Management Systems

Archival/collection management systems are often used to record object location for registration purposes, treatment and condition records, provenance, and historical context. Linking environmental data to object location records could provide useful information about historical object-specific environmental conditions that is linked to the concept of proofed fluctuation (Michalski 1993). For example, if an object is exposed to a range of RH conditions in a storage room, this may allow conservators to make informed decisions about the future environmental requirements for display. This could, in turn, provide a rationale for broadening the range of environmental conditions and potentially reduce the energy consumption by the mechanical system. If the collection management system can track issues over time, there could be opportunities to link specific damage to recorded environmental data. This would require condition assessments that are repeatable, i.e., that follow broadly agreed information reference models (Bekiari et al. 2021). Additionally, linking T and RH data to collection type, present location, and the specific preservation requirements of the collection has the potential to create a feedback loop within the Building Automation System (BAS) to refine environmental control parameters.

Staff Observations

The data collected by staff during routine inspections and site visits is invaluable to understand the condition of the collections and building. Further, this observational data, known as "paradata," provides essential context for the analysis of T and RH data. Staff observation data can be obtained by passive devices (e.g., Blue Wool Standard cards) and spot readings, and provides information on a range of events, including: mechanical or plant failure, chemical response or fading, repair/maintenance schedules, building leaks, pest counts, mold outbreaks, emergency response, and security incidents. Event data is typically recorded as observations in physical (written) or digital logbooks, and linked to other records and written reports that are organized in a local repository system.

A recorded event can consist of a single instance, such as observed dew forming on the wall, or it can encompass a range of time, such as room occupancy throughout the duration of an exhibition. The former event dataset would be interpreted by a computer as a time-stamped data object, while the latter would be recorded as a time-range object. Both of these data types will be managed differently by a T and RH analysis tool, requiring distinct encoding and parameterization to facilitate data integration and comparison.

Exterior Climate

Exterior climate is commonly recorded by climate control systems as a means of regulating the indoor climate. Outdoor climate data includes T, RH, rain, solar radiation, wind speed and direction, and barometric pressure. This information can be collected by exterior data loggers (shielded from direct sunlight and rain) and onsite weather stations, or downloaded from online weather data repositories. While monitoring of the exterior climate may be uncommon at small to mid-sized museums, installation costs for a weather station can be relatively inexpensive. If using climatic data from local weather stations, the representativeness of the data should be carefully considered given the geographic or situational differences between the weather station and the site of the collection and building.

Exterior climate data is crucial for understanding interior conditions. If environmental data within portions of the building is highly correlated to outdoor data, this may be indicative of building envelope issues. More generally, understanding how interior conditions are informed by outdoor climate can reveal opportunities and limitations of spaces with regard to passive and active climate control, and, from a preservation standpoint, inform the choice of collection materials most appropriate for the space. The relationship between exterior and interior climates is visualized in figures 2.3 and 2.5 in chapter 2 ("Analysis and Visualization").

Building Envelope/Health

Building diagnostic techniques may be employed to understand building envelope and conservation issues. These techniques can include the use of sensors to measure rainwater, airflow and moisture within the walls, surface temperature, solar gain, conductivity to measure salt levels, and wind speed and direction.

This data can be used to deepen understanding of T and RH data, make informed choices on exhibition layout, and improve control of the indoor climate. For example, data showing that part of the building envelope exhibits cold indoor surface temperatures and thus has a higher risk of mold growth can alert conservators and museum staff to the need for possible mitigation measures for object safety. Similarly, data indicating moisture issues for specific walls may inform the placement of T and RH sensors and whether monitoring of additional variables within a space is necessary.

Light

As museums strive to make collections more accessible to the public, lighting is an essential element for the display of objects, and encompasses natural light and/or electric lighting. However, this is countered by the damaging effects of light-induced fading and potential thermal deterioration. The shift from incandescent to solid-state gallery lighting also promotes sustainability by reducing energy consumption and heating in galleries. Integration of light data with T and RH tools has the potential benefit of adding useful information, such as localized heating on or near objects, and heating and solar gain inside spaces.

Light monitoring data typically consists of a mixture of logged data, spot readings, and visual passive devices (e.g., Blue Wool Standard cards) at a specific location. Sensor positioning is important to consider when analyzing light levels, as its orientation can significantly affect the amount of light interaction. The use of logged light data can be particularly useful in the identification and quantification of light exposure outside of museum opening hours (e.g., conservation treatment, installation and deinstallation, gallery cleaning, security inspections, off-hour visitation). When natural light is present in indoor spaces, the duration of exposure, time of year, and added ultraviolet component will impact monitored light levels. Daylight depends on the solar azimuth angle, elevation, and the building envelope's solar aperture, and, thus, varies significantly throughout the year.

Gaseous Pollution

Pollutants tend to damage objects faster with increasing temperature and moisture levels. Moreover, temperature can have a direct effect on the degradation of objects and can encourage an increase in off-gassing of damaging volatiles, e.g., "vinegar syndrome" exhibited by cellulose acetate materials (Grzywacz 2006 and Curran et al. 2017). Integration of T and RH tools with pollution data is useful to understand risks to both collections and visitor health.

Challenges associated with monitoring pollutants include cost, interpretation of the results, and understanding of what should be monitored from a risk-assessment perspective. The source of gaseous pollutants is often external to the building, but interior sources can play a role (e.g., synthetic fabrics). A range of pollutants are increasingly monitored in larger museums, and data can be logged over time or reported as a cumulative value for a specific time period.

Pests

Integrated Pest Management (IPM) is a common practice in cultural institutions that requires meticulous record keeping of insect types, life stages, and the locations at which they were found within the building. Select insect types can serve as indicators of moisture problems, such as water drainage buildup or leaks. It is common to find species of insects that have navigated to the interior, yet are not considered "true" pests for collections. However, if a significant number of non-pest insects are found in a part of the building, this might be an indication of building envelope issues. If IPM data can be linked with T and RH data, one may be able to predict pest infestations or mold outbreaks if certain environmental conditions are sustained over time.

Vibration

Vibration can pose a significant risk for objects that have friable surfaces, such as pastel drawings and ancient sculpture with underbound pigment. Vibration can also cause objects to shift on surfaces and tumble if unsecured. While natural disasters, such as earthquakes and hurricanes, pose the most obvious risk, collections and buildings are increasingly subject to localized vibration sources, including music events that draw large crowds, construction activity, and adjacent busy transportation thoroughfares.

Vibration can also damage objects during handling at the lending and receiving institutions and transport by land, air, or sea. The packaging materials used to cushion objects from transit-related vibration and shocks also need to buffer against external T and RH conditions; after arrival, a period of acclimatization is necessary to equilibrate between the T in the interior crate and the lending institution, to avoid the risk of condensation on the object. Integration of T and RH data with vibration monitoring offers reassurances for lending museums that their objects are safe during transport. The data collected might include timestamps and geospatial information to locate potentially damaging events; also helpful are courier observations of significant handling and transit events, which can be linked to the data.

Dust Deposition

The deposition of dust particles can reduce the value of objects by causing potential damage during cleaning, facilitating chemical reactions, or diminishing the object's aesthetics via soiling, with the extent of change usually increasing with time (Lithgow et al. 2005). Physical damage may occur when removing particles from the object surface, or when the hygroscopic nature of the dust retains moisture for prolonged periods on water-sensitive surfaces, such as metals or porous materials prone to staining. Additionally, dust represents a food source for many museum pests, which can subsequently cause damage to objects.

The management of dust in the museum is important for both the care of the collection and its appearance to visitors. Dust can be assessed indirectly by measuring the number of particles in the air or directly via examination of surface deposition. These datasets can be time stamped, cumulative, or captured as survey data based on visual assessment or perception. Dust and humidity can have common sources (e.g., visitors), so integration of these datasets can allow for a more holistic understanding of the building environment.

Occupancy

Occupancy in gallery spaces can be measured by sensors, visual counts, or ticket sales, and this dataset can be linked with T and RH data. Museum visitors can impact indoor T and RH significantly through their body heat and exhalation of moisture. A large group of visitors entering a museum space on a rainy day can yield a steep rise in humidity. Occupancy can be used to modulate the amount of outside air to be conditioned by the climate control system, potentially reducing operational and energy costs. Tracking occupancy may also provide an indication of the risks of mechanical damage to collections due to physical contact from visitor interactions.

Conclusion

Regardless of the type of data that is logged, difficulties can arise when comparing data from different sources. For instance, a museum technician may interrogate a data dashboard for the HVAC system, while a conservator independently examines data from a dashboard of a data logger vendor. Properly integrating data from various sources would promote collaboration among colleagues and facilitate monitoring reports that analyze these complementary datasets.

To better understand the relation between multiple datasets, it would be beneficial if relevant stakeholders had access to and capability with a suite of analysis tools. As discussed previously, there remain obstacles to this realization, but strong consideration should be given to more uniform data acquisition standards to more easily integrate datasets into T and RH tools. By offering an opportunity to examine correlations between different variables, one can begin to more holistically examine the museum environment and identify causative factors that may place the collection at risk.

References

Bekiari, Chryssoula, George Bruseker, Martin Doerr, Christian-Emil Ore, Stephen Stead, Athanasios Velios. 2021. *Volume A: Definition of the CIDOC Conceptual Reference Model.* Heraklion, Greece: Institute of Computer Science, Foundation for Research and Technology. https://cidoc-crm.org/sites/default/files/CIDOC%20CRM_v.7.1%20[8%20March%202021].pdf.

Curran, Katherine, Aliyah Aslam, Helen Ganiaris, Robyn Hodgkins, Jacqueline Moon, Abigail Moore, and Linda Ramsay. 2017. "Volatile Organic Compound (VOC) Emissions from Plastic Materials Used for Storing and Displaying Heritage Objects." In *ICOM-CC 18th Triennial Conference Preprints, Copenhagen, 4–8 September 2017,* edited by Janet Bridgland. Paris: International Council of Museums.

Grzywacz, Cecily M. 2006. *Monitoring for Gaseous Pollutants in Museum Environments.* Tools for Conservation. Los Angeles: Getty Conservation Institute.

Lithgow, Katy, Helen Lloyd, Peter Brimblecombe, Y. H. Yoon, and David Thickett. 2005. "Managing Dust in Historic Houses – a Visitor/Conservator Interface." In *ICOM-CC 14th Triennial Meeting, The Hague, 12–16 September 2005, Preprints,* vol. 2, ed. Isabelle Verger, 662–69. London: James and James/Earthscan.

Michalski, Stefan. 1993. "Relative Humidity: A Discussion of Correct/Incorrect Values." In *ICOM Committee for Conservation 10th Triennial Meeting, Washington, D.C., 22–27 August 1993, Preprints,* edited by Janet Bridgland, 624–29. Paris: International Council of Museums.

CHAPTER 5

DISSEMINATION, EDUCATION, AND COLLABORATION

By Joelle Wickens, Melissa King, and Rebecca Napolitano

The meticulous development of tools becomes impactful only when they are used in appropriate and effective ways. Moving forward with the development of tools for preservation specialists, it is important to consider what aspects make them accessible to promote peer-to-peer collaboration, and what is the best means of educating university-level students, mid-career professionals, and others on risk assessment strategies. Collaborative tool development processes, capabilities with transparent functions, links with complementary tools, and cross-disciplinary sharing of data all assist in the process of empowering users with appropriate tools. These elements also help educate the end user, which leads to more effective use of the tools themselves.

Online Tools for Learning Purposes

A 2017 survey on preventive conservation tools (Lambert and Katrakazis 2018) indicates that most respondents preferred learning by "doing or figuring it out on their own" (fig. 5.1a). The survey also identified "visual tools," "online tools," "mobile apps," "real-time diagnostic tools," "videos with practical demonstrations," and "free software" as resources that are sought after but hard to come by (fig. 5.1b). Furthermore, this research shows that most (83%) conservation professionals are prepared to focus on lifelong professional development by carving out a few days to a few weeks

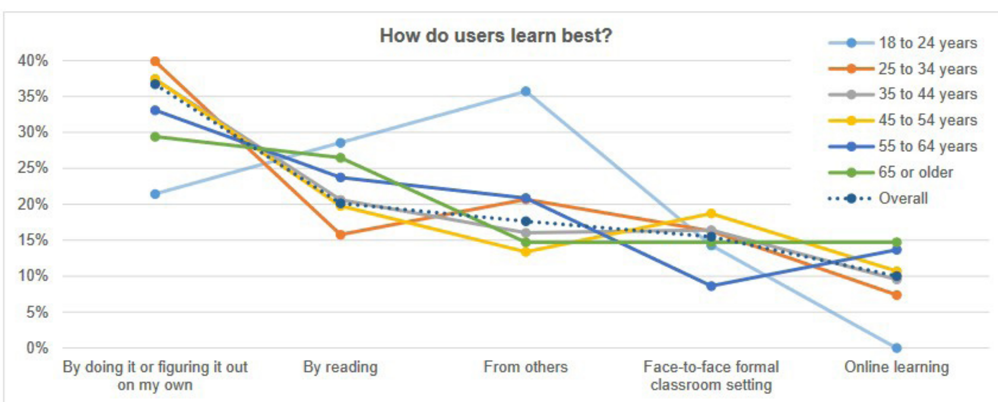


FIGURE 5.1A
Answers to the 2017 survey multiple choice question "How do you learn best?" © ICCROM and the Canadian Conservation Institute

Respondents want but cannot find
Case studies • Lessons learned • Practical information • Videos: practical demonstrations and methodologies • Aggregated information (clearinghouse) • Real-time diagnostic tool • Lists of suppliers and vendors • Visual tools: photos • Mobile apps • Contact information for other

FIGURE 5.1B
Answers to the 2017 survey open-ended question "What type of resources do you need and cannot find?" © ICCROM and the Canadian Conservation Institute

per year for focused training. When considered in combination, these findings indicate great potential for the development of free and accessible tools that assist self-learning via readings, case studies, online support, practical videos, and access to a user community.

Connecting Preventive Conservation Tools

The field of preventive conservation is currently targeted toward different types of analysis often based on risks posed by the "ten agents of deterioration" (CCI 2017). A range of methods and tools exists for the in-house assessment or mitigation of these risks. A selection is listed in table 5.1.

Currently, preservation professionals are trained to use preventive conservation tools to analyze individual variables (relative humidity, temperature, pests, dust) independent of each other. Tools that will assist with simultaneous analysis of multiple variables would help professionals think about preventive conservation comprehensively and better reflect the complexity and interconnectedness of the museum environment. Utilizing risk indices, modeling, and environmental impact life-cycle assessments of materials within various tools offers preservation professionals a means of

TABLE 5.1

Select agents of deterioration, and methods or tools to analyze and/or assist in the mitigation of risks based on in-house measurements.

AGENT OF DETERIORATION	METHOD OR TOOL
Pests & Microorganisms	• Introduction to Museum Pests (Museum of London 2013) • IPM in Collections (Brokerhof et al. 2017b) • Museumpests.net Insect Database (IPM-WG 2018) • What's Eating Your Collection (Birmingham Museum and Art Gallery 2011)
Light (visible, UV, IR)	• Light Damage Calculator (CCI 2018)
Pollutants	• MEMORI (NILU, English Heritage, Fraunhofer 2020) • IMPACT Tool (Grau-Bove and Meng Wu 2020)
Physical damage	• HERIe (Działo et al. 2013) • Building Physics for Monuments (Smulders and Martens 2014) • eClimateNotebook (IPI 2018)
T & RH (too high or low) and Mold	• Building Physics for Monuments (Smulders and Martens 2014) • Dewpoint Calculator (IPI 2018a) • eClimateNotebook (IPI 2018b) • Conservation Heating Calculator (Padfield 2010a) • Dehumidification Calculator (Padfield 2010b) • Moisture Calculator (Padfield 2010c) • GCI Excel Tools (Cosaert and Beltran 2021)
All Agents	• Risk Management for Collections (Brokerhof et al. 2017a) • ABC Risk Analysis (Michalsk and Pedersoli 2016) • Cultural Property Risk Analysis Model (Waller 2003) • Quick Scan (Brokerhof and Bülow, 2016)

diagnosing risks and supporting sustainable practice. By using existing tools and creating new ones, combined with more effective and accessible cross-disciplinary educational materials, we can encourage a systems-thinking approach to environmental museum data (Meadows 2015).

Transparency Encourages Further Learning and Collaboration

Tools themselves can be a source of learning if they are conceived and constructed in a transparent manner. When software packages and other tools are created, developers can choose to classify their programs as black box or white box (STF 2019). Black box software programs limit the user to seeing what they are putting into an application (T and RH data) and what comes out (statistics, metrics, visualizations). In contrast, white box software programs enable a user not only to see the input and output, but also to understand the inner workings of the program and learn about the methods used (e.g., dew point calculations, feature extraction). Thus, white box programs serve a didactic role since they enable a wide, interdisciplinary audience to engage with data cleaning, analysis, and visualization (fig. 5.2). Understanding how existing tools work can enable people to see gaps in current methods and be a catalyst for new tools in the future.

<table>
<tr><th>Development Style</th><th>Data</th><th>Data Cleaning</th><th>Data Analysis</th><th>Method Development</th><th>Data Visualization</th><th>Interpretation of Results</th></tr>
<tr><td>Black Box</td><td rowspan="3">What types of data should be included?</td><td></td><td></td><td></td><td></td><td rowspan="3">What can I say about these results?</td></tr>
<tr><td>White Box</td><td rowspan="2">What type of cleaning is appropriate?

What is an outlier for my data?

What is meaningful information to have?</td><td rowspan="2">What questions can I ask of this data? What type of analysis can I use?

How do different types of analysis compare for this data?

What are the limitations of different types of analysis?

For which cases are different types of analysis best?</td><td></td><td rowspan="2">How can I best visualize the answer to my question?

What is the best way to visualize this for my intended audience?

What are the limitations of different visualization types?

For which cases are different types of visualization best?</td></tr>
<tr><td>Open Source</td><td>How do certain parameters affect my analysis?

How does changing certain equations change my analysis?

Can I infer limitations I should put on my interpretation based on the equations used?</td></tr>
</table>

FIGURE 5.2
An illustration of the various levels of transparency within developing styles.

One type of white box program is open source, which indicates that the code can be freely inspected, modified, and enhanced (RedHat 2019). By making the code accessible, a wide range of people with different perspectives and disciplinary backgrounds will be able to contribute to a shared cause. While one can download the original code and make edits for new features, these edits are not integrated into the original program until these proposed features are tested and approved. This approach provides a springboard for continued tool development and a means of consistently updating the interface or analysis methods that benefit the larger community. This also promotes discourse among people from different backgrounds who are users and/or developers, and the development of new educational materials (e.g., interface tool tips, documentation, webinars) to teach people about a tool's advantages and limitations.

Since any person has the capability to improve open-source code, management of this change remains a challenge. Version control systems and code repositories such as GitHub enable developers to back up and widely disseminate their code, after which multiple coders can try different solutions that may be merged (GitHub 2020). This process provides learning opportunities for those developing the code and fosters collaboration, high-risk/high-reward ideas, divergent thinking, and creative problem solving. Figure 5.2 shows the types of questions that are facilitated in open-source programs but not in other white box programs. While version control can assist in updating software during the developmental stages, the maintenance of developed tools may be difficult in a purely research environment due to lack of funding or academic incentive. Since a majority of the tools listed above are the products of research projects, it is imperative that collaboration be fostered between research institutions and industrial partners.

Imperative of Collaborative Development

As the need and interest in heritage-focused data analysis tools increases, collaboration between developers and preservation professionals is the most effective way to create tools that will be used to great effect by target audiences. To work collaboratively, preservation professionals must learn the language of developers and the framework within which a developer must work. Developers must learn the peculiarity and specificity of conservation challenges. Subsequently, the groups can communicate about challenges such that understanding becomes the foundation of a solution. This collaborative approach ensures that practitioners know what tools exist and how to use them. Further, it can assist practitioners in understanding the science behind the data visualizations, allowing them to draw appropriate conclusions from the results produced by the tools.

More specifically, developers should be aware of the specific needs of the field and trained to reach out to a range of preservation professionals and other practitioners at the start of a project, including conservators, collections managers, facilities staff, curators, and registrars. The interfaces that developers create should not only convert raw data to results, but also promote the user's understanding of data cleaning, analysis, and visualization.

Engineers and data scientists must be trained to utilize the data produced by these tools to further their understanding of predictive modeling and improve communication to a non-engineering audience of the methods used and their implications. They must understand not only how their models can differ from reality and adversely impact practical decisions, but also how to communicate these boundaries and limitations at early stages to facilities managers and non-engineers.

Heritage preservation educators must think broadly about how to bring these groups together. During formal training years, preservation professionals can offer real-life questions and challenges to computer science students. Computer science and engineering students can be taught to reach out to preservation students and institutions looking for questions to answer or tools to develop. Preservation professionals should be trained to use software development tools at a basic level. This will help them understand the language behind and the possibilities of tool development. This training can be offered through formal degree programs as well as at conferences, stand-alone workshops, and freely available web training sessions.

Data Sharing Encourages Tool Development and Analysis

An enormous amount of data spanning decades is collected by preservation professionals, and can easily be adapted for data science studies. There are many fields outside of historic preservation from which data and tools can supplement our resources. Practitioners in these fields include, but are not limited to, entomologists, building scientists, climatologists, environmental scientists, agricultural/botanical scientists, and indoor air quality experts. The wealth of data logged from the cultural heritage sector has been and should continue to be combined in citizen science efforts (Rowe et al. 2018). In addition to potentially increasing research capacity, engaging the public in the world of preservation and tool development will expand our audience and collaborative processes and stimulate dialogue about a range of issues in cultural heritage.

Next Steps for Tool Development and Education

When looking at the future development of preventive conservation tools, there is a clear need for ongoing interdisciplinary collaboration. This can be accomplished by the creation of a space in which developers can share code for their project, and that fosters dialogue at the intersection of data science and cultural heritage. This may be achieved using existing tools such as GitHub or Slack. While relatively static information can be shared about a certain tool or technique of interest, discussion forums or channels will enable dynamic discussion among developers, heritage professionals, and other stakeholders; a recent development in this area is the creation of Con-Code, an international community of heritage and data specialists interested in coding and data science as it relates to cultural heritage preservation and research.

It is in the interest of the tool developer or educator to integrate training modules with a downloadable example dataset and step-by-step written directions or videos for potential users. To improve its relevance for the preservation field, custom training modules or case studies with downloadable environmental data could be created; these can be in the form of videos, instructional text, webinars, workshops, and courses. While this didactic material will augment existing educational materials for conservation, it is important to note that it is not necessary to make all heritage professionals data science experts. These training modules should provide insight on how tools work and facilitate effective dialogue with data scientists on tool iterations.

A particular tools dissemination challenge is that the tools themselves change. Thus, information shared by static readings, workshops, and self-learning materials can quickly become out of date. In contrast, the collaborative and fluid nature of a Wiki page is perfectly suited to the constantly evolving world of data science and the increasing accessibility of programming languages such as R, Matlab, Python, and JMP Pro 14. This and other free online resources that are open to outside contributions can become comprehensive resources for various preventive conservation topics, including environmental monitoring and data analysis. Reliability of entries on a Wiki page is less certain than peer-reviewed publications, but the ease of keeping the data and concepts current may outweigh this concern.

Conclusion

Collaborative, transparent development is key to creating tools that will function as educational platforms alongside their primary intended function. Collaboration should involve conservators, developers, and engineers, as well as other professionals from allied fields and a variety of end users. This convergence will lead to new ways of processing, interpreting, and visualizing data. Starting the collaborative training of these groups of people at the undergraduate and graduate levels will help embed collaborative working and systems thinking during the earliest stages.

References

Birmingham Museum and Art Gallery. 2011. What's Eating Your Collection? Birmingham, UK: Birmingham Museum and Art Gallery and Collections Trust. http://www.whatseatingyourcollection.com/.

Brokerhof, Agnes W., Bert van Zanen, Ko van de Watering, and Henk Porck. 2007. *Buggy Biz: Integrated Pest Management in Collections.* Amsterdam: Netherlands Institute for Cultural Heritage (ICN).

Brokerhof, Agnes W., and Anna E. Bülow. 2016. "The *QuiskScan* – a Quick Risk Scan to Identify Value and Hazards in a Collection." *Journal of the Institute of Conservation* 39, no. 1: 18–28.

Brokerhof, Agnes, Bart Ankersmit, and Frank Ligterink. 2017. *Risk Management for Collections.* Amersfoort: Cultural Heritage Agency of the Netherlands. https://www.cultureelerfgoed.nl/publicaties/publicaties/2017/01/01/risk-management-for-collections.

Canadian Conservation Institute (CCI). 2017. "Agents of Deterioration." Government of Canada. https://www.canada.ca/en/conservation-institute/services/agents-deterioration.html.

———. 2013. "Light Damage Calculator." Government of Canada. https://app.pch.gc.ca/application/cdl-ldc/description-about.app?lang=en.

Cosaert, Annelies, and Vincent Beltran. 2021. "Comparison of Temperature and Relative Humidity Analysis Tools to Address Practitioner Needs and Improve Decision-Making." In *ICOM-CC 19th Triennial Conference Preprints, Beijing, 17–21 May 2021* (forthcoming), edited by Janet Bridgland. Paris: International Council of Museums.

Działo, Artur, Mariusz Jędrychowski, Łukasz Bratasz, Leszek Krzemień, Arkadiusz Kupczak, Roman Kozłowski, Michał Łukomski, and Łukasz Lasyk. 2013. HERIe: Quantitative Assessment of Risks to Heritage Assets. Krakow, Poland: Jerzy Haber Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences. https://herie.pl.

GitHub, Inc. 2020. GitHub. https://github.com/.

Grau-Bove, Josep and Weng Mu. 2020. "IMPACT Tool: A tool that predicts indoor pollutant concentrations and deposition rates." https://josepgrau.shinyapps.io/IMPACT/.

Image Permanence Institute (IPI). 2018a. Dew Point Calculator. Rochester, NY: Rochester Institute of Technology. http://www.dpcalc.org/.

———. 2018b. eClimateNotebook. Rochester, NY: Rochester Institute of Technology. https://www.eclimatenotebook.com/.

Lambert, Simon, and Theocharis Katrakazis. 2018. "Survey of Preventive Conservation Tool and Resource Users: Summary of Findings." Rome: International Centre for the Study of the Preservation and Restoration of Cultural Property; Ottawa: Canadian Conservation Institute. https://www.iccrom.org/sites/default/files/2018-07/iccrom_precon_tools-resources_eng.pdf.

Meadows, Donella H. 2015. *Thinking in Systems: A Primer*, edited by Diana Wright. White River Junction, VT: Chelsea Green Publishing.

MEMORI Project. The MEMORI Technology: Innovation for Conservation. http://memori.nilu.no/Account/Login?ReturnUrl=%2f.

Michalski, Stefan, and Jose Luiz Pedersoli Jr. 2016. *The ABC Method: A Risk Management Approach to the Preservation of Cultural Heritage.* Government of Canada, Canadian Conservation Institute, and International Centre for the Study of the Preservation and Restoration of Cultural Property. https://www.canada.ca/en/conservation-institute/services/risk-management-heritage-collections/abc-method-risk-management-approach.html.

Museum of London. 2013. "Introduction to Museum Pests." London: Museum of London. https://www.museumoflondon.org.uk/Resources/e-learning/introduction-to-museum-pests/index.html.

MuseumPests Working Group (MP-WG). 2018. "About Us." MuseumPests.Net: A Product of the Integrated Pest Management Working Group. https://museumpests.net/about-us/.

Padfield, Tim. 2010a. "Calculator for Conservation Heating." Conservation Physics. https://www.conservationphysics.org/atmcalc/consheatcalc.html.

———. 2010b. "Calculator for Dehumidification Energy Load." Conservation Physics. https://www.conservationphysics.org/atmcalc/dehumidcalc.html.

———. 2010c. "Calculator for Atmospheric Moisture." Conservation Physics. https://www.conservationphysics.org/atmcalc/atmocalc.html.

RedHat. 2019. "What Is Open Source?" *Open Source.* https://opensource.com/resources/what-open-source.

Smulders, Harrie, and Marco Martens. 2014. "Online Applications." Physics of Monuments. Eindhoven: Eindhoven University of Technology. http://www.monumenten.bwk.tue.nl/Algemeen/Applicaties.aspx.

Software Testing Fundamentals (STF). 2019. "Black Box Testing." Software Testing Fundamentals. http://softwaretestingfundamentals.com/black-box-testing/.

———. 2019. "White Box Testing." Software Testing Fundamentals. https://softwaretestingfundamentals.com/white-box-testing/.

Waller, R. Robert. 2003. *Cultural Property Risk Analysis Model: Development and Application to Preventive Conservation at the Canadian Museum of Nature.* Göteborg Studies in Conservation, vol. 13. Gothenburg, Sweden: Acta Universitatis Gothoburgensis.

Xavier-Rowe, Amber, Paul Lankester, Dee Lauder, and David Pinniger. 2018. "Operation Clothes Moth: Where Preventive Conservation and Public Engagement Meet." Supplement 1, *Studies in Conservation* 63: 445–50. https://doi.org/10.1080/00393630.2018.1504441.

CHAPTER 6

FUTURE TOOL DEVELOPMENT

By Rebecca Napolitano, Geert Bauwens, and Bhavesh Shah

Conservators are increasingly encouraged to make data-driven decisions and risk assessments. Such a robust and quantitative process should be supported by future tools and software that create didactic frameworks. This will allow stakeholders to interact with data in meaningful ways and empower them to put into practice international guidelines (Science Europe 2018, BSI 2018, ASHRAE 2019). Historically, developing such a framework can be challenging due to the need for collaboration across several disciplines.

What Developers Need from Conservators

Knowing the target audience is best practice for robust software development projects. In a museum context, typical users of temperature (T) and relative humidity (RH) and other data management tools are conservators, registrars, collection managers, curators, facility managers, and engineers concerned with managing risks to collections. The questions that are being asked of T and RH tools will define the purpose of the software. A system should present users with a solid user experience that maximally incorporates user feedback. Effective software development offers accessibility for first-time users, depth for frequent users, and flexibility for developers. To facilitate software development, users of data analysis tools should provide input on the range of loggers that may be employed.

Development of Online Modular Tools

Future tools should strive to be open ended, open source, and modular, with methods and tools that are accessible, reproducible, and flexible. Open-source programs have source code that anyone can view, change, and enhance. Modular programming is a technique that stresses separating different functionalities of a program into independent, interchangeable modules. For example, if a tool is developed to read in T and RH data and produce plots of T, RH, and dew point, it should be built such that each function is developed as its own module (fig. 6.1).

As a user interacts with the interface, the program will pass information between different modules for analysis and visualization. Users can select the pertinent type of analysis, visualize their results, and save them. Since the tool is built modularly, the user can explore another type of analysis with a different visualization without having to read and parse the data again; this iterative concept is shown in figure 6.1 as black arrows with dashed lines.

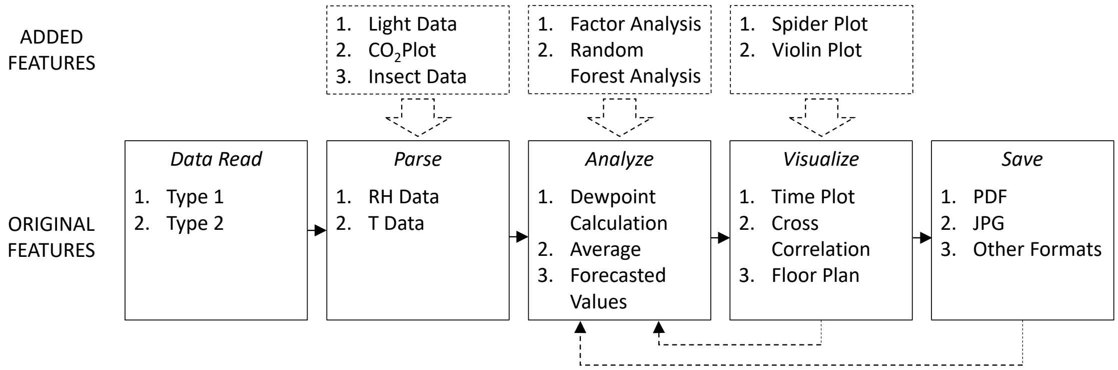


FIGURE 6.1
Flowchart depicting the modularity of original features of the WUDPAC data visualization program and illustrating how individual modules of code enable easier addition of features. This program was developed by Rebecca Napolitano, Melissa King, Joelle Wickens, Marie Desrochers, Maddie Cooper, and Michael C. Henry for the Winterthur/University of Delaware Program in Art Conservation (WUDPAC).

A modular design enables integration of new features, as indicated in the first row of figure 6.1. If users want to integrate light data, they can generate their own function, which is inserted in the parsing stage of the program, in which data is input and a data structure is created, and then connected with other existing functionalities. Similarly, users can generate a function to integrate customized analyses during the analysis stage. This process applies to different types of data files and plotting.

An additional benefit of modular design is that bugs or flaws found in the software, including newly integrated features, can be addressed separate from the rest of the program. This ensures that if one segment of the software (e.g., the dew point calculator) is being updated, other parts of the program will continue to function independently.

While open-source, modular programs can be installed on local machines, it is recommended that future tool development produce web-based applications. A web-based application uses a web browser as the interface between the program and the user. The key advantages of web-based applications are that they are accessible anywhere with a web connection, designed for a range of devices, and easier to update as installation is not required.

Connect to Data Management

A number of vendors provide monitoring systems in which data generated by physical sensors is stored in and accessed via online cloud services. However, the use of standalone loggers from which data is manually downloaded remains commonplace in the museum community. Future tools need to be flexible with regard to the format with which data is ingested (each vendor has a unique data file format) and the mode of data access (streaming data or manual downloads). Future tool developers and their partner organizations should discuss optimal ways to couple existing and future data. The nature of the data informs the range of possible data analyses:

real-time alerts only make sense when data is updated regularly, whereas assessing the quality of indoor T and RH conditions can be done both in retrospect and in real time.

Application of Machine Learning

Machine learning modules analyzing T and RH data provide an opportunity to apply "big data" techniques in order to more deeply understand the behavior of the data (Wickham 2014). The volume of data collected by museums measuring varied aspects of the environment, climate control system operation, IPM, etc., can be used by machine-learning algorithms to ascertain patterns and correlations between datasets that are difficult to discover manually. Interior T and RH data, which can be cyclic and dependent on other factors, such as the weather, may correlate with the various datasets discussed in chapter 4. Machine-learning models can then provide predictions of future conditions or be analyzed themselves. Potential questions that can be addressed by machine learning include:

- Are there patterns or cycles that emerge in this data? Such findings may guide the researcher to look for underlying causes that can inform future monitoring or environmental control strategies.
- Are there correlations with other datasets, such as weather data, climate control system operation, pollutants, mold development and progression, vibration, mechanical response, and IPM? Discovering relationships between datasets can lead to data-driven actions (e.g., removal of plants in specific rooms, drawn curtains for certain building orientations).
- How are alarms and warnings, which can frequently be false, automatically processed to ensure that appropriate staff can respond in a timely manner when action is needed?
- How can we predict risks and future events, such as a pest or mold outbreak, to ensure the safety of the collections being cared for? How can information about potential risks better inform various activities (e.g., tour group scheduling, automation of environmental control systems based on high-traffic events)?

The potential for museums to improve collection care, and reduce risks and energy consumption, are motivators to incorporate machine learning. Machine learning can be coded in modular online "toolboxes" that users can optionally connect to their datasets. Due to the large volume of calculations required for some machine-learning algorithms, online hosting of computations is naturally suited.

Connection to Other Preventive Conservation Tools

Online tools for the analysis of different types of datasets (discussed in chapter 4) have been successfully developed, with one such example being CCI's Light Damage Calculator. The development of online tools should consider the range of possible museum data types as a means of holistically examining an inherently complex and interrelated system. Via well-designed programming interfaces and open-source code repositories, online tools can make available part of their specific functionalities to other developers.

Guidelines for More Efficient Creation and Compatibility

The efficiency of creating tools will be greatly enhanced by the use of standardized data formats. Data that follows "tidy data" principles, which inform how data should be organized within a dataset, will aid future developers by limiting the need for additional code for "structuring datasets to facilitate analysis" (Wickham 2014). Additionally, if data both is tidy and has been assigned standard formats (e.g., ISO standard dates and times), datasets are considered "clean" and can be seamlessly integrated with other clean datasets. Use of the tidy data standard facilitates the development of analysis tools that efficiently interact with each other, without the need for translation of data into tool-specific formats.

Added features can be developed so that one variable can be replaced by another to perform a similar analysis or plot, or to conduct factor analysis of a combined dataset containing T, RH, light, pollution, etc. Having clean and tidy data facilitates the production of accessible, reproducible, and flexible tools.

Mechanism for User Feedback

There are many free mechanisms for facilitating communication between users and developers, including GitHub (GitHub 2020) and Bitbucket (Atlassian 2020), which are online version control tools and code repositories. These mechanisms are versatile and can support smaller (one to two coders, one to two users) and larger projects (one-hundred-plus code developers, millions of users [e.g., source code for a Linux operating system]); this flexibility is particularly valuable as collaborations between computer scientists and conservation professionals become more common. When source code is uploaded to such a service, it provides a centralized forum for communication. If users have a new idea or feature request, or find a bug in the program, they can access an "issues" tab (fig. 6.2) to explore the history of requests for this code, and, if no prior requests are relevant, submit a new issue. This service also allows for communication from developers to users: after a user submits an issue, a developer can directly engage the user in this space to obtain further information or clarification.

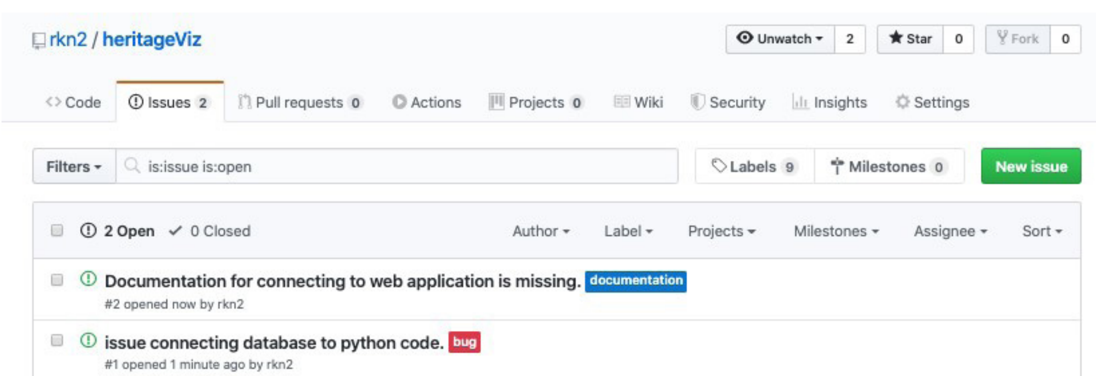


FIGURE 6.2
Screenshot showing features of a git repository including the "issues" tab; additionally, other capabilities such as actions and insights can be accessed through most git repositories.

To lower the barrier for user feedback, the analysis tool itself can provide a means for the user to communicate directly with developers. Developers can then offer support or evaluate whether questions or suggestions from the user warrant the addition of new features to the tool.

Mechanism for Dissemination to Field

Collaborative online publications can disseminate information on tools and their development to the cultural heritage field. These can discuss a range of tools and compare their motivations for the use of different data types, analyses, visualizations, and report types. By adapting the language and discussed concepts to the audience, they can support stakeholders from different backgrounds and with varying expertise in data analysis. It is recommended that any developments are published in open-access and peer-reviewed forums, so as to establish a permanent record of the intent and assumptions of each program.

When uploading project source code to a code repository, the code should be accompanied by thorough documentation so a user can understand each stage of the program. Additionally, the source code should include relevant metadata, such as authors, contributors, version number, and license (if applicable). Access to the history of changes to the program in the code repository can also provide an example to others in the field of what was successful for these types of applications. The programs themselves can be hosted either locally or on a web platform, and web links can be widely disseminated via publications, conference proceedings, institutional websites, and heritage forums.

Conclusion

Future approaches should seek to reduce the barrier to data analytics for heritage professionals in traditionally non-computational roles such as conservation and environmental management. Additionally, these approaches should aim to widen the scope of quantitative results conservators can attain when exploring questions such as, "How can we optimize sensor placement?" or "Can we predict future trends to inform collection placement?" By expanding the questions that those preserving collections and managing museum environments can grapple with, future work has the potential to significantly advance preservation practice and collection access.

References

ASHRAE. 2019. "A24—Museums, Galleries, Archives, and Libraries." Chap. 24 in *ASHRAE Handbook—HVAC Applications*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers. Also issued as IP edition, 2019.

Atlassian. 2020. Bitbucket. https://bitbucket.org/.

BSI. 2018. *BS EN 16893:2018 Conservation of Cultural Heritage: Specifications for Location, Construction and Modification of Buildings or Rooms Intended for the Storage or Use of Heritage Collections*. London: British Standards Institution.

GitHub, Inc. 2020. GitHub. https://github.com/.

Science Europe. 2018. Brussels: Science Europe. https://www.scienceeurope.org.

Wickham, Hadley. 2014. "Tidy Data." *Journal of Statistical Software*, 59, no. 10: 1–23.

CHAPTER 7

CONCLUSION

The discussion of temperature (T) and relative humidity (RH) analysis tools initiated at the 2019 Winterthur Museum meeting organized by the Getty Conservation Institute and furthered by this document represents an entry point into a broader dialogue about the development and application of preventive conservation tools. As evidenced by the experiences shared by the multidisciplinary meeting participants, as well as emerging connections between heritage professionals, educators, engineers, and computer scientists, there is a growing interest in this topic and considerable potential for supporting and advancing preventive conservation practice.

Preventive conservation tools can play an important role in supporting an evidence-based decision-making process for environmental management. Further, a suite of preventive conservation tools, rather than a single tool, can better address the varied needs and questions of heritage professionals; the modular development of a "toolbox" may provide the user efficient access to a range of functionalities. In addition to understanding the data, the range of analyses and visualizations that can be made available to the researcher allows one to tailor the presentation of information to match the expertise of the audience and more effectively communicate the findings with the various stakeholders.

While initially motivated by the analysis of T and RH data, it is equally important to link this information to data for other environmental factors, such as light, pests, pollution, and vibration. In many cases, incorrect T and RH may not pose the most acute risk to a collection, and tools that examine multiple agents of deterioration can place T and RH within the larger context of collection risk. The inclusion of observational information may also be key in identifying specific events or conditions that are not readily captured by numerical data. The investigation of a more holistic dataset presents an opportunity for the researcher to gain a deeper understanding of the collection environment, and potentially employ "big data" analysis techniques that can recognize less obvious relationships in the dataset and model environmental performance.

Tools developed for preventive conservation should remain widely accessible to the field and supported by effective didactic material. With the vast majority of heritage institutions represented by small to mid-size organizations whose staff often adopt a variety of roles, these tools should also aim to be intuitive and easy to use. To achieve these goals, it is key that these tools be collaboratively developed by tool developers—data scientists, computer scientists, and building physicists—and staff responsible for museum environmental management—collection care professionals, facilities managers, and HVAC engineers. This interdisciplinary dialogue allows for the development of a common language that aligns ideas and strategies for data analysis, and is being increasingly facilitated by online forums and networks where tool users and developers can share their experience and feedback.

APPENDIX 1

MEETING PARTICIPANTS

Geert Bauwens, Dr. Ir. Arch.
Project Lead – CHARP Art Care
Postdoctoral Researcher – Katholieke Universiteit Leuven

Geert Bauwens is project lead at CHARP Art Care and a postdoctoral researcher at Katholieke Universiteit Leuven (KU Leuven). In 2004 he received the Kunstbende award in New Media based on his undergraduate research on algorithmic art. After completing with honors his M.Sc. in Applied Sciences and Engineering: Architecture at KU Leuven in 2009 he held an architecture internship at BOB361 Architects in Brussels. In 2011 he embarked on a PhD in engineering science at KU Leuven, on assessing the actual energy performance of buildings. He was closely involved in Annex 58 and Annex 71 projects as part of the International Energy Agency's Energy in Buildings and Communities program. After earning his PhD in 2015, he received grants from Flanders Innovation & Entrepreneurship and KU Leuven, which allowed him to lead project teams developing innovative products for the construction sector. To raise awareness around indoor air quality in building, he developed a practical syllabus for secondary school students. In 2015 he founded the CHARP incubation project, which offers services and develops software to monitor energy performance and indoor climate of buildings.

Vincent Laudato Beltran
Associate Scientist
Getty Conservation Institute

Vincent Laudato Beltran is an associate scientist at the Getty Conservation Institute and is active in the GCI's Preventive Conservation Science group and Managing Collection Environments Initiative. Since joining the GCI in 2002, he has participated in a range of research projects and teaching efforts on topics such as the mechanical characterization of historic materials, microfading tester practice, packing case performance during transport, and environmental management systems in hot and humid climates. His work in this final area of study has been summarized in the book *Environmental Management for Collections: Alternative Conservation Strategies for Hot and Humid Climates* (Los Angeles: Getty Conservation Institute, 2015), which he co-authored with the late Shin Maekawa of the GCI and Michael C. Henry of Watson & Henry Associates. He holds a B.S. in general chemistry from the University of California, Los Angeles, and an M.S. in oceanography (geochemistry) from the University of Hawai'i at Mānoa.

Annelies Cosaert
Scientific Collaborator
Royal Institute for Cultural Heritage (KIK-IRPA)

Annelies Cosaert, a native of Belgium, received her M.S. in conservation and restoration with honors from the University of Antwerp in 2014. Although her initial areas of specialization were glass, metals, ceramics, and archeological objects, she developed a strong interest in preventive conservation. She held a postgraduate internship at the Royal Institute for Cultural Heritage (KIK-IRPA) in the Department of Preventive Conservation and gained experience in climate monitoring and analysis, condition reporting, and advising on the care of mixed collections. In 2018 she joined the Collections department at the Getty Conservation Institute as a professional fellow, working on the Managing Collection Environments Initiative, where she studied data analysis tools in the field of preventive conservation. She returned to KIK-IRPA in 2021 as part of the Climate2Preserv project, which helps museums integrate short- and long-term energy-saving measures while reducing risk to collection care.

Melissa King
Conservation Liaison
Conserv

Melissa King is a senior conservation liaison at Conserv, where she aids in the development and distribution of preventive conservation software through partnerships with researchers and practitioners. Prior to Conserv, she was the Samuel H. Kress Fellow in Preventive Conservation in a joint appointment between the Smithsonian National Museum of Natural History (NMNH) and the Museum Conservation Institute (MCI), where she planned a quantitative risk analysis to evaluate storage options for large vertebrate specimens on open shelving. In 2020, she received her M.S. from the Winterthur/University of Delaware Program in Art Conservation, where she specialized in preventive conservation. Melissa's work in data science for conservation includes environmental monitoring projects, research at English Heritage with Dr. David Thickett to evaluate models for predicting internal relative humidity of showcases, and study of the R programming language at MCI to evaluate storage options for their abilities to create microclimates. This focus led her to co-found an online community, ConCode, for education in coding as it applies to cultural heritage preservation and research.

Michael C. Henry, PE, AIA
Watson & Henry Associates,
Preservation Architects & Engineers

Michael C. Henry is Principal Engineer/Architect at Watson & Henry Associates and consults on:

- Sustainable environmental management for museums for preventive conservation of collections
- Investigation, monitoring, analysis, and assessment of historic buildings
- Investigation and analysis of the performance of historic and contemporary building envelopes
- Engineered stabilization and relocation of large museum objects

He has consulted on museums throughout the US and in Cuba, Mexico, Brazil, Rwanda, Tunisia and India. With Shin Maekawa and Vincent Laudato Beltran, he co-authored *Environmental Management for Collections: Alternative Conservation Strategies for Hot and Humid Climates* (Los Angeles: Getty Conservation Institute, 2015). Michael is an adjunct professor of architecture in the graduate program in historic preservation at the University of Pennsylvania, and lectures on buildings and conservation environments in the Winterthur/University of Delaware Graduate Program in Art Conservation. He was a Fulbright Distinguished Scholar and a visiting teacher in the Master's program at the Centre for Sustainable Heritage, University College London. Michael is a registered professional engineer and a registered architect in New Jersey. He holds an M.S. in engineering from the University of Pennsylvania.

Rebecca A. Kaczkowski
Preventive Conservator
Smithsonian Museum Conservation Institute

Rebecca A. Kaczkowski is the preventive conservator at the Smithsonian's Museum Conservation Institute, where she undertakes a variety of projects related to exhibit design, museum environments, the care and storage of collections, and collection care training initiatives. She is an inaugural member of the Preparedness and Response in Collections Emergencies (PRICE) team, a new initiative launched at the Smithsonian in the fall of 2016 geared toward developing and maintaining a robust collections emergency plan and culture for the institution. Previously, she worked on preventive and interventive conservation initiatives at the Smithsonian's National Museum of Natural History (NMNH) as the Samuel H. Kress Fellow and has also documented and treated a wide range of historic artifacts and scientific specimens. She has held internships at institutions including the Cleveland Museum of Art, the National Gallery of Art, the Walters Art Museum, the National Air and Space Museum, the National Museums Scotland, and the NMNH, as well as an eight-year apprenticeship in gold leaf conservation and restoration with GoldenRhodes LLC in Alexandria, Virginia. She is a graduate of the Winterthur/University of Delaware Program in Art Conservation, where she focused on objects conservation. She also holds a B.A. in art history and German language and literature and an M.A. in museum studies from the George Washington University. Rebecca is a Professional Associate of the American Institute for Conservation (AIC) and serves as the vice chair for the AIC Collection Care Network and chair of the Materials Selection and Specification Working Group.

Rebecca Napolitano
Assistant Professor of the Built Environment Analytics and Modeling (BEAM) Lab
The Pennsylvania State University – The Department of Architectural Engineering

Rebecca Napolitano is an assistant professor at the Pennsylvania State University. Her research focus is at the intersection of civil engineering, computer science, and historic preservation as it pertains to diagnostics and monitoring of existing infrastructure. She studies how dimensionality reduction techniques, physics-based modeling, and cyber-physical systems can be used to monitor existing structures amid the move toward green infrastructure and smart cities. Her current research initiatives include the use of unmanned aerial vehicles for infrastructure inspection and the fusion of nondestructive evaluation for multi-modal documentation and dimensionality reduction. Her awards include Female Innovator of the Year, Woman of Innovation, the School of Engineering and Applied Science at Princeton Award for Excellence, and the Graduate School of Princeton University Teaching Award. As a National Science Foundation Graduate Research Fellow, she received her PhD in civil and environmental engineering at Princeton University in 2020. She received her bachelor's degree in physics and classical languages at Connecticut College in 2015.

Bhavesh Shah
Scientist (Environment)
Victoria and Albert Museum

Bhavesh Shah is a scientist (environment) at the Victoria and Albert Museum, London. Since joining in 2007, he has maintained the museum's environmental monitoring system and has experience in climate analysis and advising on the display and storage of collections for V&A public program. Other research includes monitoring dust, pollutants, and light levels in the museum and analyzing objects using FTIR and XRF techniques. He holds an MChem in chemistry from Nottingham Trent University and is currently pursuing an M.S. in Data Science for Cultural Heritage at University College London. In this program he applies data science methods to analyze cultural heritage data. Additionally, he is interested in treating data as a means to research collections for their care and interpretation. Currently he is the website manager for the Institute of Conservation Modern Materials Network.

Joelle Wickens, PhD
Assistant Professor
Associate Director, Winterthur/University of Delaware Program in Art Conservation (WUDPAC)
Department of Art Conservation, University of Delaware

Joelle holds a PhD and an M.A. (distinction) from the Textile Conservation Centre, University of Southampton, UK, and a B.A. in American Civilization from the University of Pennsylvania. She co-founded the American Institute for Conservation's Collection Care Network in 2011 and served as its first chair from 2011 to 2014. In 2016, she led the creation of a preventive conservation major at WUDPAC, and began supervising its first major in 2018. She is currently assistant professor of preventive conservation at the University of Delaware and WUDPAC Associate Director. As WUDPAC Associate Director, she oversees curricula and supports student and faculty learning and teaching. As assistant professor of preventive conservation she is responsible for the development and implementation of education in this specialty. Previously, she was a preventive conservator for the Winterthur Museum, Garden & Library, where she directed a team of professionals who develop and implement preventive conservation policies and practices at the institution.

APPENDIX 2

GLOSSARY

Airflow Rates (Volumetric Flow Rate)
Mechanical ventilation uses fans and ducts to induce a flow of air into and through a building. The duct construction determines the volumetric flow rate (Q or V, m3/s) through the system. The air change rate (ACH or ACPH) is a measure of the air volume added to or removed from a space in one hour, divided by the volume of the space.

Arrhenius Equation
The Arrhenius equation describes the changing rates of chemical reactions as a function of temperature. This relationship is used by lifetime (which is the reciprocal of rate) calculations to model the effect of temperature.

Average
The average or mean is a sum of values divided by the total number of values. A moving average indicates the average of a specific time period (e.g., 24 hours, 7 days) that is then shifted forward through the end of a dataset. Moving averages, particularly with respect to relative humidity, can be more relevant to objects with slower response times.

Biological Response
A biological response can be caused by any type of animal or micro-organism. This response can take the form of damage such as fungal growth, being eaten by insects, and reactions with animal droppings (biochemical).

Black Box Software
Black box software programs limit users to seeing what they are putting into an application (T and RH data) and what comes out (statistics, metrics, visualizations), without knowledge of its internal workings.

Box Plot (or Box and Whisker Plot)
A box plot is a method for graphically depicting probability for a numerical dataset. The box always encompasses data within the 25th and 75th percentile (also known as the interquartile range or IQR) and an intermediate line is used to denote the median. The lines or whiskers extending from the top and bottom of the box can have variable definitions (e.g., maximum and minimum, 95th and 5th percentile). The x-axis identifies the classification of each box (e.g., individual spaces, seasons, years), while the y-axis shows the variable of interest.

Building Diagnostics
Building diagnostics is the process of determining the causes and solutions to problems in buildings. This holistic process encompasses data collection methods and techniques regarding inspection and analysis, and predictions of the condition, interior environment, and performance of a structure. Variables commonly analyzed include water, surface temperature, conductivity (salt), moisture in walls, airflow, wind speed and direction, and solar gain.

Building Envelope
The building envelope (or building enclosure) encompasses all of the elements of the outer shell that maintain a dry, heated, or cooled indoor environment and facilitate its climate control. While providing structural support and meeting desired aesthetic finishes, building envelope performance is often focused on the control of matter and energy flow, particularly with respect to air, heat, vapor, and liquid water.

Building Management System (BMS) (or Building Automation System [BAS])
A Building Management System (BMS), or Building Automation System (BAS), is a computer-based control system (including hardware) that controls and monitors a building's mechanical and electrical equipment such as ventilation, lighting, power systems, fire systems, and security systems.

Building Performance Simulation (BPS) (or Building Energy Simulation [BES])
Using a mathematical model based on fundamental physical principles and sound engineering practices, a Building Performance Simulation (BPS) quantifies aspects of building performance that are relevant to the design, construction, operation, and control of buildings. A Building Energy Simulation (BES) is similar to a BPS but focuses on energy use.

Chemical Response
A chemical response or change to an object is caused by a variety of factors, including material instability and contact with a chemical component. The rate of chemical response can also be exacerbated by elevated temperature. Chemical damage can take the form of discoloration and may lead to mechanical damage, such as detachment.

Climate Control System
Climate control systems includes all elements used to manage the interior climate, and can often focus on the use of heating, ventilation, and air conditioning (HVAC) to provide thermal comfort and acceptable indoor air quality. In the context of cultural heritage collections, climate control is also used to establish an appropriate preservation environment.

Cloud Services
Clouds or cloud services are IT environments that abstract, pool, and share scalable resources across a network. All infrastructure, platforms, software, or technologies that are accessed via the internet without requiring additional software downloads can be considered cloud computing services. Real-time measurements stream data across cloud services to transfer, save, and share data.

Code Repositories
A code repository is where source code for software programs are organized and archived. In addition to storage, repositories allow one to track the history of change of the source code. Examples of online code repositories include GitHub and Bitbucket.

Collection Management / Archival Systems
A Collections Management System (CMS) or archival system is used by staff in museums, libraries, archives, and galleries to track information related to physical or digital objects or intangible heritage. Early Collections Management Systems were cataloging databases that were essentially digital versions of card catalogs, while more recent and advanced software systems can facilitate communication among staff members and automate and manage collections-based tasks and workflows.

Cumulative Relative Frequency (CRF)
Cumulative relative frequency (CRF) describes the distribution of data for an individual variable by indicating for each data point the proportion of observations that are less than or equal to that specific value. CRF plots display the variable of interest on the horizontal axis and its CRF (from 0 to 1) on the vertical axis. Note that the IQR is denoted by values corresponding to CRFs of 0.75 (75th percentile) and 0.25 (25th percentile). If the dataset is relatively complete, a CRF plot can determine the percentage of time that the data resides within a target zone.

Diurnal Cycles
A diurnal cycle is any pattern that recurs every 24 hours as a result of one full rotation of the Earth around its own axis. The diurnal cycle is one of the most basic patterns of climate that can be recognized in daily trends of solar radiation, terrestrial radiation, air temperature, wind, cloud cover, and humidity. Within structures, diurnal patterns can be associated with alternating periods of occupancy and non-occupancy.

Energy Use / Consumption
Energy use or consumption is the total amount of energy used to perform an action. Typically expressed as Kilowatt-hour (KWh), energy use can tap into multiple sources, such as electricity, gas, and water.

Enthalpy
Enthalpy is a thermodynamic property that can be defined as the sum of a system's internal energy and the product of its pressure and volume. Similarly, specific enthalpy (h), which is depicted on the psychrometric chart, is the sum of the internal (heat) energy of a moist air parcel. HVAC engineers use total change in enthalpy or heat content, expressed as joules per kilogram of dry air (SI) or BTU per pound of dry air (I-P), to help calculate the total capacity of an HVAC system.

EPW File Format
An EPW file format contains weather data saved in a standard EnergyPlus format, and is often used by EnergyPlus simulation software developed by the U.S. Department of Energy (DoE). EPW weather data is available for more than 2,000 locations around the world.

Factor Analysis
Factor analysis is a statistical technique that reduces a large number of variables into fewer numbers of underlying factors, promoting the investigation of complex systems. Each factor is associated with a factor loading, which quantifies the amount of variation described by that specific factor. Factor analysis can be used as a tool for exploration (unknown data structure) or confirmation (known data structure).

Feature Extraction
Feature extraction seeks to reduce the number of resources needed to describe a large dataset. Since analysis of a large number of variables requires large memory and computation

power and may cause an algorithm to overfit to training samples, feature extraction constructs combinations of variables that describe the data with sufficient accuracy and allow for more effective development of models.

Human or Thermal Comfort
Human comfort, or thermal comfort, is the condition of the mind that expresses satisfaction with the thermal environment, and is assessed by subjective evaluation. Factors directly affecting thermal comfort can be separated into personal (metabolic rate, clothing level) and environmental (air temperature, mean radiant temperature, air speed, and humidity).

Humidity

- Humidity ratio is the ratio of the mass of water vapor in a given air parcel to its mass of dry air, and is expressed as gram/kilogram, pound/pound, or grains/pound. Humidity ratio is depicted on the right y-axis of a psychrometric chart. It is also known as absolute humidity or mixing ratio.
- Relative humidity (RH, %) is the ratio of the amount of water vapor in the air and the total amount of water vapor the air can potentially contain at a given temperature. RH will vary with temperature, as its water vapor holding capacity will lessen at lower temperatures and vice-versa. At 100% RH, air is saturated and will result in condensation.

Hygrothermal Behavior
Hygrothermal behavior refers to the movement of heat and moisture through buildings. Computer-based simulations of this behavior can aid in understanding the performance of various building assemblies, and evaluating and minimizing risks from condensation, fungal growth, and material degradation.

Integrated Pest Management (IPM)
Integrated Pest Management (IPM) for cultural heritage is the practice of monitoring and managing pest and environmental information with pest control methods to prevent pest damage to movable and immovable heritage.

Interface
In computing, an interface is a shared boundary across which two or more components of a computer system exchange information. This exchange can be between software, computer hardware, peripheral devices, and humans. A user interface is a point of interaction between a computer system and humans, where data can be transferred using any number of modalities (e.g., graphics, sound, position, movement).

Machine Learning
Machine learning is the study of computer algorithms that improve automatically through experience, and is seen as a subset of artificial intelligence. Machine learning algorithms build a model based on "training data," which can then make predictions or decisions without being explicitly programmed to do so.

Mechanical Response
A mechanical response is the structural change of an object caused by an impact or changing environmental conditions. The resulting damage can take the form of cracks, swelling, shrinking, undulations, or deformations. See also, "preservation metrics"; "mechanical."

Median
The median value separates the upper half of a dataset from its lower half, and can be described as the "middle value" or 50th percentile. An advantage of a median compared to the mean is that it is not skewed by extremely large or small values, and may better represent a "typical" value.

Metadata
Metadata provides information about one or more aspects of the data. This information can be used to summarize basic information about data, which can simplify tracking and working with specific data. With respect to images, metadata may describe its size, color depth, resolution, and/or date of creation.

Modular Design
Modular design or modular programming is a software design technique that emphasizes separating the functionality of a program into independent, interchangeable modules, such that each contains everything necessary to execute only one aspect of the desired functionality.

Object Response
Object response is an expression of a mechanical change (e.g., swelling, shrinking, deformation, cracking) that occurs when an environment changes. The object response time describes the time that it takes for a given object to experience an environmental shift.

Off-Gassing
Off-gassing or outgassing is the release of a gas that was dissolved, trapped, frozen, or absorbed in a material. Potential sources of off-gassing include construction materials, carpeting, cabinetry, furniture, paint, and any

number of household goods. In collection environments, sources for off-gassing may include packaging materials, exhibition materials, and the collections themselves.

Open Source

Open source is software code that is made freely available for anyone to view, change, and enhance. Note that open source represents a subset of white box programs, which enables users to better understand its inner workings.

Paradata

Paradata are usage data about learning resources that include quantitative metrics (e.g., how many times a piece of content was accessed) and pedagogic context, as inferred through the actions of educators and learners.

Parsing

Parsing is a frequently used term in both the realm of data quality and computing in general. It can mean anything from simply "breaking up data" to full Natural Language Parsing (NLP), which uses sophisticated artificial intelligence to allow computers to "understand" human language. A parser is the program that parses imported data; its two tasks are (1) checking if the imported data has the correct structure and (2) transferring the input to a structured representation that is readable to a computer.

Passive Data Gathering Tools

Passive data gathering tools are used to measure the exposure of a collection to a certain environment to predict or link to a certain type of damage. They are typically placed in an area of interest for a specific amount of time and focus on one aspect of the collection environment. Unlike real-time data, the results integrate the environmental data to which it was exposed during the entirety of the exposure period. Examples include traps (pest management), Blue Wool Coupons (light), and A-D strips (pollution/off-gassing).

Percentile

A percentile is expressed by a value below which a given percentage of observations in a dataset falls. For example, if the 90th percentile of relative humidity data is 65% RH, then 90% of the dataset is below this RH value. Note that a percentile and quartile divide a dataset into 100 and 4 segments, respectively; thus the 25th and 75th percentiles are equivalent to the 1st and 3rd quartiles, which also define the interquartile range or IQR.

Preservation Metrics

- Preservation metrics express the probability of change, be it temporary or permanent (damage). The different types of damage include mechanical (e.g., cracks, deformation, swelling, and shrinking), chemical (e.g., oxidation, color changes, and material decay), and biological (mold growth). The following are select metrics:
- Mechanical
    - Equilibrium Moisture Content (EMC): The value of the Equilibrium Moisture Content depends on the material and the relative humidity and temperature of the air with which it is in contact. The speed with which it is approached depends on the properties of the material, the surface-area-to-volume ratio of its shape, and the rate at which humidity is carried away or toward the material.
    - Dimensional Change (% DC): Dimensional change expresses a change in the dimensions of an object compared to its original dimension.
    - Risk Index (RI): The Risk Index expresses the probability and degree of deformation of a certain material over a climatically defined period in time; 0 is the object as is, between 0 and 1 is the object within the elastic range, and over 1 the objects suffers from some permanent deformation.
- Biological
    - Mold Risk Factor (MRF): The Mold Risk Factor expresses the risk of mold germination and the potential for mold growth. An MRF of 0.5 or less indicates an environment with little or no risk of biological decay. An MRF greater than 0.5 indicates that mold spores are halfway to germination. An MRF greater than 1.0 indicates that mold spores have germinated, entering a vegetative mold state, and that visible mold could actively be growing.
- Chemical
    - Time Weighted Preservation Index (TWPI): The Time Weighted Preservation Index expresses a rate of chemical decay as determined by the rate of spontaneous chemical change in organic materials. The higher the TWPI, the longer it will take for a given amount of decay to occur. The TWPI can be used to compare the environment in one location to another or to evaluate a change in the preservation quality of a location from one time period to another.
    - Lifetime Multiplier (LM): The Lifetime Multiplier (LM) is a preservation metric that compares a predicted lifetime of a specific object/material at a standard temperature of 20˚C and relative humidity of 50% to its predicted lifetime exposed to its actual environment. The higher the lifetime multiplier, the longer the lifetime of an object.

Programming Languages

- JMP: JMP (pronounced "jump") is a suite of computer programs for exploratory visual analytics developed by the JMP business unit of SAS Institute. The JMP Scripting Language (JSL) is a proprietary interpreted language for automating the JMP software.
- R: R is a programming language and free software environment for statistical computing and graphics supported by the R Foundation for Statistical Computing. The R language is widely used among statisticians and data miners for developing statistical software and data analysis. The capabilities of R are extended through user-created packages. RStudio is an integrated development environment for R.
- Python: Python is an interpreted, high-level, and general-purpose programming language. Python's design philosophy emphasizes code readability with its notable use of significant whitespace. Its language constructs and object-oriented approach aim to help programmers write clear, logical code for small- and large-scale projects.
- MATLAB: MATLAB ("matrix laboratory") is a proprietary, multi-paradigm programming language and numeric computing environment developed by MathWorks. MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages.

Proofed Fluctuation / Object Memory

The proofed fluctuation or object memory is the largest RH or T fluctuation to which the object has been exposed in the past; alternatively, it can be described as the lowest and highest RH and T past conditions. The risk of further mechanical damage beyond that already accumulated from fluctuations smaller than the proofed value is extremely low. Note that conservation treatments may nullify the proofed fluctuation concept by removing the safety margin provided by fractures from historical conditions.

Psychrometric Chart or Mollier Diagram

A psychrometric chart graphically depicts the thermodynamic parameters of an air parcel at a constant barometric pressure (or elevation). The x- and y-axes show dry bulb temperature and humidity ratio, respectively, while relative humidity is defined by isohumes (lines of constant relative humidity) that curve to the upper right. Also commonly depicted are dew point temperature, enthalpy, wet bulb temperature, and specific volume. Preferred in Europe, the Mollier diagram is an alternative psychrometric chart depicting identical parameters.

Psychrometric Strategies

Psychrometric strategies can be applied to a parcel of air to modify its environmental conditions, and include cooling, heating, humidification, and dehumidification. These strategies can be mechanical or non-mechanical in nature, and are associated with an overall directionality on the psychrometric chart; that is, movement to the left indicates cooling, movement to the right indicates cooling, upward movement indicates humidification, and downward movement indicates dehumidification.

Range

A range is the difference between two specific values of a dataset, with the maximum and minimum commonly used. The range can also be defined by a specific time interval, such as a 24-hour period; this time period can be shifted across the dataset, allowing one to calculate a moving range. Used to define the box in box plots, the interquartile range encompasses values between the 25th percentile (or 1st quartile) and the 75th percentile (or 3rd quartile).

Risk Analysis

Risk analysis is the analysis of the degree of a certain risk and can be part of a wider risk assessment. Risks can be related to high or low T and RH, or any other agent of deterioration (light, pollution, physical forces, theft and vandalism, water, fire, pests, and neglect), though some are more quantifiable then others.

Risk Assessment

Many organizations use risk assessment and risk management as a decision-making tool, especially for managing risks to health and the environment. By identifying threats and their associated risks, organizations can target resources to protect people and property more efficiently through the planning process. In doing so, risks are prioritized and more substantial threats are managed before lesser threats.

Sensible Heat Ratio (SHR)

The sensible heat ratio (SHR) is the ratio of the sensible cooling capacity to the total cooling capacity of an HVAC unit, and describes the split between the sensible and latent cooling capacity. An evaporator with an SHR of 100% will only cool the air (sensible load), while an SHR value of 80% indicates that 80% of the load is used to cool air (sensible load) and 20% provides dehumidification (latent load).

Set Point Relaxation

In the context of collection care, set point relaxation allows for a wider range of temperatures and/or relative humidity to which objects are exposed. This decision may be based on the material composition of a collection or a desire to reduce energy consumption.

Setbacks

HVAC setbacks allow for the setting of lower building temperatures during specific periods (e.g., nighttime, weekends, winter) as a means of reducing energy usage. While human thermal comfort is often a primary consideration, temperature reductions may also benefit collections with low chemical stability.

Solar Aperture

In a passive solar heating system, the solar aperture or collector is a large glass area through which sunlight enters the building. The aperture should face southward and not be shaded by buildings or trees during the heating season.

Solar Azimuth Angle

The solar azimuth angle describes the position of the Sun, with its horizontal coordinate defining the Sun's relative direction along the local horizon and its solar zenith angle defining the Sun's altitude.

Source Code

Source code is the fundamental aspect of a computer software that is created by a programmer. Source code can be created using a text editor, visual programming tool, or an integrated development environment, and can be either proprietary (the user only has access to executables and the associate library files) or open (the user can download and modify the software code).

Specific Volume

Specific volume is a material property depicted on the psychrometric chart, where it is defined as the number of cubic meters occupied by one kilogram of dry air and its associated water vapor. This parameter is useful when conducting calculations in which the moisture content shifts during the process (humidification or dehumidification), as the amount of dry air will remain constant while the amount of water vapor will change.

Spot Readings

Spot readings are measurements that have been taken at a specific location for a brief duration (as little as one data point). Examples include the use of handheld instruments without data logging capability to measure parameters such as light, temperature, relative humidity, and particulates. The portability of such instruments allows for flexibility of location, but the data represents a snapshot in time that may be difficult to interpret without more context.

Standard Deviation

The Standard Deviation (SD, σ) specifies the amount of variation or dispersion of a set of values. A low SD indicates that values are close to the mean value of the dataset, while a high SD indicates a wide spread of values.

Systems Thinking

Systems thinking is a holistic approach to analysis that focuses on the interrelationships among a system's constituent parts and how systems work over time and within the context of larger systems. This process is based on the belief that the component parts of a system will act differently in isolation from other parts of the system. As complex systems continually evolve, systems thinking can facilitate adaptive management and organizational and social learning.

Target Conditions / Zones

Target conditions or zones are the desired interior environmental conditions, which can be defined by set points or ranges. The selection of target zones for an individual space or entire building can be based on various factors, including occupancy (public or non-public), purpose (exhibition or storage), or material composition of objects.

Temperature

- Dry bulb temperature: The dry bulb temperature (DBT, °C or °F) is the temperature measured by a thermometer freely exposed to air, but shielded from radiation and moisture. DBT is what is commonly implied when discussing air temperature. Note that DBT is shown on the x-axis of a psychrometric chart.
- Wet bulb temperature: The wet bulb temperature (°C or °F) is measured by passing air over a thermometer wrapped in wet muslin. Wet bulb temperature is the same as dry bulb temperature at 100% RH; at lower humidity values, wet bulb temperature is always lower than dry bulb temperature, reflecting the conversion of liquid water into vapor using thermal energy in the air.
- Dew point temperature: The dew point temperature (DP, °C or °F) is the temperature to which air must be cooled to become saturated with water vapor. An elevated dew point value indicates the presence of more moisture in an air parcel.

Time Series

A time series plot is a common data visualization that depicts time on the x-axis and a variable(s) of interest on the y-axis. The utility of time series plots is increased as multiple types of data are compared, including variables recorded at separate locations (e.g., interiors, exteriors), different statistical data treatments (e.g., moving average, moving range), related variables (e.g., air temperature, relative humidity, dew point temperature), and target conditions.

Vinegar Syndrome

Vinegar syndrome is a term used to describe the chemical reaction that takes place during the deterioration of a cellulose triacetate film support. When cellulose triacetate begins to decompose, "deacetylation" occurs and the acetate ion reacts with moisture to form acetic acid, producing a vinegar odor when the film can is opened.

Volatiles

Volatiles, or Volatile Organic Compounds (VOCs), are a large group of chemicals with a low boiling point that are found in many products used in building materials. When present in interior spaces, they can be released or can "off-gas" to be inhaled by occupants or exposed to various surfaces, including objects.

Web-Based Application

A web-based application or web app is software that runs on a web server. In contrast, computer-based software programs are run locally on the operating system (OS) of the device. Web applications are accessed by the user through a web browser with an active internet connection.

White Box Software

White box (also called "clear box" or "glass box") software programs enable a user not only to see the input and output, but also to understand the inner workings of the program and learn about the methods used (e.g., dew point calculations, feature extraction). Note that open source, which freely allows users to view and modify its software code, represents a subset of white box programs.

A P P E N D I X 3

TOOL DESCRIPTIONS

This appendix briefly describes select tools for analyzing temperature (T) and relative humidity (RH) data in the context of cultural heritage that were shared at the 2019 Winterthur meeting. This by no means is intended to be a comprehensive list; rather, it begins to flesh out a suite of analysis tools that are available to the collection care professional. Further, tools may be continually refined by the developer based on user experience; thus, this section represents a snapshot in time of each tool. These tools were also the focus of discussion in a 2021 ICOM-CC paper by Cosaert and Beltran.

A3.1. Getty Conservation Institute Excel Tools

Developed by Vincent Laudato Beltran for the Getty Conservation Institute

The GCI Excel Tools developed at the Getty Conservation Institute (GCI) make accessible common analysis and visualization techniques employed in the interpretation of T and RH data. Many of these visualizations can be generated by third-party analytics software that may be expensive and have a significant learning curve (particularly if requiring knowledge of a programming language), both of which are barriers to more widespread use.

In 2017, the GCI's Managing Collection Environments (MCE) Initiative offered the course "Preserving Collections in the Age of Sustainability," which included modules on environmental monitoring and the analysis and visualization of environmental data. The GCI Excel Tools created a suite of analysis and visualizations within Microsoft Excel, a more universally accessible software platform, for teaching purposes and practical use. Many of the graphs shown in chapter 2 were produced using the GCI Excel Tools.

Functionality

The GCI Excel Tools are composed of five modules:

- "data_stats": This is the entry point into the GCI Excel Tools, where the user inputs paired T and RH data from various locations, all ideally anchored to a common date and time and with a consistent time interval. Also input is the elevation of the site. Calculated for each data row are humidity ratio (W), dew point temperature (DP), and rolling 24-hour and 7-day mean and range values. Statistics for the entire dataset and user-defined subsets are generated, including the ability to determine the percentile associated with any dataset value and vice-versa. Subsequent modules can be accessed in any order, and will utilize input data, calculated data, and statistics from the "data_stats" module.
- "time_series": Time series plots are the most common graph category, and the focus of this module is to provide templates for specific data presentations. These include:
  - Comparisons of T, RH, and DP to examine the driving force of RH changes at one location (fig. A3.1)
  - Comparison of input T or RH data and rolling 24-hour or 7-day means to examine relevance for objects with longer response times (fig. A3.2)
  - Manual overlay of target T or RH conditions on time series data (e.g., input, 24-hour range) to identify periods of time outside of spec (fig. A3.2)
- "crf": The cumulative relative frequency (CRF) module and the "box plot" module allow for an examination of probability distribution within a dataset. CRF plots are particularly effective at determining the proportion (or percentile) of observations less than or equal to any specific value (fig. A3.3).
- "box plot": This module provides a visualization that is complementary to the CRF plot produced in the previous module. Box plots indicate given proportions (or percentiles) using relative positioning of visual markers (box and whiskers), and may better facilitate comparisons between locations (fig. A3.4).

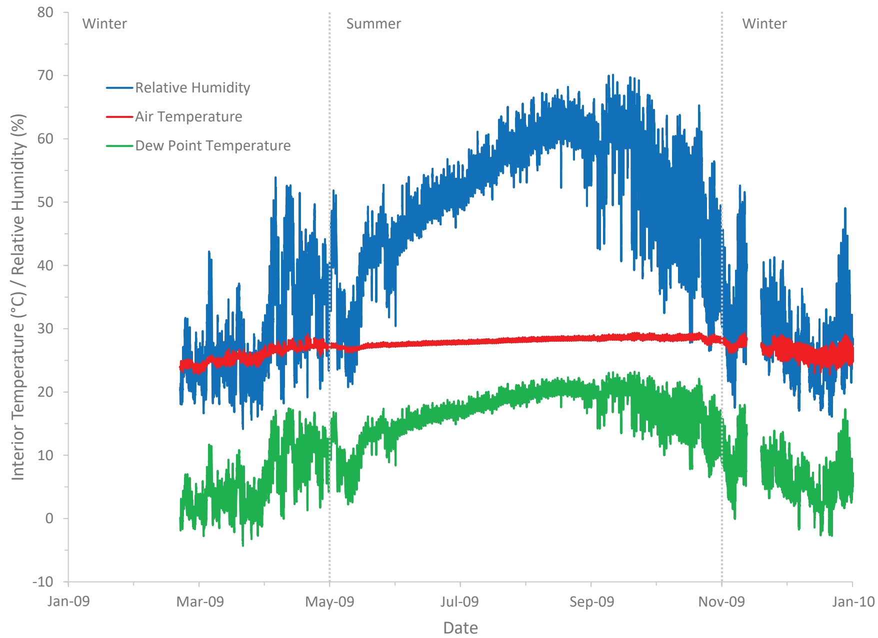


FIGURE A3.1

Time series plot overlaying data for interior T, RH, and dew point temperature.

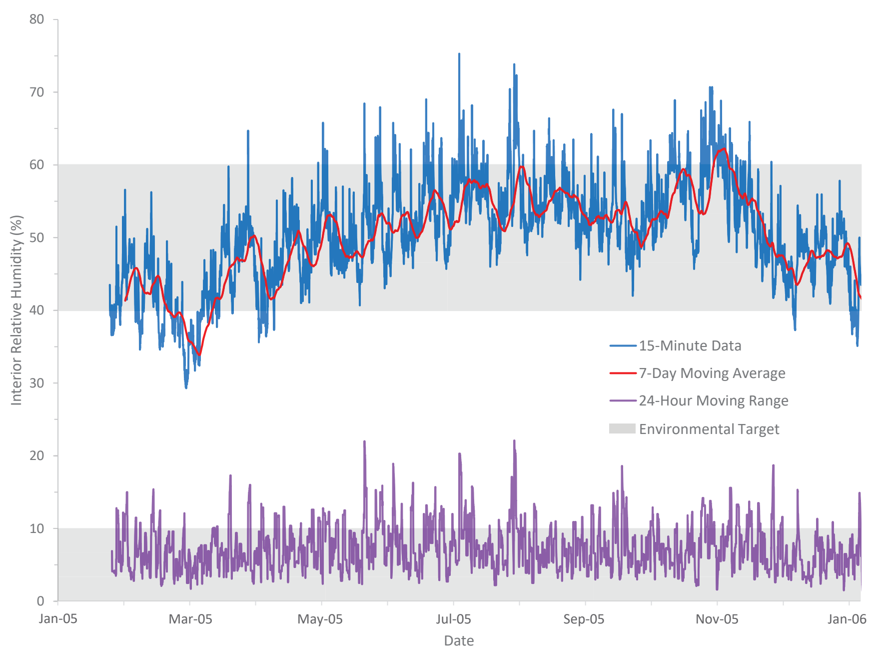


FIGURE A3.2

Time series plot showing 15-minute RH data, 7-day moving RH average, and 24-hour moving RH range. Overlain on the data are target zones for the raw data and moving average (40%–60%RH) and range (0%–10%RH).

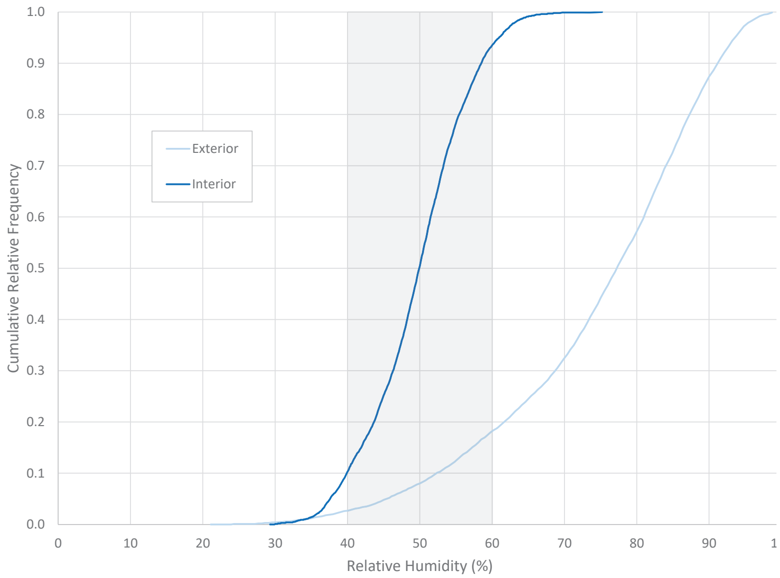


FIGURE A3.3

Cumulative relative frequency (CRF) plot of interior and exterior RH with a target zone from 40%–60%RH.

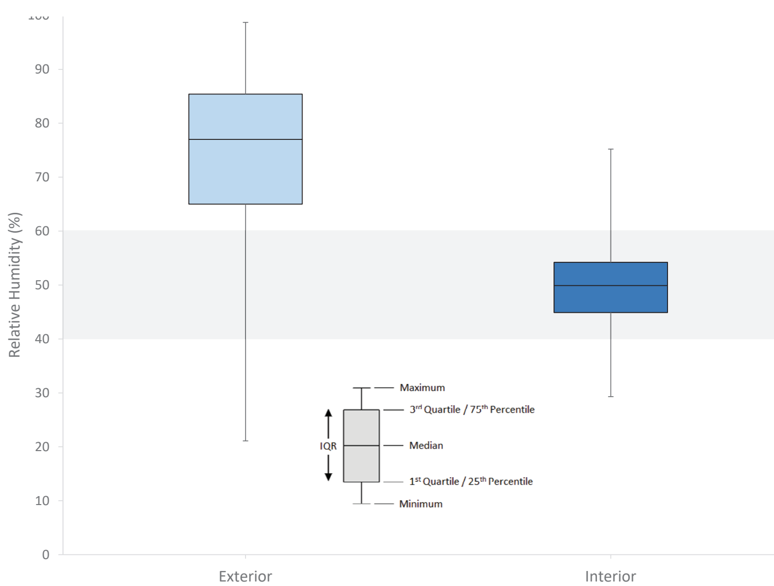


FIGURE A3.4

Box plot of interior and exterior RH with a target zone from 40%–60%RH.

- "psyc_chart": This visualization uses input T data and calculated humidity ratio values to overlay environmental data on an elevation-specific psychrometric chart (fig. A3.5a). Targets can be manually drawn to include both T and RH boundaries, allowing for identification of points outside of spec and, based on relative positioning with respect to the target, informing psychrometric strategies (i.e., heating, cooling, dehumidification, humidification) to reposition the state point within or closer to the target (fig. A3.5b).

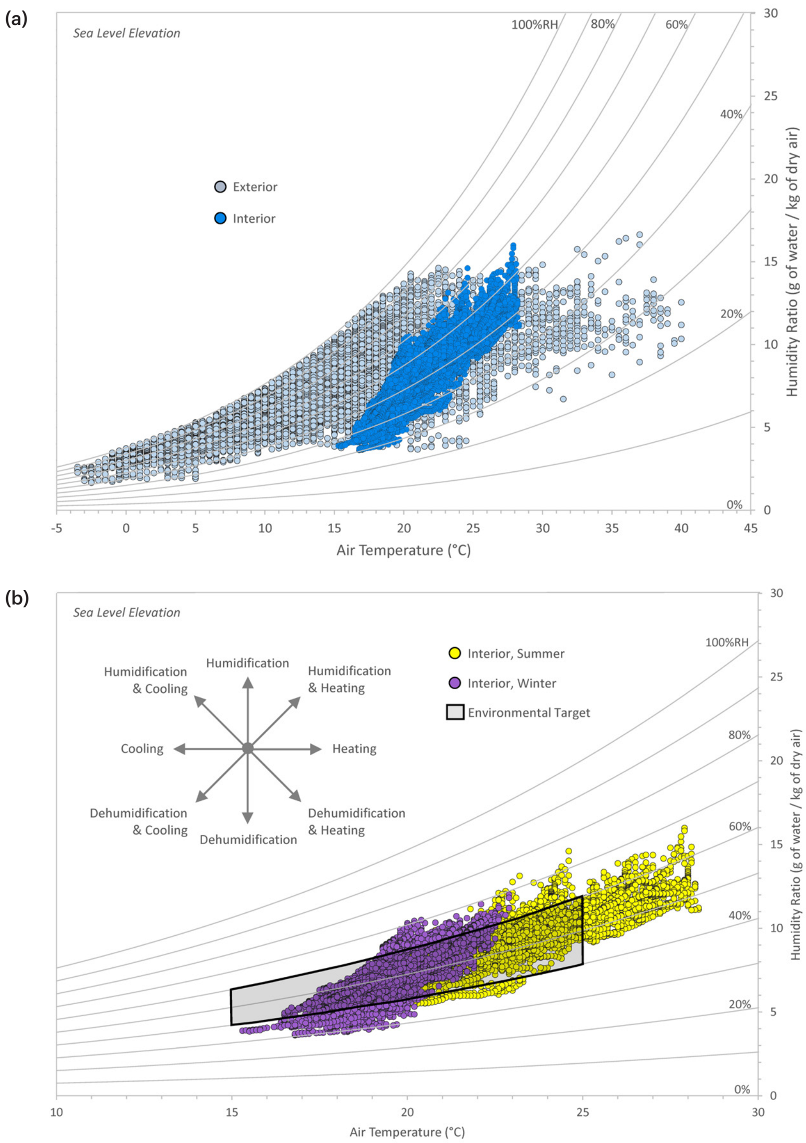


FIGURE A3.5

Psychrometric charts showing (a) exterior and interior data, and (b) interior seasonal data, a target zone, and a directional compass of psychrometric strategies.

Current and Future Use

Use of the GCI Excel Tools has been largely limited to MCE course participants and subsequent virtual AIC workshops, but they are available upon request from Vincent Laudato Beltran (vbeltran@getty.edu). It is expected that the GCI will soon make them widely available on its website. In some cases, the need for a baseline comfort level with Excel has redirected use of the tools toward a colleague with more facility in Excel—this likely will be the most significant obstacle to widespread use of the tools, though this may be addressed by training via a detailed protocol and tutorial videos (both are currently available; the protocol includes general concepts and specific tips for Excel), and workshops. Excel itself also poses a limitation on the utility of the tools, particularly with respect to the analysis of large datasets (prone to freezing) and implementation of more complex visualizations (e.g., unable to add contour lines to psychrometric charts). As with many T and RH analysis tools, a benefit of the GCI Excel Tools is the ability to enhance dialogue between the user and project stakeholders about environmental conditions via clear and succinct visualizations reflecting the varied levels of expertise in the subject. The widespread availability of Excel also ensures access to the GCI Excel Tools for nearly all practitioners.

A3.2. Conservation Physics Calculators

Developed by Tim Padfield

On his Conservation Physics website (https://www.conservationphysics.org), Tim Padfield created and compiled a wealth of articles on topics such as climate, light, material properties, microclimates, air conditioning and building physics, sensors and measurement, and environmental standards. Included among this material are four calculators focused on basic climate concepts; these tools give the user an idea of how climate data is interrelated and what some of the practical implications are for energy consumption.

Functionality

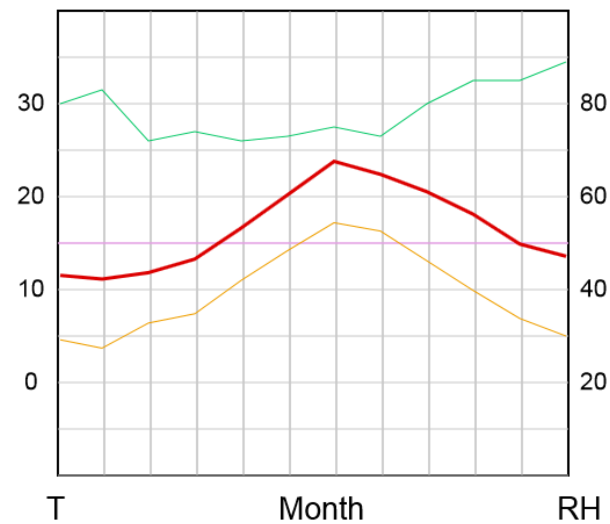
The Calculator for Atmospheric Moisture illustrates the capacity of air to store a certain amount of water. After defining any two climatic variables, the remaining values are automatically calculated. This tool helps one understand the relation between air temperature and humidity, and can be compared to the Dew Point Calculator integrated in eClimateNotebook.

The Calculator for Conservation Heating provides optimum monthly conservation heating set points to establish a desired interior RH (fig. A3.6). This calculation is based solely on monthly average outdoor T and RH and does not take into account the quality of the building envelope or human comfort.

Enter monthly av. temperature (°C)in the first column
Enter monthly average RH (%) in the second column
The default values are for Birmingham UK
Enter the target RH below and then press 'calculate'
The temperatures for conservation heating will appear in the third column
To check a single temperature/RH pair, just fill in data for January

January	4.6	80	12
February	3.7	83	11
March	6.4	72	12
April	7.4	74	13
May	11	72	17
June	14.2	73	20
July	17.2	75	24
August	16.3	73	22
September	13.1	80	21
October	9.9	85	18
November	6.9	85	15
December	5.0	89	14

Target RH 50 Calculate **Average temperature excess:** 6.85



Conservation heating temperature

Outdoor temperature **Outdoor RH**

Target RH

What is conservation heating?

FIGURE A3.6

Left: monthly fields for T, RH, and the Conservation Heating T set points. Right: a time series plot of these variables (including the target RH).

Storage spaces or archives are the focus of the Calculator for Dehumidification Energy Load, as this tool takes into account the buffering capacity of active cellulose. This calculator is suited to a museum storage or archive in which the climate is controlled solely by dehumidification, allowing for temperature to wander freely (though it is assumed that temperature is heavily buffered by the ground beneath).

	Outside climate		Inside climate		
Month	T	RH	T	RH	kWh/m3
January	4	81.8	18.6	46.3	16
February	4.4	76.5	19	47.5	16
March	7.9	78.0	19.3	48.1	12
April	12.5	68.4	19.8	50.3	7.8
May	14.6	66.8	20.4	52.3	6.3
June	19.0	63.8	22.1	53.8	3.0
July	19.5	72.0	23.3	57.1	3.4
August	18.9	69.4	22.7	55.4	3.5
September	18.8	70.3	23.5	54.0	4.5
October	15.3	78.3	20.5	58.0	4.9
November	9.0	81.1	19.2	51.3	11
December	5.9	82.1	19.6	45.7	14

Building characteristics *need help?*

Surface to volume ratio: 1 **U-value:** 0.5
Air changes per hour: 2 **Light energy (kWh/m^3.year):** 0

Calculate **Annual energy for climate control (kWh/m^3)** 102

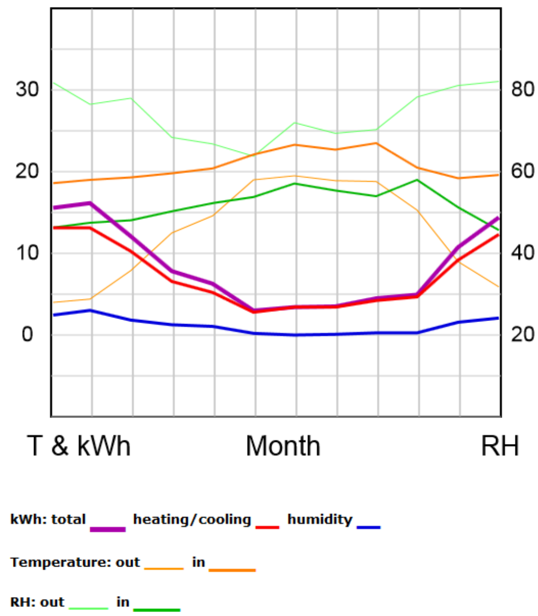


FIGURE A3.7
Left: monthly fields for interior and exterior T and RH, and the resulting energy use. Right: a time series plot of these variables (including the target RH).

The Calculator for Energy Use in Museums is based on both interior and exterior monthly averages, and allows the user to define an air exchange rate and U-value (rate of heat transfer for a material) for the space (fig. A3.7). While the basic heat loss calculations carried out by this tool are insufficient for modeling, the tool remains a useful didactic resource to understand the general relation between the environment and energy consumption.

Users

While the four calculators on the Conservation Physics website represent simplifications of what can be a complicated system (e.g., reliance on monthly averages without accounting for variability at shorter time scales), these tools remain highly useful as didactic resources, and provide an opportunity to gain basic insights into various aspects of the museum environment. The ability to easily manipulate the data allows one to compare different environmental scenarios (e.g., winter closure of a historic house) and, particularly when paired with Tim Padfield's illuminating and entertaining descriptions, can help communicate these concepts to key stakeholders responsible for environmental management.

A3.3. eClimateNotebook

Developed by the Image Permanence Institute (IPI) at the College of Art and Design at Rochester Institute of Technology (RIT)

eClimateNotebook (https://www.eclimatenotebook.com/) is an online tool that supports the IPI's broader program of sustainable practice, environmental science, and image preservation. This software also communicates with IPI's PEM2 environmental monitoring hardware (discontinued as of July 2020). Developed from a storage and archives perspective, eClimateNotebook looks at a collection as a whole and does not differentiate between collection subsets, with the exception of metal corrosion.

Functionality

The Image Permanence Institute has developed metrics to quantify chemical decay, biological decay, and mechanical response, which are incorporated into eClimateNotebook. These metrics are briefly described here, but more detailed information is available in a 2011 IPI document titled *Understanding Preservation Metrics* by research scientist Douglas W. Nishimura.

- Chemical decay is associated with the Preservation Index (PI) and Time Weighted Preservation Index (TWPI). PI expresses the preservation quality of an environment in units of years, assuming T and RH do not change from the time of measurement. TWPI is also reported in units of years, but takes into account changing T and RH conditions and averages the impact discrete periods have on the overall decay rate. With respect to TWPI, values below 45 indicate a "poor environment," those between 45 and 75 indicate an "OK environment," those between 75 and 100 indicate a "good environment," and above 100 are an "excellent environment" (fig. A3.8).

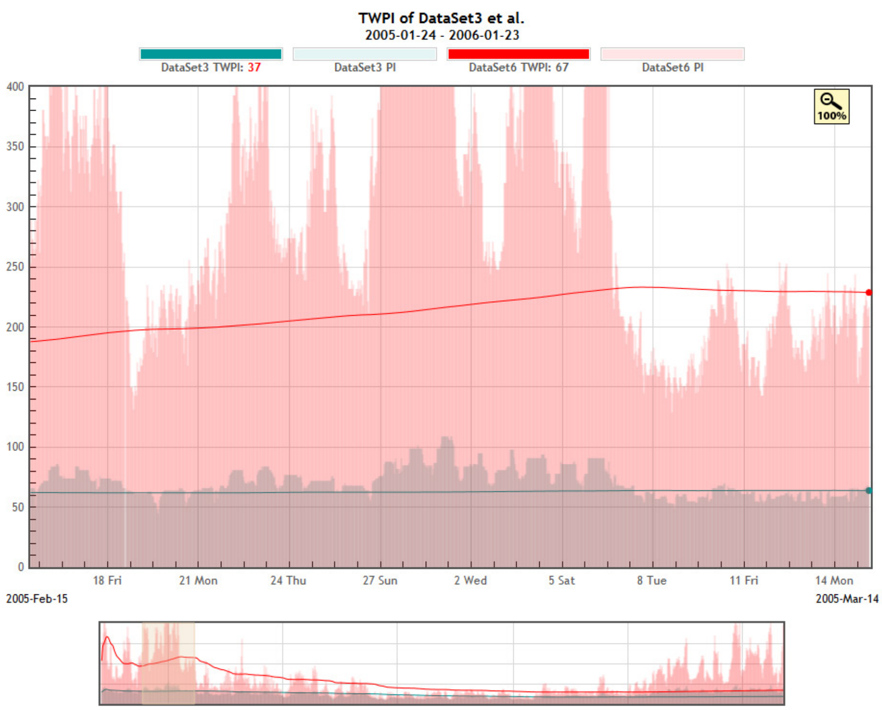


FIGURE A3.8

Time series of Time Weighted Preservation Index (TWPI). Note that the upper plot depicts a subset of the data shown in the lower plot.

FIGURE A3.9

Interpretations for different combinations of Equilibrium Moisture Content (EMC) and Dimensional Change (DC) metrics.

Mechanical Damage Metrics	Interpretation
Min EMC ≥ 5% AND Max EMC ≤ 12.5% AND %DC ≤ 0.5%	GOOD
Min EMC ≥ 5% AND Max EMC ≤ 12.5% AND 0.5% < %DC ≤ 1.5%	OK
Min EMC < 5% OR Max EMC > 12.5% OR %DC > 1.5%	RISK

- Mechanical or physical damage is expressed by dimensional change (DC) of a non-specified object and is related to the Equilibrium Moisture Content (EMC). The combination of these two metrics indicates the potential for physical damage in organic materials due to excessive water absorption or minimal water adsorption. Note that T plays a lesser role than RH with respect to EMC. The interpretation of these metrics is shown in figure A3.9.
- Metal corrosion risk is based on the moisture level present in the environment and is defined by the maximum EMC (Max EMC). Higher Max EMC values will promote corrosion in vulnerable metal objects or those with metal components, including select images, textiles, and inks. Levels of metal corrosion risk correspond to Max EMCs below 7 ("good"), between 7 and 10.5 ("OK"), and above 10.5 ("risk").
- Biological risk is expressed by the Mold Risk Factor (MRF), which is based on a model of mold growth at which growth is optimized at a specific temperature and slows when it is warmer or colder. Similarly, MRF accounts for an optimum temperature at which the least amount of water is required to facilitate mold growth. MRF integrates the approximate growth progress for each measurement period and can be visualized over time (fig. A3.10). MRF values below 0.5

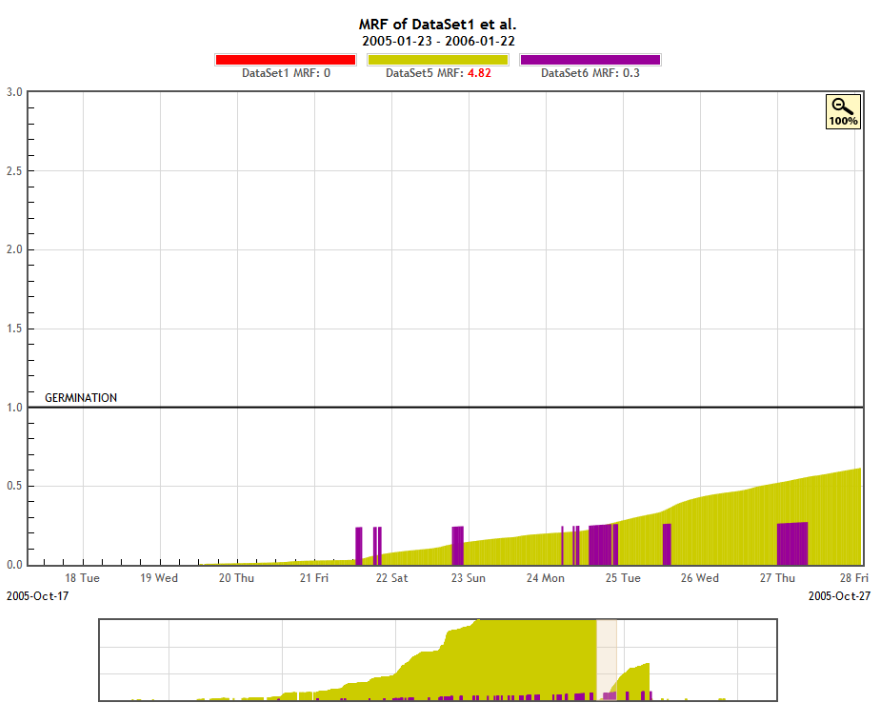


FIGURE A3.10

Time series of the Mold Risk Factor (MRF) preservation metric.

indicate a “good” environment (0 is “ideal”), between 0.5 and 1 denote “some risk,” and above 1 specify “active mold” that should be verified by visual inspection of the objects.

Users

Following several iterations of environmental data management products, eClimateNotebook was released in 2012 and has amassed a large number of users. Many of these users also employ IPI’s PEM loggers, which communicate well with eClimateNotebook. At the time of publication, the free version of eClimateNotebook accommodates three dataset locations, with a paid annual subscription needed to examine more locations. Additionally, a paid subscription is needed to upload data in a .csv format, allowing for integration of data collected by non-PEM data loggers.

eClimateNotebook allows users to create several types of reports, though this requires a paid subscription. An “Overview Report” provides an automated visual evaluation of preservation quality, while a “Performance Report” includes histograms indicating when the environment is outside of prescribed or self-defined environmental target zones. A “Compare Report” can be used to compare risks for different datasets for a specified data range. Customizable reports are also available at higher subscription levels.

A3.4. Physics of Monuments

Developed by Harrie Smulders and Marco Martens at Eindhoven University of Technology for the Climate for Culture Project

The Physics of Monuments tool (http://www.monumenten.bwk.tue.nl/) from the Eindhoven University of Technology was created in 2013 for the European Union Climate for Culture project with the goal of making information on building physics more accessible to museum professionals. T and RH data is uploaded via a free user account and saved on a server. The software produces a suite of visuals that provide insight into the museum environment.

Functionality

The graphical output from the Physics of Monuments tool consists of time plots, climate evaluation plots, and risk plots. These plots will be briefly described below, but additional information is provided on the website and in Martens (2012).

- Time plots allow one to examine how T and RH data recorded at different locations evolve over the period of data collection.
- The Climate Evaluation plots consist of three complementary visualizations
    - The left plot in figure A3.11 is a Mollier diagram, which combines display of T and RH data into one figure. (Note that the Mollier diagram is a variant of the psychrometric chart, with each showing similar information.) The data points are color coded to indicate pre-defined northern hemisphere seasons. Overlain on the data are a fungal growth curve and an environmental target zone (self-defined or based on existing standards).
    - On the lower right side of the Mollier diagram are five distribution charts (overall and seasonal) in the form of 3 x 3 matrices (fig. A3.11). The central value of each matrix corresponds to the percentage of time within the target zone, while the other values correspond positionally to data that is outside the target zone.

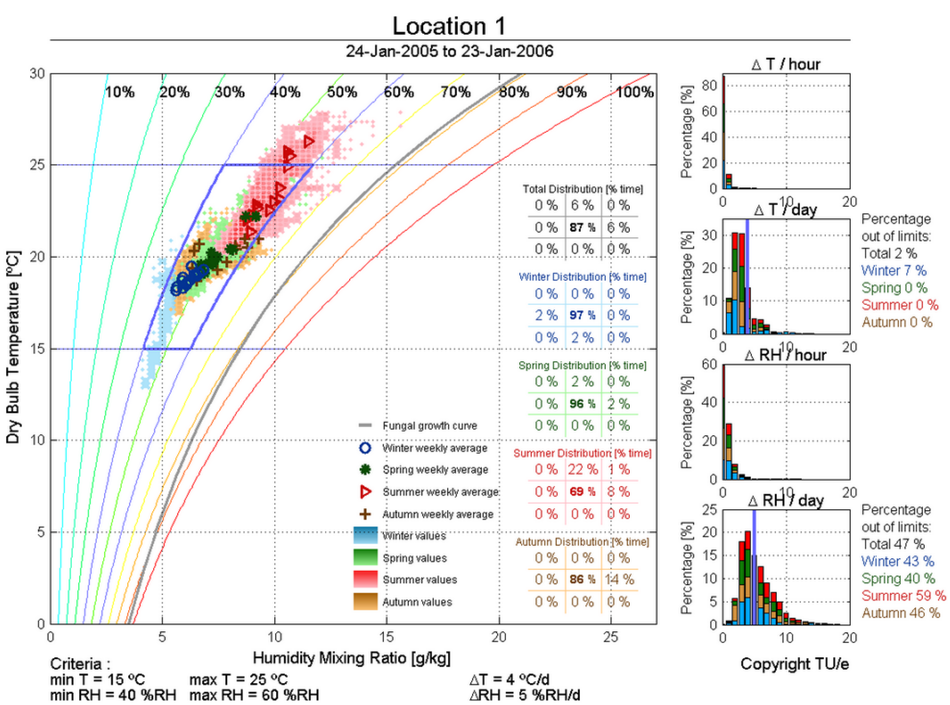


FIGURE A3.11

Climate evaluation plots showing a Mollier diagram, distribution matrices (right side of Mollier diagram), and T and RH fluctuation histograms (to the right of the Mollier diagram).

- To the right of the Mollier diagram are four histograms, which show hourly and daily fluctuations of T and RH by season (fig. A3.11). To the right of each histogram is the percentage of time that the data is beyond the pre-defined T and RH fluctuation limits.

- Two types of risk plots are included in the Physics of Monuments tool
  - A General Risk plot visually displays the T and RH data over time with respect to six ASHRAE control class bands as described by the 2007 ASHRAE chapter “Museums, Galleries, Archives, and Libraries” (fig. A3.12). (Note that the 2019 version of this chapter adds a “long-term outer limit” parameter not present in earlier iterations.) Also defined is the percentage of time that the T and RH data is within these ASHRAE control classes, allowing one to determine the current level of environmental control.
  - The Specific Risk plot focuses on biological risk (mold), chemical risk (lifetime multiplier), and mechanical risk (for the base material and pictorial layer) for four object types: paper, panel paintings, furniture, and sculpture (fig. A3.13). The upper section of the plot lists interpretations of these risk factors. The bottom section includes related visualizations, with green zones considered safe, orange zones denoting moderate risk, and red zones indicating high risk. The underlying calculations are complex and described in chapter 5 of Martens (2012), but important factors include the object type, the materials and mechanical behavior of the object, its construction, and object response time.

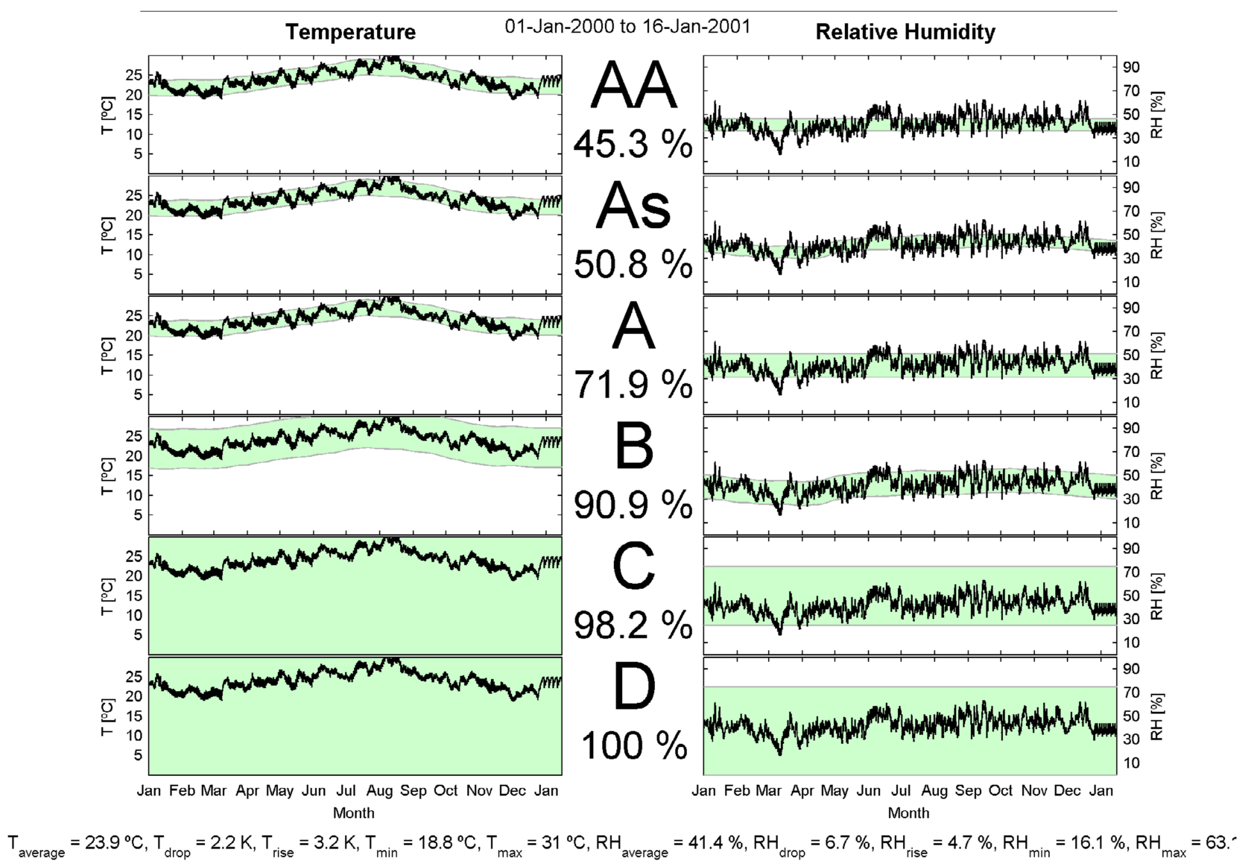


FIGURE A3.12

A General Risk plot comparing the T and RH data to six ASHRAE control class bands defined by the 2007 ASHRAE chapter “Museums, Galleries, Archives, and Libraries.”

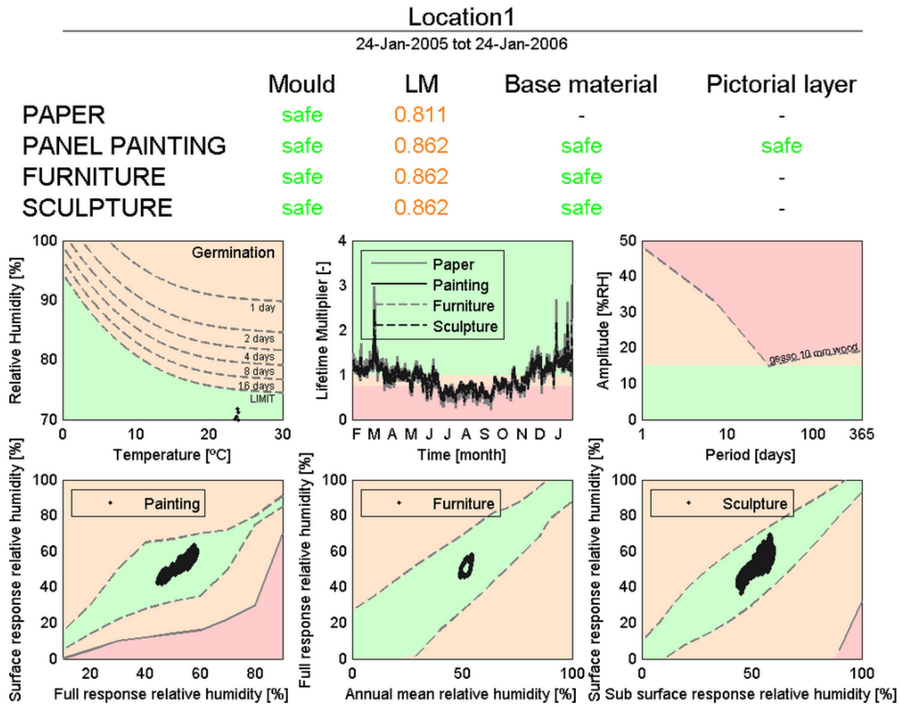


FIGURE A3.13

A Specific Risk plot showing interpretations of biological, chemical, and mechanical risk for four object types (upper section) and related data visualizations (bottom section).

Users

This Physics of Monuments tool was developed in collaboration with heritage professionals and has been employed in measuring campaigns at historic buildings and as a didactic tool, though its use has largely been limited to Belgium and the Netherlands. The Climate Evaluation plots, in particular, have been praised for communicating many different types of information within a single graphic. The ability to define one's environmental target zone has also spurred discussion on the use of prescriptive set points and what is achievable at a given museum. Note that the tool's use of four pre-defined seasons will be the reverse of the seasons in the Southern Hemisphere, and does not easily accommodate regions that have different seasonal categories. Further, the Mollier diagram lacks an elevation component and may not be accurate for higher elevation sites.

A3.5. HERIe

Developed by the Jerzy Haber Institute of Catalysis and Surface Chemistry

Created for the HERIVERDE research project (2013–17) on the "Energy efficiency of museum and library institutions" (HERIe 2013), HERIe is a free online software tool (https://herie.pl/) that recalculates climate history into dimensional change (or strain) for select object types, based on modeling conducted with finite element analysis (FEA). In doing so, the user is able to quantitatively assess the climate-induced risk of physical damage to the object.

A motivation for developing this tool for the cultural heritage field was to examine more closely the risk of mechanical damage amid the shift toward more sustainable environmental management. This is manifested often by a relaxation of environmental specifications for galleries and storage. Environmental guidance such as the 2014 IIC/ICOM-CC joint declaration, BSI 2018, and the 2019 ASHRAE chapter "Museums, Galleries, Archives, and Libraries" provides general specifications suitable for many classes of hygroscopic objects. However, at the object level, environmentally induced physical damage is a function of the intensity of the hazard (environmental fluctuation), physical change in the object (dimensional response), and the risk of actual damage (the critical level of restrained dimensional response resulting in failure).

Functionality

The user of HERIe engages the risk analysis tool by uploading T and RH data (one year is recommended) and defining object type and characteristics. The tool currently allows for assessment of panel paintings, fully restrained wooden panels, and parchment, and the following features are specified for the panel objects:

- Wood species (lime/linden, poplar, or oak) and cut (radial or tangential)
- Diffusion model (one- or two-sided)
- Gesso stiffness (stiff or soft, for panel paintings)
- Object thickness (5 to 40 mm)
- Mean T (7°C to 25°C, or calculated from uploaded data): This is taken into account when determining the water vapor diffusion coefficient of the material
- Mean RH (30% to 70%, or calculated from uploaded data): This indicates the equilibrium condition for the object where zero strain is assumed

The software then conducts the following steps:

- Decomposition of the RH data into a set of elementary RH cosine cycles: This separates long-term seasonal cycles (e.g., winter heating) from irregular medium- and short-term changes (e.g., weather shifts, opening/closing of doors and windows, visitation, intermittent operation of climate control system), allowing for the selection of appropriate time windows based on the response time of the defined object.
- Translation of RH cosines into elementary strain cosines: To reduce calculation time, HERIe accesses a lookup table of pre-calculated strain cosines centered at 50% RH. This database is based on finite-element numerical simulations of water vapor transport and moisture-related strain for the designated object types, and specific physical properties of the object materials.
- Superposition of elementary strain cycles when zero strain is assumed at 50% RH: This obtains the full-strain history of an object (dimensional response to climatic variations within a given time window) by summing up the elementary strain cycles corresponding to the elementary RH cycles. (Recall that the strain cosine database is centered at 50% RH.) In addition, water vapor diffusion coefficients used in the strain cycle calculations are based on the mean temperature from the uploaded environmental data.
- Definition of strain versus time histories when zero strain is assumed at an RH other than 50%: This first shifts the strain history so that zero strain corresponds to the assumed acclimatization RH level of the object, followed by a scaling of the amplitude of the strain history. The latter reflects the fact that similar RH cycles yield different elementary strain cycles depending on the RH level at which zero strain is assumed.

- Calculation of risk indices: The final step of the HERIe analysis is the assessment of mechanical risk by comparison to a critical level of restrained dimensional response resulting in damage. Taken from laboratory studies or object and collection monitoring, this damage criterion is typically the yield strain of the material, so that materials are not loaded beyond the elastic (reversible) region, or degree of curling in the case of parchment.

Output

HERIe outputs several results from its analysis. The first is a plot of the uploaded RH data (fig. A3.14a). The second is a plot of the calculated strain history of the defined object as a function of time (fig. A3.14b). Also overlain on the strain history are yield strain thresholds for gesso (panel paintings) or wood (fully restrained wooden panel) beyond which the object might be at risk of physical damage. In the case of parchment, the degree of curling is also shown over time (fig. A3.14c). The overall

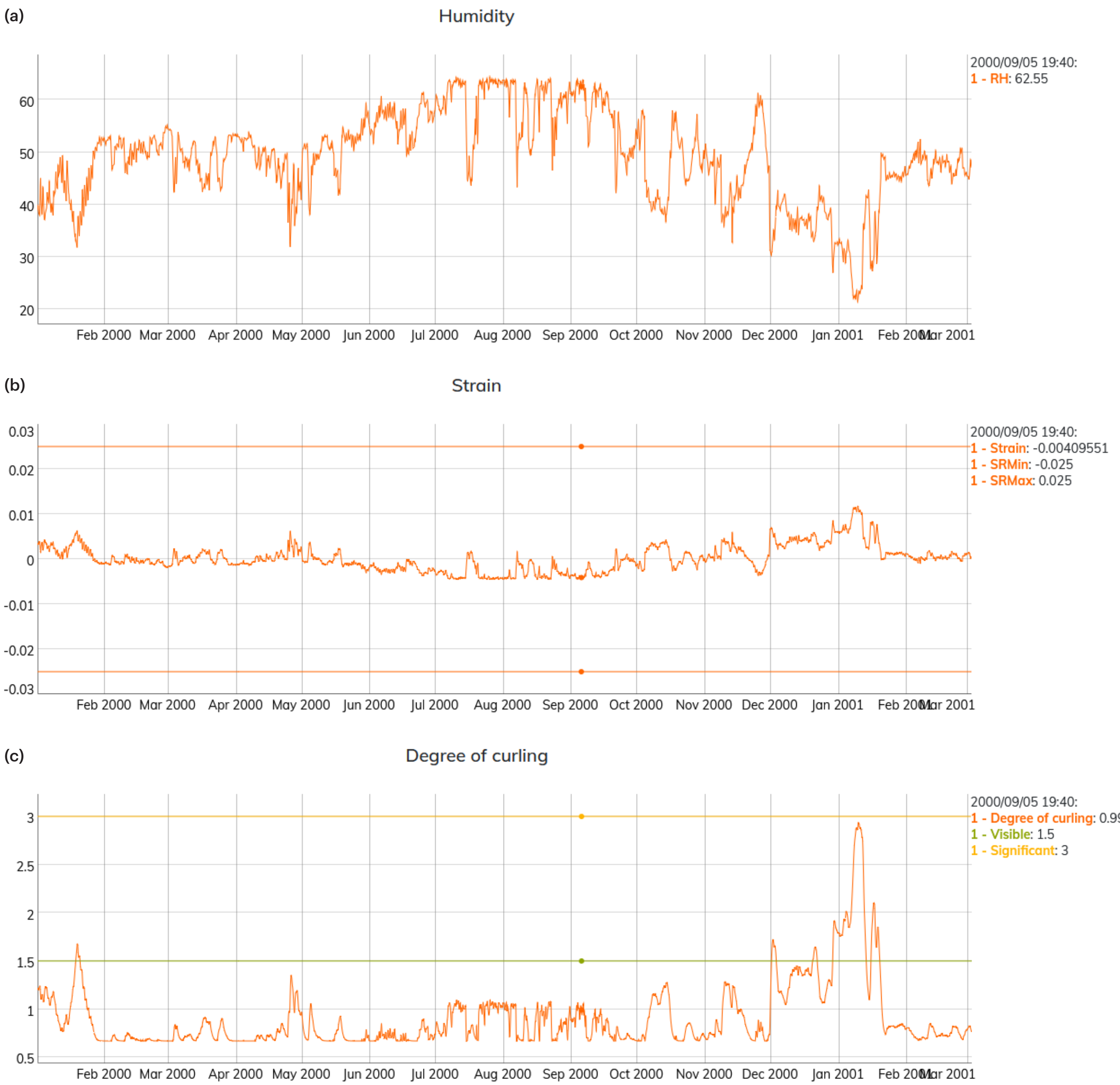


FIGURE A3.14
Time series of (a) RH, (b) strain history (with criteria overlain), and (c) degree of curling (with criteria overlain).

mechanical risk is expressed by a numerical Risk Index between 0 and 1, with 0 indicating minimal risk and 1 indicating high risk. If the maximum magnitude of strain is less than the yield strain or greater than the strain at failure, the Risk Index is 0 or 1, respectively—intermediate maximum strain magnitudes will linearly increase the Risk Index.

Current Use and Future Development

The HERIe tool has been presented at numerous conferences since its release, and, since 2017, the Jerzy Haber Institute and the GCI's Managing Collection Environments (MCE) Initiative have partnered to support its further development. The tool provides a unique means of assessing the mechanical risk to a defined object type based on exposure to specific environmental conditions, whether they be real or projected. When specifically defining the acclimatized T and RH conditions of an object (rather than using mean values from the uploaded data), one can examine the risk of environmentally induced physical damage when moving the object between two environments. The tool has also been used by MCE as a hands-on exercise when teaching about material properties and object response during the course "Preserving Collections in the Age of Sustainability."

Since February 2021, the HERIe tool has expanded to examine multiple agents of deterioration, including incorrect T and RH, light, fire, and contaminants. At the time of publication, the tool now incorporates modules to examine mechanical degradation (discussed here), chemical degradation, fire risk, light damage risk, and pollutant concentration and deposition rates. It is expected that additional modules will be added in the near future to broaden the applicability of HERIe and establish it as a repository of a range of risk analysis modules.

References

ASHRAE. 2019. "A24—Museums, Galleries, Archives, and Libraries." Chap. 24 in *ASHRAE Handbook—HVAC Applications.* Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers. Also issued as IP edition, 2019.

———. 2007. "Museums, Galleries, Archives, and Libraries." Chap. 21 in *ASHRAE Handbook—HVAC Applications.* Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers. Also issued as IP edition, 2007.

BSI. 2018. *BS EN 16893:2018 Conservation of Cultural Heritage: Specifications for Location, Construction and Modification of Buildings or Rooms Intended for the Storage or Use of Heritage Collections.* London: British Standards Institution.

Cosaert, Annelies, and Vincent Beltran. 2021. "Comparison of Temperature and Relative Humidity Analysis Tools to Address Practitioner Needs and Improve Decision-Making." In *ICOM-CC 19th Triennial Conference Preprints, Beijing, 17–21 May 2021* (forthcoming), edited by Janet Bridgland. Paris: International Council of Museums.

Działo, Artur, Mariusz Jędrychowski, Łukasz Bratasz, Leszek Krzemień, Arkadiusz Kupczak, Roman Kozłowski, Michał Łukomski, and Łukasz Lasyk. 2013. HERIe: Quantitative Assessment of Risks to Heritage Assets. Krakow, Poland: Jerzy Haber Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences. https://herie.pl.

IIC and ICOM-CC. 2014. "Environmental Guidelines – IIC and ICOM-CC Declaration." London: International Institute for Conservation of Historic and Artistic Works; Paris: International Council of Museums – Committee for Conservation. https://www.iiconservation.org/sites/default/files/news/attachments/5681-2014_declaration_on_environmental_guidelines.pdf.

Martens, Marco H. J. 2012. *Climate Risk Assessment in Museums: Degradation Risks Determined from Temperature and Relative Humidity Data.* Eindhoven: Eindhoven University of Technology. https://doi.org/10.6100/IR729797.

Nishimura, Douglas W. 2011. *Understanding Preservation Metrics.* Rochester, NY: Rochester Institute of Technology. https://s3.cad.rit.edu/ipi-assets/publications/understanding_preservation_metrics.pdf.

Getty
Conservation
Institute

getty.edu/conservation