Managing Collection Environments

Technical Notes and Guidance

Guidelines

Joel Taylor
Michael C. Henry
Vincent Laudato Beltran
Walt Crimm
Matthew Eckelman
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Jeremy Linden
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Edited by Joel Taylor and
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Getty
Conservation
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Getty Conservation Institute
Los Angeles

The Getty Conservation Institute works internationally to advance conservation practice in the visual arts—broadly interpreted to include objects, collections, architecture, and sites. The GCI serves the conservation community through scientific research, education and training, model field projects, and the dissemination of the results of both its own work and the work of others in the field. In all its endeavors, the GCI focuses on the creation and delivery of knowledge that will benefit the professionals and organizations responsible for the conservation of the world's cultural heritage.

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Contents

Technical Note 10: Considerations for the Process of Managing Collection Environments

Joel Taylor

Technical Note 11: Nonmechanical Environmental Management Strategies

Michael C. Henry, PE, RA

Technical Note 12: HVAC Options, New Constructions, and Microcontrol

Jeremy Linden

Technical Note 15: Negotiation and Consensus Building

Jane Henderson

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INTRODUCTION

Joel Taylor

This volume of collected technical notes presents a holistic approach to the sustainable management of collections in cultural institutions (museums, galleries, libraries, and archives). It is part of the Getty Conservation Institute's Managing Collection Environments (MCE) initiative. The initiative is designed to empower collections professionals to develop approaches to preservation that engage with the wider goals of sustainability.

This holistic perspective emphasizes the analysis of situations and data, as well as considerations for and approaches to managing indoor climate. Further still, this volume moves beyond the traditional domains of conservation to consider systems theory, consensus building, and communication, among other topics. Managing collection environments isn't just a technical, communication, practical, or organizational matter, or a matter of know-how. It is all of these and more. The certainty of prescriptive approaches to preservation has eroded to reveal that no single field of study holds the solution and no one solution can be applied universally.

A better understanding of climatic zone, building qualities, resources, capacity, and needs means that instead of battling the outside climate we can work with it. With effective analysis, we understand what is possible, and with a broad perspective on the needs of a collection, we understand what is necessary for preservation. Good communication and broadened perspectives can make traditional opponents into natural allies in developing preservation approaches that contribute to institutional and global sustainability efforts without compromising the collection.

The technical notes were originally developed for the MCE course *Preserving Collections in the Age of Sustainability*. Designed for mid-career professionals involved in collection preservation, it was attended by facilities managers, conservators, registrars, conservation scientists, collection managers, and departmental managers. Decision makers from museums, galleries, libraries, and archives all over the world, large and small, were represented.

As well as fundamental concepts like climate and the physics of relative humidity, and practical issues such as options for improving environmental management, the course covered broad-scale issues such as the historical and organizational contexts and external influences of museum environments, and the analysis of climate data, project management, building consensus, leadership, and influence. It also involved the application and implementation of course teachings within participants' institutions. This approach was intended not only to deepen understanding of preservation issues but also to help bring about sustainable change.

The course involved ten weeks of online tasks and readings, including the technical notes, followed by a two-week workshop comprising seminars, exercises, and case studies that embodied the complexities and interrelationships of the course issues. Workshops were limited to eighteen participants because they focused on discussion rather than simply transmitting information. Participants were asked to bring their institutions' climate data, building plans, organizational charts, and mission statements, among other things. The workshop ended with an action plan that each person created for applying course knowledge to introduce change to their specific situation, the kinds of institutional changes that could not be achieved by one individual. Projects included reviewing and reducing energy consumption, improving storage conditions, collaborating with capital projects teams, widening climate parameters, contributing to new building projects, developing methods for climate management in historic houses, and writing new guidance for climate management. Different contexts, different problems, different approaches; the same holistic perspective. For a six-month period, participants were guided by a mentor—one of the expert workshop instructors—and supported by one another to begin that change.

The participants were often very accomplished in their areas but had not necessarily been exposed to the other specialist fields. The technical notes were a common reference point for the varied experiences and a foundation for the discussions and case studies. Discussion was rich but a common language and a basic understanding of one another's worlds was needed. Technical notes were key to the course because they can enlighten the uninitiated and allow the experienced to reflect on their knowledge. Breaking down the established principles and stepping back allowed for different questions to be raised, new discussions fostered, and new reflection on old practices and situations. Discussion of case studies with many dimensions was only possible with this holistic overview. The notes were written to reconsider assumptions and promote discussion through evidence rather than polemic argument.

The value of the technical notes arose before the class met, and after they parted. After the workshops, not only did they become resources for implementing plans, but participants would sometimes share them with colleagues to deepen understanding and promote discussion in their institutions.

* * *

This collection is divided into four areas. The first provides an overview to understand the context and background of the issues and to help readers see the wider issues that influence collection preservation and climate management. As well as reviewing the fundamentals of climate physics in an accessible manner, this section illustrates how understanding change over time helps manage future change, and how understanding the influences of different factors in a dynamic situation helps diagnose and address needs and challenges.

The following section is about creating the data for evidence-based analysis and good decision-making. This involves breaking down the environment through monitoring and analysis, and also breaking down the kinds of guidance and standards that have arisen and the actual mechanics of change induced by climate.

Thirdly, we discuss synthesis—connecting the data to consider sustainable approaches, rather than defaulting to set courses of action or prescribed solutions. Where many approaches are developed to "solve problems," this section helps define situations and risks, and how to use information. It also contains practical advice on mechanical and nonmechanical options for climate management.

The final section is about making it happen. This includes both getting to the table and building consensus in cultural institutions, which is often the hardest part of introducing change. This encompasses being equipped to develop pre-project program briefs, expressing long-term perspectives in concrete terms, considering communication plans, and influencing those who may not be interested in sustainability or collection preservation.

Each note is self-contained and can stand alone to provide insight or to help in preparation for a seminar or meeting. You don't necessarily need to know about HVAC to read about leadership (or vice versa), but we recommend reading the whole collection. Collectively, the notes contribute to an interdisciplinary whole. This is the perspective that the MCE course brings. Following the progress of participants' efforts to apply the course knowledge to their institutions has made it clearer that these elements needed to be interwoven. Even if these matters connect differently with different situations and roles in an institution, technical knowledge can open up opportunities to communicate. Effective communication and presentation can lead to greater insight. It's all connected.

The information comes from authors with considerable experience in the subjects. Because the notes range from highly technical topics, through practical approaches, to project management and communication, the voices and sources of the authors are distinct.

In preparation for the course, the notes were circulated among instructors and GCI staff for comments before being "road-tested" in the workshops, with feedback provided afterward. In preparing the notes for wider publication, they were anonymously peer reviewed by an all-star cast to ensure their relevance for a broader audience and their longevity beyond the course.

Personally, I believe that the secret weapon of any course is the participants. Although course creators don't know all the specific experiences, skills, and stories that participants might bring, we know they are far from empty vessels. As well as finding ways to instruct them or empower them with perspectives, knowledge, and tools, there is immeasurable benefit in finding ways for participants to empower themselves and one another. The technical notes are an important part of that, as a means to promote lasting communication. In other words, these short texts are not just meant to be reference material. They allow readers to reflect upon their own experiences and relate to others, to review their institutions and situations, and learn about new materials and topics. They also serve as a platform for exchanging those experiences and ideas with others around you.

Managing change is a complex process. It requires many different kinds of resources. For our efforts, these technical notes were essential. We hope they support your efforts.

PART 1: CONTEXT AND BACKGROUND

Introduction

This first set of four technical notes is designed to give the reader context and common background before delving into the broader issues influencing collection preservation and environmental management. A key concept of this section is the notion of systems and systems thinking. When the term "system" is mentioned in the collection care field, HVAC systems immediately come to mind, evoking elaborations on the relationship between air temperature and relative humidity or how the building envelope buffers the exterior climate. But a broader view of "systems" considers HVAC systems alongside connected factors of climate change, institutional organization, deterioration mechanisms, and decision-making processes, all of which represent systems of influences, flows, and feedback loops.

In the introductory technical note, "Context and Use" by Michael C. Henry, the author discusses how temporal and physical contexts of the objects we value as cultural heritage are interrelated with their past and present. An object's past contexts and uses influence its significance and how it is understood in the present and, consequently, its preservation in the future. Understanding these connections is not an easy task. The contexts are formed by a complex array of natural, social, economic, and technological forces acting dynamically on large and specific scales. By identifying the connections, trends, and influences of the object's past uses on its present state and analyzing the interaction of physical contexts with these uses, we can begin to develop more effective and sustainable preventive conservation strategies. Without this, we risk investing significant resources to treat the effect, before understanding the cause.

The next technical note, "Systems Thinking for Collections Environments" by Michael C. Henry, describes systems and systems thinking in depth, defining their essential elements, describing methods for visualization, such as causal loop diagrams and stock and flow diagrams, and how they can be used as a tool to resolve problems and optimize results. This sets the stage for applying "systems thinking" to environmental management in museums, as well as to related museum systems such as the building envelope, collection deterioration, institutional operations, visitor experience, and funding.

In the technical note "Psychrometric Processes for Environmental Management," Vincent Laudato Beltran presents a practical application of systems thinking concepts through a primer on psychrometrics (the physical and thermodynamic properties of a mixture of moisture and air) that explains why "temperature and relative humidity are connected." This provides important background for subsequent readings. The technical note also describes the psychrometric processes—heating, cooling, dehumidification, humidification—that can be employed to manage interior environments and how a graphical tool such as the psychrometric chart not only visualizes these connections, but also plays a key role in defining possible environmental management strategies.

This suite's final technical note, "Museums and Their Exterior and Interior Environments," explores the building environment system. Michael C. Henry accessibly reviews concepts such as climate, building envelope, hygrothermal properties, bulk and capillary flow of liquid water, convective moisture transport, and moisture adsorption and diffusion. The complex system of interactions between temporal and physical contexts and shifting use is practically presented to demonstrate how the building and its macro- and microenvironments are connected, and how this affects the collections housed within.

TECHNICAL NOTE 1: CONTEXT AND USE

Michael C. Henry, PE, RA

Introduction

The sites, buildings, and objects that we value as cultural heritage are the survivors of past contexts and use. The future survivability of this cultural heritage will be influenced by our stewardship decisions and how well these decisions anticipate the impacts of present and future contexts and use.

Temporal contexts—past, present, and future—are the time frames within which physical contexts act on a specific site, building, or object.

Physical contexts include a range of environmental, social, economic, and technological forces acting on global, regional, and local scales. Natural forces range from the external environment, including effects of climate change and seismic events, to the constant yet subtle transport of mass and energy necessary to maintain atmospheric moisture equilibrium. Societal forces range from human conflict to local issues of health and crime. Economic forces range from international trade agreements to local employment and poverty. Technological forces include the effects of basic infrastructure, such as water supply, on health, the impact of air conditioning systems on expectations for human thermal comfort, and the effects of the internet and social media on the transmission speed of information and misinformation.

These macro-forces cannot be influenced directly, but we can manage their effect at the level of the site or building. At best, we may be able to accurately predict the occurrence and severity of recurring large-scale forces, such as weather, and respond by preparing to mitigate their adverse effects. At the local level, we may be able to respond to some societal forces by engaging the community when making site management decisions. At the object level, we may move an object to a less damaging location (perhaps a showcase or storage) or return objects to community stewardship to reduce the loss of the potentially significant historical or cultural relationship between the object and its community.

Use—the utilization or employment for a specific aim or purpose—also results in a variety of forces and processes that act on a site, building, or object. The word "use" implies utility, but not necessarily consumption. Use may also include storage and vacancy, although neglect and abandonment could be considered consumption by default. Conventional notions of stewardship often favor use as an interpreted site, a museum, or a collections object on display as the preferred method for ensuring survival and longevity. However, failures in cultural heritage stewardship provide examples that raise doubts as to the universal validity of this assumption. For example, a historic site steward may gauge success in terms of a large number of visitors, but increased visitation can accelerate wear and tear of historic building fabric and necessitate visitor amenities and services that can substantially alter the site and its surroundings. On the other hand, low visitation numbers may prevent an institution from attracting sufficient funds for ongoing preventive maintenance, resulting in deferred maintenance, loss of original fabric, and ultimately the need for episodic interventions.

Understanding the effects and interplay of past context and use on cultural heritage enables us to understand a site, building, or object in its present form. By identifying vulnerabilities, strengths, and resilience, we are better able to develop sustainable preventive conservation strategies. Understanding trends in climate change, such as increases in annual precipitation or storm intensity, can identify future threats to cultural resources. Likewise, comprehending societal, demographic, or technological trends will help us anticipate potential implications of social and economic changes.

By taking a "long" view to past and future contexts and uses, present stewardship can make better informed decisions for the continued survival of the resource.

Our Sense of Time

The world in which we live and work measures time in increasingly smaller increments, as a result of advancing technology and the accelerated speed of communication and delivery of information. This can result in an apparent compression of the notion of what constitutes the future. Stewart Brand (1999) noted that:

"Civilization is revving itself into a pathologically short attention span. The trend might be coming from the acceleration of technology, the short-horizon perspective of market-driven economics, the next-election perspective of democracies, or the distractions of personal multi-tasking. All are on the increase. Some sort of balancing corrective to the short-sightedness is needed – some mechanism or myth that encourages the long view and the taking of long-term responsibility, where 'the long term' is measured at least in centuries."

Brand (1999) also scaled the long now relative to the present in figure 1.1.

It might be argued that, as stewards of cultural heritage, we already have a good grasp of "long time." However, we must accomplish our stewardship goals within the social, economic, and political systems that function within different, and increasingly shorter, perceptions of time. By understanding and reinforcing the importance of the temporal contexts of cultural heritage, we are better equipped to analyze and interpret the effects of the past on cultural heritage. This, in turn, informs our choice of sustainable strategies for future stewardship, enabling us to make a more persuasive argument for stewardship in the present.

Time and Stewardship

As stewards of cultural resources, we may strive to assure the permanence of the resources for which we are responsible. This is a noble objective, but not necessarily achievable, given that the second law of thermodynamics assures the ultimate impermanence of all matter (Lambert 2006).

For the cultural heritage steward, managing the rate of change of cultural heritage is the realistic objective. It is an objective for which effectiveness can potentially be measured, provided that we can quantitatively or comparatively establish the change and the time over which the change occurs.

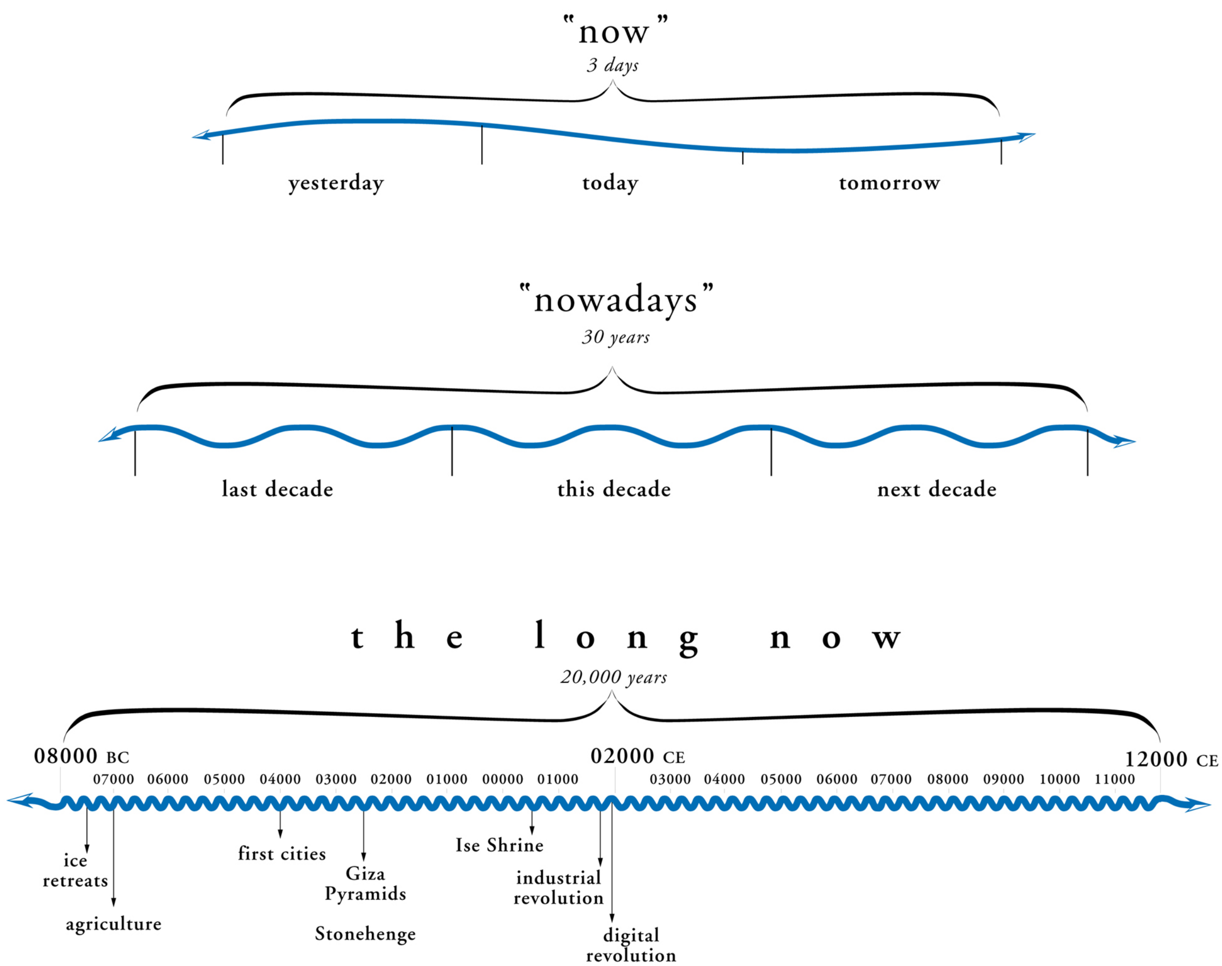


FIGURE 1.1. The temporal relation between "now," "nowadays," and "the long now" (Brand 1999).

Managing the present and future rates of change requires that we understand the arc of past time and the change that occurred over that time, including the past contexts and the factors that have enabled the observed change.

We may mistakenly aspire to provide permanence for cultural heritage, even as we acknowledge that the second law of thermodynamics assures their ultimate impermanence (Lambert 2006). Some objects, and occasionally some complex assemblies, such as buildings, may be long lived by virtue of their materials and method of assembly or by the lack of exposure to contexts that would damage or accelerate deterioration. Understanding the materials and methods of assembly as well as the object's history helps us distinguish why they remain with us.

Understanding survivability requires a more holistic approach to the resource and its response to the effects of contexts. This holistic approach considers a larger view of the resource than mere analysis of the processes of degradation. The organic implications of survivability (as opposed to permanence) echo the shift to sustainability rather than perfect preservation in our stewardship strategies.

The Temporal Context

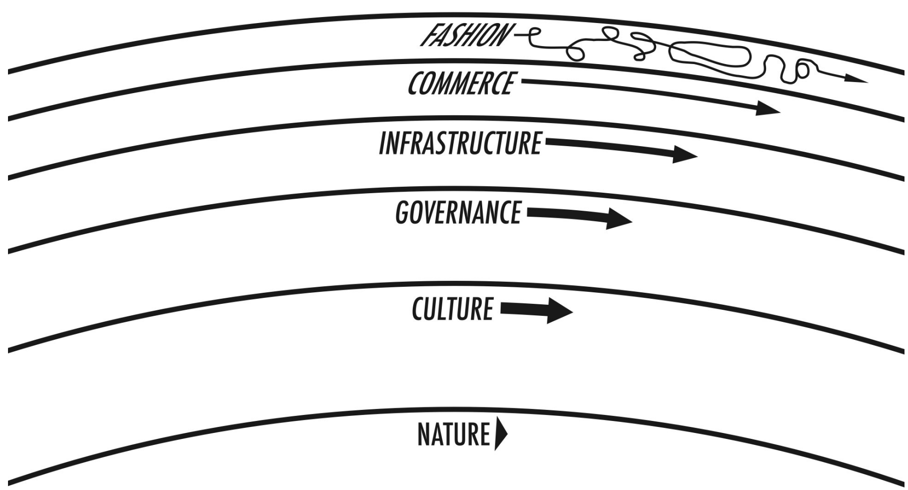
Past context also defines the trajectory of events and actions that have resulted in the present form of the resource. Understanding the past context of a resource provides insights into how and why the resource has survived; these insights can be essential to formulating a strategy for the future. These insights may also include an understanding of how the resource has been adapted over time, thereby maintaining its usefulness and enhancing its chances of survival. In some cases, such as the periodic ritual rebuilding of the Grand Shrine in Ise, Japan, the emphasis may be on the survival of the resource as defined by a philosophy, an ideal, and an institution, rather than by material fabric.

By placing the present in the temporal context of past effects and future possibilities, we can more effectively communicate the importance and necessity of our current plans to the social, economic, and political institutions within which we work as professionals.

Rates of Change

A fundamental part of thinking in the temporal context is understanding rates of change, such as an object's rate of deterioration. Brand (1999) posited that at a macro scale, rates of change can be understood as layers. Layers with slower rates resist change and layers with faster rates cause change, with shearing forces acting at contact surfaces between layers moving at different rates or speeds. Brand, working with Brian Eno, illustrated the interaction of these layers of change in a healthy civilization (fig. 1.2):

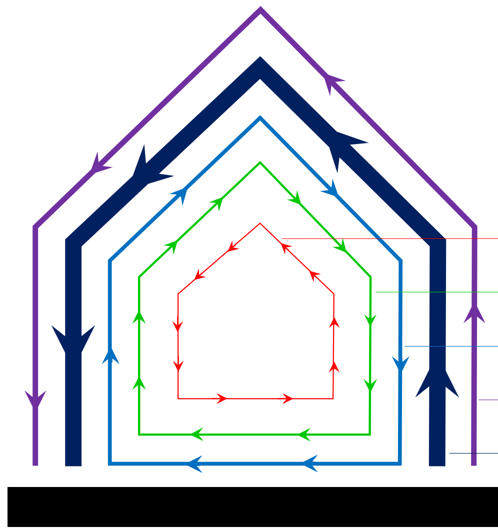
FIGURE 1.2. Pace and layers of change (Brand 1999).



In Brand's analogy, the forces of change move faster as we progress from the core (nature) to the edge layer (fashion) or, to put it another way, the time unit of change is smaller as we move from nature to fashion. This graphic could be updated to reflect the present context for change by adding "Information" as a fast-moving shearing layer outside of "Fashion." Adding the "Second Law of Thermodynamics" below "Nature" would be a reminder of the inevitability of deterioration. Lastly, inserting a layer for the "Troposphere and Climate" above the "Nature" layer would acknowledge the increasing speed with which humankind is influencing this metastable portion of "Nature" in the Anthropocene.

Brand (1994) also applied this graphical method in illustrating British architect Frank Duffy's concepts for the interaction of site, building, and objects by ranking layers in ascending order of the relative rates of change (fig. 1.3). The layers, in order of increasing rate of change, are site, building structure, building skin (exterior and interior), building systems, building space plan, and, lastly, stuff (furnishings and objects). As with the previous graphic, the addition of information technology as a very fast-moving layer, faster than "stuff," would be an appropriate update.

FIGURE 1.3. Shearing layers of change in buildings with approximate lifespans of the various elements (after Brand 1994). Credit: Vincent Laudato Beltran



We can also view these differential rates of change in buildings in terms of the inverse quality, expected service life. In either measure, rate of change or expected service life, we are comparing the relative durability of a site, structure, or object. The durability of one component may not change relative to another component, but the rate of change is clearly increasing, particularly with respect to building services. Building services may be technically obsolete before they reach the end of service life because more energy-efficient equipment or more environmentally friendly refrigerants are available. Information systems, controls for HVAC systems, and fire and security systems often become obsolete before the end of their physical service life because changes in firmware, software, or communications protocols do not support their continued operation.

The increasing frequency of alteration or replacement in building services and information systems has serious implications in terms of resource stewardship. For example, historic building systems that possess significant technology may be removed in the process of replacement, especially when space is at a premium. When building services and information systems are concealed behind or embedded in historic building fabric and finishes, the increased frequency of replacement may adversely impact historic integrity.

Physical Contexts—Large Scale and Resource Specific

Within the temporal context of past, present, and future, large-scale and resource-specific physical contexts affect the survival of a site, building, or object.

Large-scale physical contexts encompass natural factors, such as soils and geology, subgrade and surface hydrology, and seismicity. The natural forces of climate and weather include temperature (thermal energy), atmospheric moisture, precipitation, wind, and solar radiation, all of which are affected by the orientation of the building and site. Large-scale physical contexts also include human activity in proximity to the resource, such as land use, gaseous pollutants, dust, and particulates from agricultural, transportation, or industrial activities. Infrastructure such as energy, water and sewage utilities, and information/communication networks, public transportation, and fire and police services are critical physical contexts that can lower or increase the physical risks to a resource. Lastly, cultural and societal considerations, such as governance, community, education, employment, health, poverty, and crime also influence the physical context.

At building scale, physical contexts of the structural system, shape, plan, height, and organization of spaces will have an impact on the resource. The building envelope, including its function and performance with respect to the exchange or transport of moisture, air, light, and thermal energy, will have an impact on the interior environment of the resource, as will the building services and systems infrastructure, their condition, and their performance.

The resource-specific contexts include those influences that are intrinsic to the resource and its site, such as topography, surface water drainage, pavements, access, landscapes, flora and fauna, pests, and habitats. At the building scale, the physical contexts of the structure, form, spatial organization, building envelope, and building services and systems will have an impact on the resource.

Opportunities to influence or reduce the effects of small-scale physical contexts are likely to arise, but large-scale contexts are more difficult to change.

As stewards of cultural heritage, our training and experience typically include consideration of physical contexts, especially when analyzing and identifying the causes and effects of present conditions. As we seek sustainable strategies for stewardship, we must understand that the physical contexts act on the resources as an interrelated and synergistic set of systems of influences and feedback loops.

Consider, for example, the ceramic tile (fig. 1.4) in the choir loft of a former church in a hot and humid coastal climate. When we observe this tile, we might conclude that the damage results from a moisture-enabled process of deterioration, such as salt migration and a range of treatment possibilities to remove the efflorescence may spring to mind.

However, the entire context reveals a more complex situation. If we turn around, we see the immediate context of the church interior (fig. 1.5). If we step outside, we see the exterior face of the masonry wall, with a porous stucco finish (fig. 1.6). We note that a large tree shades the wall from sunlight during most of the day and prevents opportunities for drying the exterior. We also note exterior site features that accumulate water and elevate exterior atmospheric moisture. If we look at the climate data for this resource, we find that this facade receives the prevailing winds coincident with periods of greatest precipitation. As we process the information from these resource-specific and large-scale physical contexts, we begin to see a large set of processes and enabling factors that contribute to the readily observable damage to the tile.

With this information and perspective, a sustainable approach to preventive conservation might include tree management and surface water management to reduce the availability of moisture in the wall containing the tiles. Ideally, this approach would balance conservation of the church and its interior with preservation of a mature tree, keeping the tree canopy to a manageable size and restricting root spread to prevent damage to the church's foundations and site drainage infrastructure.

FIGURE 1.4. Damaged tiles in a choir loft at the Museu de Arte Sacra in Salvador, Bahia, Brazil. Photo: Shin Maekawa. © J. Paul Getty Trust

FIGURE 1.5. Interior context of choir loft. Photo: Michael C. Henry

The example of the deteriorating wall tile illustrates how large-scale and resource-specific physical contexts are connected in the mechanisms that lead to readily observable deterioration in a resource. In the case of the tile, the causal factors range from evaporative moisture transfer and soluble salt migration through a small tile, to the moisture dynamics of a shaded courtyard and prevailing winds and precipitation. This understanding is essential if we are to successfully identify, evaluate, and select effective sustainable strategies for preventive conservation.

Physical contexts change with time. Some changes may be rapid, as with technology, while other changes in physical context, such as climate change, may be difficult to perceive because the rate of change is measurable, but appears to be slow. Some casual factors may have occurred in past contexts, but the damage is observed in the present context. Ultimately, the effects of climate change may be more critical to loss or survival of a resource than the influence of present physical factors.

Projections for climate change indicate that a wide range of environmental parameters will increase risks to cultural heritage, some at increasing rates of change. Depending on location, these changes may include increases in atmospheric temperature, moisture, wind speed, and cloudiness. Experts predict that extreme weather events will be more frequent and more intense. Changes in climate will result in sea-level rise, as well as migration of plants, animals, insects, and microorganisms. Human migration will take place as land is lost and as agriculture and economies shift geographically.

FIGURE 1.6. Exterior wall with choir loft near the top of the building. Photo: Michael C. Henry

Changes in physical contexts may accelerate with time. Air conditioning, the simultaneous cooling and dehumidification of air for comfort, was discovered at the beginning of the twentieth century. It took three decades for air conditioning to be introduced into the White House in the United States. It is now a standard feature of most new construction for occupied buildings in the US and other industrialized countries. The declining cost of manufacture and technology for air conditioning has increased its affordability in terms of capital cost; the social response to its increased availability is an escalated expectation of human comfort in hot weather, exacerbated by the need to keep computers and data servers cool.

In contrast to air conditioning, the changes in information technology from the introduction of the first personal computer kit in 1974 to today's smart phones and tablets have been incredibly fast, as have changes in data storage capacity and technology, and in networking capabilities. Data centers and servers for digital data storage and access now consume a significant amount of energy for cooling (Pearce 2018).

The world has been networked through the internet, allowing exchange of information (and misinformation) and economic commerce to be transacted in real time across great distances. The implications of this on natural and human-made environments have yet to be completely understood, but it is clear that there will be significant impacts on society and our definitions of culture, community, employment, education, and governance. These changes, triggered by technological change, affect how we use and protect our undeveloped natural environment as well as how we use our cities and towns. The internet deeply affects how we perceive, experience, and value the real world with the convenience of access at a distance.

The implications of change in natural and technological contexts are equally important to us as stewards of cultural heritage. The first is perceived to be slow and cumulative but is not necessarily so; the latter is rapid and highly synergistic. We seem able to adapt better to the latter than the former, yet both will present opportunities for, and challenges to, cultural heritage in the short and long term.

Utility as Survival

Our cultural heritage is populated by sites, buildings, and objects that were each created for a specific first use and purpose. Over time, these have become valuable and significant to us for reasons that may be quite different than their original purpose.

Some sites, buildings, and objects survive because of their intrinsic cultural or economic value, or perhaps their value simply as curiosities. But for most sites, buildings, and objects, survival requires continued usefulness. Their utility is often related to the mutability or adaptability of the site, building, or object with respect to new or extended use.

The nineteenth-century eel trap (fig. 1.7), woven from strong, durable, rot-resistant wood strapping, and tarred to repel water, served a vital functional and economic purpose for a fisherman on the Delaware Bay in the mid-Atlantic region of the United States. It had to trap and contain eels, from which individuals and communities derived their livelihood.

FIGURE 1.7 Example of a nineteenth-century eel trap. Photo: Sydney Harold Smith, York Museums Trust, Object #: YORYM:S91

More than one hundred years later, this object has acquired multiple values—as lost craft, as abstract objet d'art, as a link to the past lives and livelihoods of the bayside community in which it continues to reside. In accruing these values, however, it has passed from its first use, as a functional tool that was routinely submerged in the mud and turbid water of a tidal bay.

A hand-carved wood and polychrome devotional statue, or Santo, in a Spanish colonial Roman Catholic Church in California has significance as an object of active devotion for the parish community. Its value is enhanced by the continuity of use across generations of families. Active devotion includes handling, clothing, adorning, and surrounding with lit candles and possibly food. If "rescued" from this first use (abuse, perhaps, in the eyes of some conservators or curators), it would be a strong candidate for conservation cleaning and exhibition in a museum. However, its value and significance are sustained by its first use; and this devotional use in turn spiritually sustains the parish community responsible for the stewardship of the statue as well as the church building, a heritage structure. We need to consider the totality of the object, its original purpose, its value and significance, as well as its physical integrity. In doing so, we need to manage devotion and conservation so that the whole is indeed greater than the sum of its parts.

Use—the utilization or employment for a specific aim or purpose—results in a variety of forces and processes that act on the site, building, or object. Conventional notions of stewardship often favor a museum or interpreted use as the preferred method for ensuring survival and longevity, but this is not always the case.

Changes in *use* of significant heritage buildings and sites can result in traumas to the historic fabric or site context, even when the *present use* is the interpretation of the *original use*. Restroom facilities, automobile and tour bus parking lots, museum retail shops, security lighting, and the seemingly ever-present wayfinding/cautionary signage have become accepted necessities in the interpretation of cultural heritage. Audible encroachments include office telephones, staff intercoms and radios, landscaping equipment, air conditioning condensers, fans, and gas- or electric-powered carts for staff transport. Each of these intrudes upon, and confuses, the interpretive experience. For each of these encroachments there are also corresponding physical intrusions of supporting infrastructure that are installed and maintained at considerable financial cost, energy cost, and staff time. With the drive toward increased visitation, the institutional focus risks a shift from stewardship to operations.

For interpreted heritage resources, the essential question for stewards may be, "How much _________ is necessary and sufficient to responsibly fulfill our mission to the resource and the public? " or, alternately, "What ________ is needed to sustain responsible fulfillment of our mission to the resource and the public?" The blank may be completed with the issue of the day, whether it is visitation, retail shop sales, energy costs, staff size, or similar issue(s).

While restroom facilities and tour bus parking are among the most visible impacts of the interpreted use, consider the following two examples of less obvious, but highly significant impacts.

The nineteenth-century water-powered sawmill in figure 1.8 used a wood-lined raceway to transport water from a lake to the turbine pit.

In its economic heyday, sawmill operation was cyclical, a pragmatic consequence of the fluctuations in the lake's water level. During periods of low water levels, the sawyers drained the wood raceway and repaired the wood liner, using harvested cedar sawn at the mill. This was an integrated and organic, self-sustaining activity. Once the site became an interpreted historic resource, the public agency responsible for its stewardship could not provide the staff needed to operate the mill. Generally idle and infrequently used for active interpretation of the equipment, the wood raceway lining and structure succumbed to rot and the cast iron turbine become clogged by the secretions of native iron-forming bacteria that thrive in stagnant water. In the first thirty years of interpretative use, the raceway and turbine underwent two major restorations, with the second restoration costing over US$500,000 (1989 USD). This raises the question as to whether original or interpreted use is more economically sustainable and which results in better long-term care of the resource. Perhaps this resource warrants an integrated form of stewardship linking entrepreneurial

FIGURE 1.8. Nineteenth-century sawmill at Batsto Village in New Jersey, United States. Photo: Batsto Citizens Committee, Inc.

opportunity with natural resource management and historic resource interpretation and conservation. This might entail selling traditionally sawn wood to underwrite staffing, thereby perpetuating the sawyer's craft, creating employment, and affording the opportunities for continuous maintenance, rather than episodic repair and restoration.

A similar situation has been observed with nineteenth-century lighthouses in the United States. While in service, the lighthouses were actively maintained by professional light keepers, charged with instructions and directives from the Lighthouse Board. These directives even detailed the types of brushes to be used for various tasks and the quantities of spare materials to be kept at hand for repairs and maintenance. Inspectors verified compliance. In effect, the lighthouses enjoyed a program of continuous preventive maintenance as part of their first use; this activity offset the aggressive physical conditions of the coastal environment. In the twentieth century, the United States Coast Guard took advantage of advances in navigational technology and refitted lighthouses for automated, unstaffed service. Unnecessary lighthouses were decommissioned and sold or abandoned; in many instances, the decommissioned lighthouses were acquired by government and nonprofit institutions for interpretation as heritage structures. Whether automated for navigation or repurposed as heritage structures, the earlier program of continuous maintenance by a resident light keeper ceased, leaving the masonry and metal work vulnerable to the aggressive environment. Preventive maintenance was replaced by decades-long intervals of deterioration and episodic, capital-intensive restoration campaigns.

The interpreted use of significant cultural heritage often presents relatively straightforward dilemmas for stewards. The need to retain the substance and character of the resource is often paramount. Stewardship of lesser heritage resources, for example secondary buildings of a historic district, "the architectural prose of everyday life" (Tung 2001), pose more difficult questions. The balance between retention and economic sustainability is complex and includes interdependency of multiple resources that constitute the whole historical context or the conservation area. We can look to the successes (and failures) of World Heritage Sites that are historic urban cores to see the complex interrelationship of use and physical contexts, particularly in relation to government policy and economic vitality, on the survival of these large resources assembled from discrete and disparate elements.

The word *use* implies activity. Broadly defined, *use* may also include storage or vacancy, but not neglect. In certain instances, significant cultural heritage may survive by virtue of its vacancy, especially cultural heritage that has its roots in economic enterprises, such as mines, mills, factories, and occasionally multi-resident housing. The vacancy of these resources, often in as-left condition, may be attributable to the legalities of bankruptcy, sheer size, remote locations, hazardous materials contamination, or undesirable adjacencies. These changes in physical contexts may have precluded continued use and, perhaps, demolition or substantial alteration. The survival of these vacant resources may result from their robust structural fabric, durable materials, or local climate. Future *use* of these vacant resources poses special challenges in resolving the contextual issues related to their vacancy, their ongoing conservation/preservation, and their future sustainability.

Common to the stewardship of all heritage resources, regardless of use, is the issue of modern infrastructure, systems, and services. For sites and buildings, infrastructure systems are internal, or integral, to the resource. For objects, systems are typically external to the resource. In either case, the implications of modern systems must be addressed. Some systems improve convenience and human thermal comfort, but other systems are essential for cultural heritage such as fire and intrusion detection systems, environmental monitoring systems, and information technology systems. Drainage and irrigation systems may be needed to manage the impact of climate-induced flooding or drought on building foundations or archaeological sites. Lighting and interior environmental management systems have the greatest implications in terms of capital and operating cost, construction and operational effects on fabric, and potential for calamity due to failure. These systems constitute an ever-increasing portion of the budget for new construction (about 40% at present) and an even larger part of many restoration budgets. Systems, however, are not as durable as structure, and their functional durability may be further shortened by obsolescence. Obsolescence in existing systems may be driven by improvements in controls, advances in energy efficiency, or development of environmentally friendly refrigerants. The US$500,000 heating, ventilating, and air conditioning system installed today is likely to require replacement in fifteen to twenty-five years. Assuming a 3% per year return on investment, an institution would have to set aside approximately US$19,000 per year for twenty years to cover the cost of future replacement, not counting inflation or escalation in cost.

The adaptation of historic buildings or sites to the effects of climate change remains in its infancy. In some regions, we know that we will need to consider larger capacity rainwater and drainage systems to divert water safely away from buildings; these will impact historic pavements, gardens, and buried archaeology. Although these adaptations may be intrusive, the question we must answer is whether these intrusions are acceptable compared to the losses that will result from inaction.

Future Change in Context and Use

When we understand the influences of a resource's past uses on its present state and analyze the interaction of physical contexts with those uses, we can begin to envision possible scenarios of physical contexts and uses. These scenarios, based on what we know of the past and present, including the dynamic change of use and contexts (trends), can inform our development of sustainable strategies for future stewardship. Scenario building is a formalized method for planning and development and for understanding their implications for an area of interest. Scenario building is beyond the scope of this technical note, but the methodology is described in *The Art of the Long View: Planning for the Future in an Uncertain World* (Schwartz 1996).

Understanding Contexts with Systems Thinking

The complex interplay of rates of change, physical contexts, and use over time is comprehensible if we view events and trends as the result of interactive systems of flows and feedback loops. Suzanne Keene (2002) addresses the application of systems thinking to museums and to preservation strategies; systems thinking will be explored in greater detail in the subsequent technical note.

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TECHNICAL NOTE 2: SYSTEMS THINKING FOR COLLECTIONS ENVIRONMENTS

Michael C. Henry, PE, RA

> You can't navigate well in an interconnected, feedback-dominated world unless you take your eyes off short-term events and look for long-term behavior and structure; unless you are aware of false boundaries and bounded rationality; unless you take into account limiting factors, nonlinearities and delays.—Donella H. Meadows, *Thinking in Systems: A Primer*

Introduction

Systems thinking is essential to successful organizations, management of collections environments, and preventive conservation of collections and cultural heritage. Systems thinking enables us to understand organizations, interior and exterior environments, and deterioration of collections as dynamic processes, and the factors that influence their behavior, so that we may identify measures through which we can influence or optimize those responses.

This technical note is an introduction to systems and systems thinking in the context of museums, their collections, and their environments. The listed resources should be considered essential reading to understand systems thinking as it more broadly applies to museums and cultural heritage.

This technical note:

- defines systems and their essential elements;
- introduces methods for visualizing systems and their essential elements;
- discusses the importance of system behaviors as revealed by events, patterns, and trend graphs; and
- presents systems thinking as a tool for resolving problems and optimizing performance and results.

Systems Defined

"A system is a set of things—people, cells, molecules, or whatever—interconnected in such a way that they produce their own pattern of behavior over time. The system may be buffeted, constricted, triggered, or driven by outside forces. But the system's response to these forces is characteristic of itself, and that response is seldom simple in the real world." (Meadows 2008)

Meadows (2008) defined a system as a "set of elements or parts that is coherently organized and interconnected in a pattern or structure that produces a characteristic set of behaviors, often classified as its 'function' or 'purpose.'"

A system may be physical, as with an environmental management system or a system of biological decay. A system may also be intangible, such as the generation and dissemination of new knowledge through published research activities.

The essential characteristics or elements of a system are:

- a defined boundary, encompassing the system;
- a set of elements or parts within the boundary;
- interconnectedness of the parts through flows of material, energy, and/or information; and,
- purpose or function of the system.

Each of these essential characteristics is discussed below.

The System Boundary

“There are no separate systems. The world is a continuum. Where to draw a boundary around a system depends on the purpose of the discussion.” (Meadows 2008)

Large complex systems found in nature, in organizations, or in controls of processes and equipment such as HVAC systems or autonomous vehicles are comprised of seamlessly integrated and interacting subsystems. It is difficult to analyze and comprehend the behavior of the entire system as a whole without first understanding the behaviors of the individual subsystems. Consequently, a starting point for analyzing a large system is to separate it into a set of smaller subsystems and analyze each of those as separate systems. This requires that we define artificial boundaries around each subsystem so that we can account for the matter, energy, and information that flow across those boundaries to interacting subsystems. In some instances, we have to make simplifying assumptions about those flows so that we can study the behavior of the subsystem within the boundary.

As we understand how the elements of a subsystem interact and behave within the boundary that we have applied, we can reset the boundaries to include other elements and subsystems, repeating the process until we understand the larger, more complex system. Subsystems may be interconnected in series, one following the other, or in parallel, or they may be nested within a larger subsystem. Understanding large systems by considering their simpler subsystems is an appropriate methodology as long as we recognize that each of the smaller subsystems is ultimately influenced by factors from the systems to which it is interconnected, and we study those interconnections when we rejoin the subsystems to form the whole.

All systems are bounded in space and time, so the first step in our analysis of a subsystem and its behavior is to define the spatial and temporal boundaries of the system, as well as the elements that are within the boundaries and the flows that cross the boundaries into and out of the system. Spatial boundaries typically relate to physical features, such as surfaces, and are easily recognized, but temporal boundaries are equally important and should be explicitly stated in the description of the subsystem.

In the case of a single object, the spatial boundary could be defined as the surfaces of the object. The flows across that boundary would be the thermal energy and moisture from the room environment, and the elements of interest would be the moisture content and dimensional stability of the object. The feedback loops would describe how these material elements respond to changes in room temperature and relative humidity. The temporal boundary of this small, simple system would be defined by a duration (hours, days, or months) and the state of the object at the beginning of the analysis, such as its moisture content in equilibrium with room conditions of 70°F (21°C) and 50% relative humidity.

A slightly more complex subsystem might be a building envelope that has evidence of a salt migration on the interior surface of an exterior wall. In this instance, the spatial boundary would probably occur at all of the surfaces of the exterior wall, including the portions of the wall that extend into the soil, so all of the potential moisture sources and sinks that might affect the moisture flows through the wall can be accounted for in the analysis. The temporal boundary would necessarily include a statement of the condition of the wall and exterior/interior conditions at initiation.

In the case of analyzing the interior environment of an entire building, we might define temporal boundaries by whether the building is open or closed for tours, or whether visitation is high or low on a given day.

Key Elements within a Boundary

Within the system boundary, the key elements are:

- one or more variables of interest—in a museum, examples of variables would include visitors, money, thermal energy, moisture vapor, or deterioration of an object;
- a process or accumulation (stock) of a variable that can be measured;
- flows of the variable(s) into, and out of, the stock or process; and,
- feedback loops, which are rules, signals, or information that affect the rates of flow into or out of a stock or process.

There are two types of feedback loops: balancing and reinforcing. Balancing feedback loops have a stabilizing effect on flows and stocks. For example, a balancing feedback loop will typically reduce inflow to an accumulator as the desired level is approached. Reinforcing feedback loops increase flows, often exponentially, and can have a destabilizing influence on stocks.[1] Anthropogenic climate change is an example of the synergy of several direct and indirect reinforcing feedback loops.

Interconnectedness of the Parts within the Boundary

Within the boundary, the key elements are interconnected through flows of material, energy, and/or information. For example, in analysis of building environments the typical material flows include moisture and dry air, but other "material" flows, such as visitors passing through the building, may need to be included. The typical energy flows of interest for building environmental management include thermal energy, light, and ultraviolet radiation, as well as electrical and fuel flows for mechanical systems. Information flows for building environmental management may include signals from devices such as thermostats and humidistats that automatically operate the HVAC system, as well as monitoring data, which may be used to influence decisions by conservators and facilities staff about system set points.

From a site or museum management perspective, it might be necessary to examine visitation as a system. The spatial boundary may be defined as the site entrance/exit, the museum building, or a specific exhibit.

1. Note that the descriptions for feedback loops do not use the terms "positive feedback" or "negative feedback."

The temporal boundaries might be operating hours, days of the week, specific holidays, or seasons of the year. The flows would likely include the visitors, tickets, and ticket sales, but could also include the number of staff guides, wait times, "dwell" times at specific exhibits, and overall duration of visit. Information flows could include advertising and promotion, visitor comments during the visit, formal visitor surveys during or after the visit, or sampling of visitor comments on social media. Looking at visitation from a wider perspective, we might also consider distinct subsystems that comprise a museum visit, such as automobile parking, public transportation, the museum café, the museum retail shop, and restroom facilities.

System Purpose or Function

The purpose or function of a system may seem to be self-evident, but system function and purpose must be clearly understood and stated in order to evaluate system performance.

An HVAC system for an office suite has the primary purpose of making the space comfortable and healthy for the occupants when they are present. Some building owners or tenants might add that this comfort should be accomplished with energy efficiency and others might add that energy efficiency should be accomplished with minimum carbon emissions in construction materials and energy consumption. A healthy environment may be defined by building codes with respect to particulate control, gaseous pollutants, relative humidity, and fresh air. Human thermal comfort, however, is highly individualized and dependent on physiological and psychological factors, so this fundamental objective will unlikely be met for all occupants at the same time. For this reason, the engineering profession has defined the objective for human thermal comfort in buildings as providing an environment that is neither too cool nor too hot for 90% of the population, given an assumed level of metabolic activity and an assumed type of clothing (ASHRAE 2021).

In the earlier example of visitation to a museum, the quality of a visitor experience could be defined by a number of measurable variables, all of which can impact a visitor's sense of satisfaction. A more fundamental question must be answered as well, that of how the museum and the visitor see the purpose or function of a visit to the museum, and how closely these understandings align. For complex organizational systems like museums, the system purpose may be effectively expressed as the organization's mission. How this is communicated to the prospective visitor is an important information flow.

"Open" and "Closed" Systems

An open system is self-organizing and can evolve or adapt to change and sometimes repair itself in order to continue to fulfill its purpose. This resiliency is a characteristic of "open" systems, which include biological, environmental, and organizational systems. Because of their inherent complexity and large scale, open systems may be influenced or somewhat managed, but are not controlled.

A "closed" system is designed and constructed to fulfill a specific function and its ability to adapt to change is limited. Closed systems include mechanical and physical systems such as automobiles, computer software, and building systems for environmental management (HVAC), fire protection, and security. Closed systems can be controlled for stability, but there have been notable failures, such as the 1986 nuclear reactor accident at Chornobyl in Pripyat in the Ukrainian Soviet Socialist Republic of the Soviet Union. Artificial intelligence or "machine learning" in closed physical systems provides opportunities for self-organization, evolutionary adaptation, self-learning, and self-repair, resulting in optimization in system performance.

Visualizing Systems

Two common methods to visualize systems and their structures are stock and flow diagrams and causal loop diagrams. Kim (2000) provides a detailed guide to stock and flow diagrams and causal loop diagrams, and stock and flow diagrams are used by Meadows (2008).

Stock and Flow Diagrams

Stock and flow diagrams, sometimes referred to as accumulator and flow diagrams, are useful tools for visualizing system structures where accumulation of a variable, such as thermal energy, moisture, visitors, or money, is of interest and measurable.

Stock and flow diagrams are illustrated using the elements shown in figure 2.1.

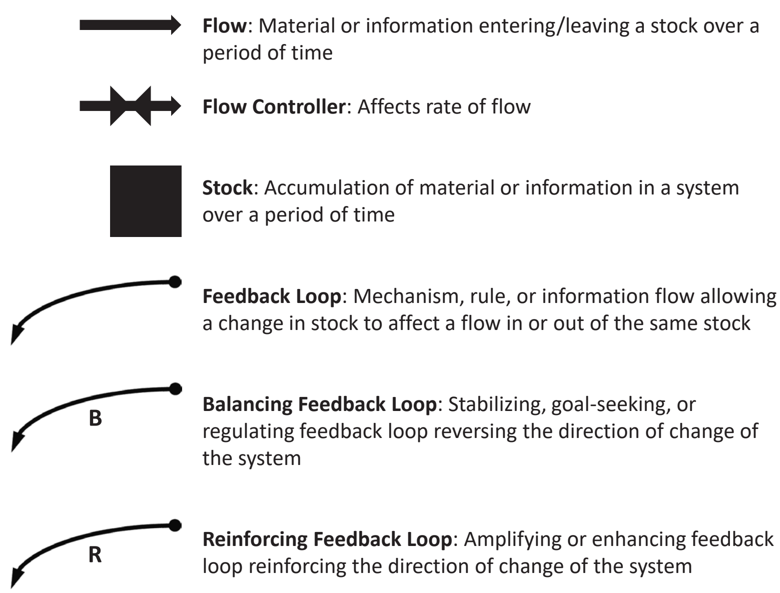


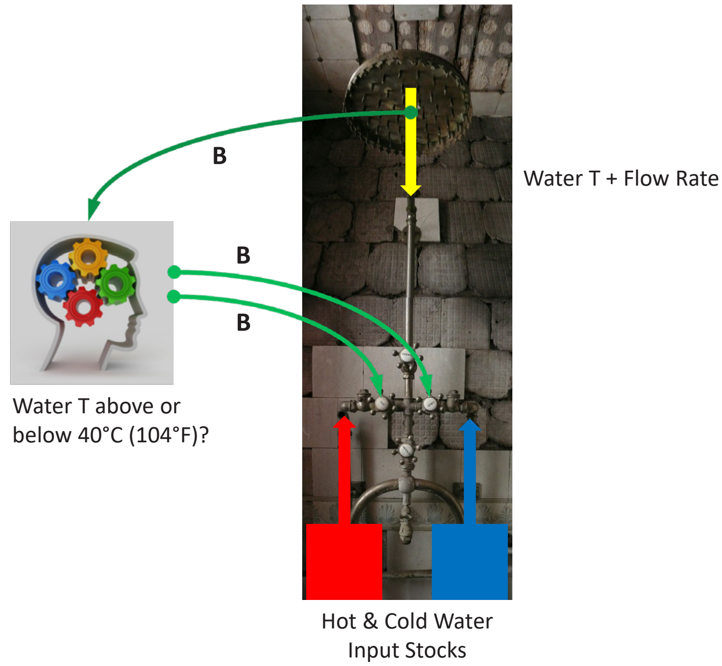
FIGURE 2.1. System elements used in a stock and flow diagram. Credit: Michael C. Henry

As an example, we can develop a simple system stock and flow diagram for the activity of taking a shower under steady-state equilibrium conditions. The spatial boundary can be set as the shower enclosure and the temporal boundary can be set as the interval when "steady-state equilibrium" occurs, that is, when the supply temperatures of the hot and cold water are constant, and the shower enclosure conditions are stable and comfortable for the person taking the shower.

The system elements for the stock and flow diagram might look like figure 2.2.

The key variables in this simple system might be the temperature of the hot and cold water, the temperature of the combined water flow at the shower head, the individual flow rates of the hot and cold water, or the opening of the valves (taps). The qualitative thermal comfort of the person taking the shower would be important as well. These could be plotted on a system trend graph, which by definition of a steady-state condition, would show little variation or change in these flows within the interval of the temporal boundary.

FIGURE 2.2. Steady-state equilibrium in the shower. Credit: Michael C. Henry



If we were to expand the temporal boundary but retain the spatial boundary, the hot water temperature is likely to start to drop because the hot water heater cannot keep up with the flow of hot water. This is no longer a steady-state condition, and the person taking the shower is likely to respond to the change by increasing hot water flow, decreasing cold water flow, or adjusting both flows. Comfort level will change as well. With all of these factors in transition, the trend graph becomes more dynamic and other factors may need to be added in order to understand the system, including the experience of the person taking the shower with the performance of the water supply, especially the hot water heater.

Next, we might put this same system in a more dynamic state by widening the temporal boundary to include the initiation of the shower on a cold winter day with the hot and cold water tanks remote from the chilly bathroom. Because of the expanded temporal boundary, we have to consider a number of new elements, previously ignored, as shown in figure 2.3.

By moving the temporal boundary to include the starting conditions, we need to consider additional flows taking place in the shower enclosure. For example, the person taking the shower will lose some body heat to the cold enclosure wall and to the surrounding cool air until the shower water can heat these two elements up. There will be a time delay before hot water arrives at the shower at a high enough temperature to have an effect on skin temperature. For purposes of a trend graph for this system we might want to know wall temperature and air temperature in addition to the variables previously considered. The time at which the person enters the shower will affect the comfort variable. The trend graph would likely show dynamic changes in all of the variables and is highly dependent on personal preference and experience with the shower as a system.

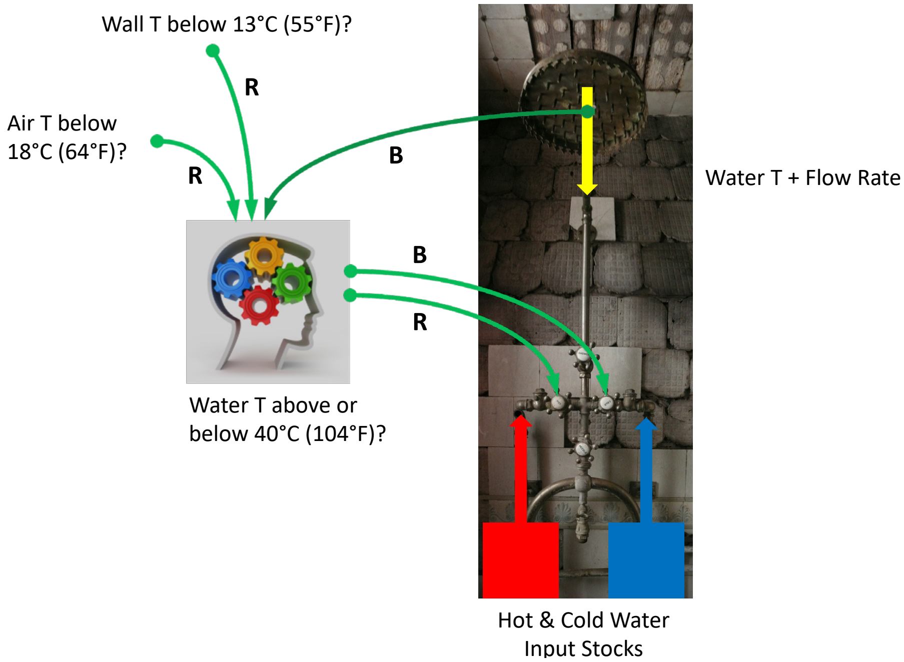


FIGURE 2.3. Transient dynamic equilibrium in the shower. Credit: Michael C. Henry

Causal Loop Diagrams

Causal loop diagrams show the interconnection of balancing and reinforcing feedback loops and processes. The graphical language of causal loops is illustrated in Kim (2000).

For our example of a thermostatically controlled heater and a room, the casual loop diagram might look like figure 2.4.

However, our causal loop diagram only illustrates the loop governing the heater; other factors, such as outside temperature and heat loss through the walls, will also affect the room temperature.

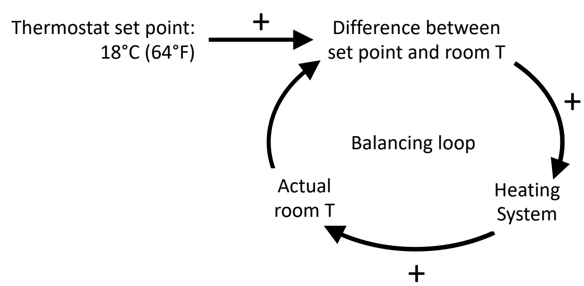


FIGURE 2.4. Causal loop diagram for a room with thermostatic heating. Credit: Michael C. Henry

System Behavior—Events, Patterns, and Trend Graphs

In performing its purpose or function, a system will exhibit a time-based, dynamic response; this is referred to as system behavior. Most system behaviors are nonlinear and complex, but some systems behave simply and predictably, such as the binary on-off action of thermostatic control in response to changes in temperature. In the overall process of heating or cooling a room, the thermostat is one of many interconnected subsystems that include the exterior climate, heat and moisture flows through the building envelope, response of the heater or furnace, and room occupants and their metabolic activities.

Behavior patterns can be seen in trend graphs, sometimes called behavior over time (BOT) diagrams. Trend graphs allow us to identify system behavior and the possible relationship of variables within a system.

Trend graphs of temperature and relative humidity in a museum are used to monitor environmental conditions in collections and to identify whether or not the closed system of the building and the mechanical system are maintaining the interior environment within desired limits, as in figure 2.5.

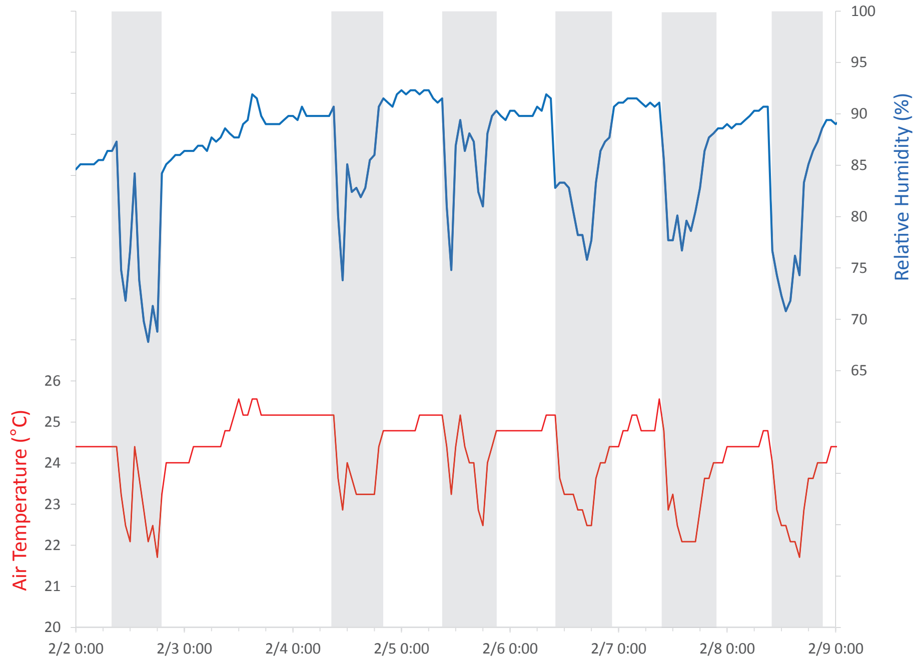


FIGURE 2.5. Trend graph of interior air temperature and relative humidity with shading indicating operation of the air-conditioning system (data courtesy of Franciza Toledo).

Understanding System Behavior

The variables in trend graphs are critical to their usefulness in understanding system behavior and must be carefully selected so that we might link cause and effect in system behavior. System behavior is apparent as measurable or observable patterns of events over time. Typical system behaviors can be linked to aspects of the system structure, particularly feedback loops. Meadows (2008) and Kim (2000) provide numerous examples of system structures and typical resultant system behaviors.

In the above example of the thermostat in a room, room temperature is the resultant behavior of the system, but the thermostat set point and outside temperature data were also critical to our interpretation and understanding of how well the system was performing. Although the example is simplified, we can conclude that in order to fully understand system behavior, it is important to show other influences, coincident in time with the system behavior. For a real-world version of the example, other measurable information, such as the on-off cycling of the heating/cooling system, occupancy of the room, and opening of any doors to the room would add further depth to our analysis and understanding.

Systems Thinking

We are surrounded by, and interact with, a large set of open and closed systems. In order to understand how these systems affect us, and perhaps to influence a system for some benefit or improvement, we must be proficient in the soft methodologies of systems thinking.

In the introduction to *Thinking in Systems: A Primer*, Diana Wright writes:

"Today, it is widely accepted that systems thinking is a critical tool in addressing the many environmental, political, social, and economic challenges we face around the world. Systems, big or small, can behave in similar ways, and understanding those ways is perhaps our best hope for making lasting change on many levels… Systems thinking will help us manage, adapt, and see the wide range of choices we have before us. It is a way of thinking that gives us the freedom to identify root causes of problems and see new opportunities." (Meadows 2008)

Systems thinking has been defined as:

"… a discipline for seeing wholes. It is a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static 'snapshots.'" (Senge 2006)

Therefore, systems thinking is a way of looking at, and understanding, the pattern of behavior of an environment, organization, or mechanism as a system so that we may identify ways to influence or alter the system's structure for improved behavior results and outcomes.

Systems thinking was first applied in two seemingly unrelated fields, biology and control theory, to understand the behavior of complex systems such as the environment or organizational operations. Keene (2002) describes how systems thinking may be applied through either "hard" or "soft" methodologies, the former utilizing mathematical modeling and quantitative analysis to predict system behavior and the latter utilizing a qualitative approach. Both methods employ abstract diagrammatic models that provide insights into how real-world systems may behave in response to change.

The iceberg model (fig. 2.6) is a way of illustrating the depth and potential leverage of systems thinking. In the iceberg model:

- events are what we observe or experience on a day-to-day basis. In a museum, this might be damage to an object or high relative humidity in a gallery;
- patterns are events that can be seen as trends or recurrences. Damage patterns might be seen among objects of the same material, and trends may be seen in damage over time;
- systems structure is the organization of a system that produces the behaviors that result in the observed patterns or trends in events. With respect to collection, damage would be the result of a deterioration system or process;
- mental models are what we think about how the world and its systems work. These models may have strong congruence with reality but fail to account for complexity and nonlinearity in its systems and their behaviors.

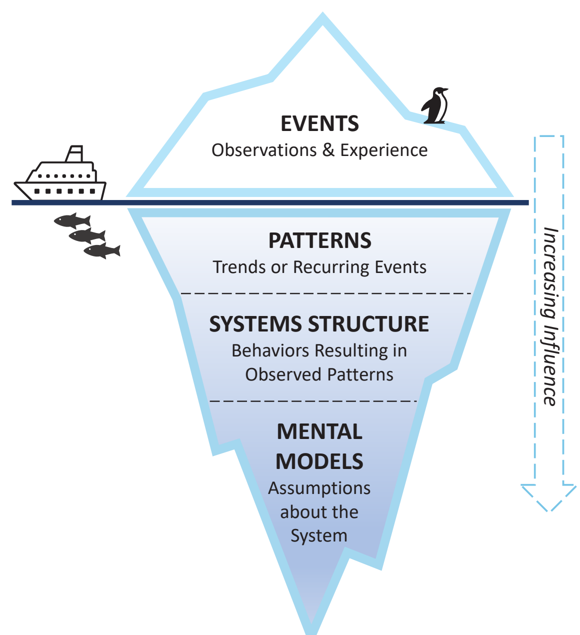


FIGURE 2.6. The iceberg model of systems thinking (after illustration from the Donella Meadows Project).

Events happen in real time, and extreme events can capture our attention, distracting us from noticing more subtle events and patterns that are potentially significant. Today, the immediacy and volume in which irrelevant and trivial data are delivered to us can prevent us from seeing or recognizing patterns and trends in information that are important. To see these patterns, we must "stand back" to view events in a wider time scale, and possibly in larger spatial dimensions as well.

Systems Thinking for Open Systems in Cultural Heritage

Systems thinking is easily applied to closed systems such as those for environmental management in museums. Systems thinking can also be applied to the complex, open systems that are also encountered in a museum, which include the following elements or combinations thereof:

- Institutional and organizational operations
- Visitor flows and visitor experience/satisfaction
- Deterioration of collections due to environmental conditions
- Funding and cash flows
- Building envelope and environmental management systems performance

Numerous resources discuss the application of systems thinking methodology. Both Meadows (2008) and Kim (1999, 2000) have case studies and examples of systems, systems structures, and systems thinking that apply to the environment, business, and economics.

Senge (1990) identifies systems thinking as the fifth, and cornerstone, discipline among five "competent technologies" that build and sustain learning organizations.

Keene (2002) presents a systems thinking methodology that employs "rich picture" conceptual models of complex open systems in museums. Keene's "rich picture" conceptual models focus on issues, rather than on the processes and flows of structural models.

Regardless of the methodology employed, systems thinking is essential to improving understanding and managing conservation in museums, including collections environments.

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TECHNICAL NOTE 3: PSYCHROMETRIC PROCESSES FOR ENVIRONMENTAL MANAGEMENT

Vincent Laudato Beltran

Introduction

Adapted from a chapter in *Environmental Management for Collections: Alternative Preservation Strategies for Hot and Humid Climates* (2015), this technical note describes basic psychrometric processes—heating, cooling, dehumidification, and humidification—that may be used as part of an overall interior environmental management strategy. It will demonstrate how a psychrometric chart can be used to depict temperature and relative humidity conditions of a given space (e.g., galleries, storage, display case microclimates), show target ranges for conservation and thermal comfort, and identify the psychrometric processes needed to achieve these targets.

The Psychrometric Chart

Psychrometrics is an engineering field focused on the physical and thermodynamic properties of gas-vapor mixtures, the most common mixture being water vapor and air due to its relevance for heating, ventilating, and air-conditioning (HVAC) engineers. A psychrometric chart is a graphical tool that represents the interrelationships among these thermodynamic properties of moist air. This chart is produced for a specific barometric pressure or elevation, accounting for changes in air density. Standard and simplified versions of the psychrometric chart are shown in figure 3.1, with both relating three common psychrometric properties:

- *Temperature*: measure of hot or cold air as recorded by a typical thermometer (also known as dry bulb temperature), and shown on the x-axis of the psychrometric chart in units of degrees Celsius (inch-pound: degrees Fahrenheit).
- *Humidity Ratio*: this relates the masses of water vapor to dry air, and provides a measure of the total moisture content of the air. Also known as the mixing ratio, this variable appears on the y-axis of the psychrometric chart in units of g of water per kg of dry air (inch-pound: grains of water per pound of dry air). Humidity ratio is also closely connected to dew point temperature, the temperature at which an air mass will reach saturation and condense to liquid. To determine dew point temperature, extend a line from a humidity ratio value on the y-axis until it intersects the saturation line (100% RH), at which point extension of a vertical line to the x-axis indicates the associated dew point temperature.
- *Relative Humidity*: the percent ratio of water vapor pressure to the theoretical water vapor pressure of saturated air for a given temperature. If the dew point temperature and the temperature of an air mass are nearly equal (note that dew point temperature is always less than or equal to air temperature),

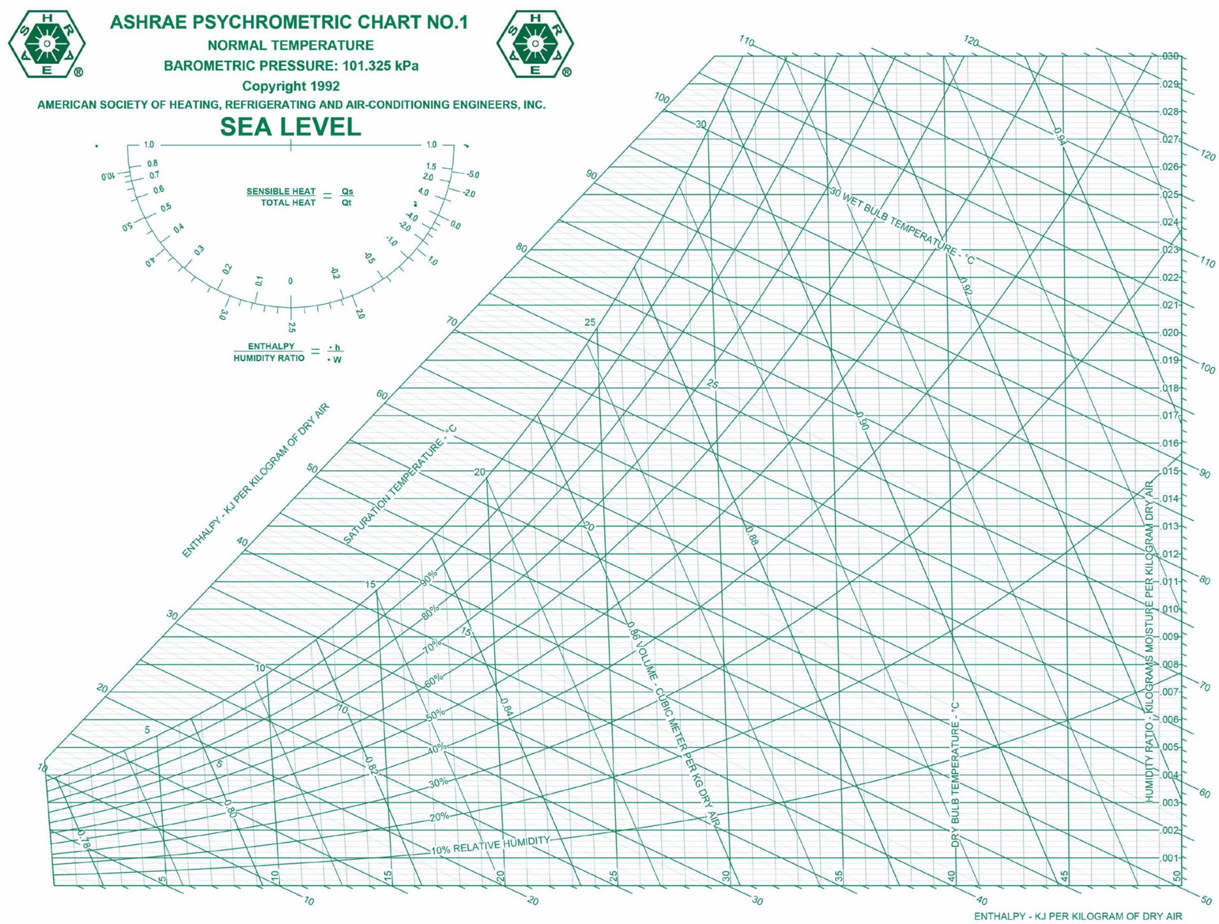
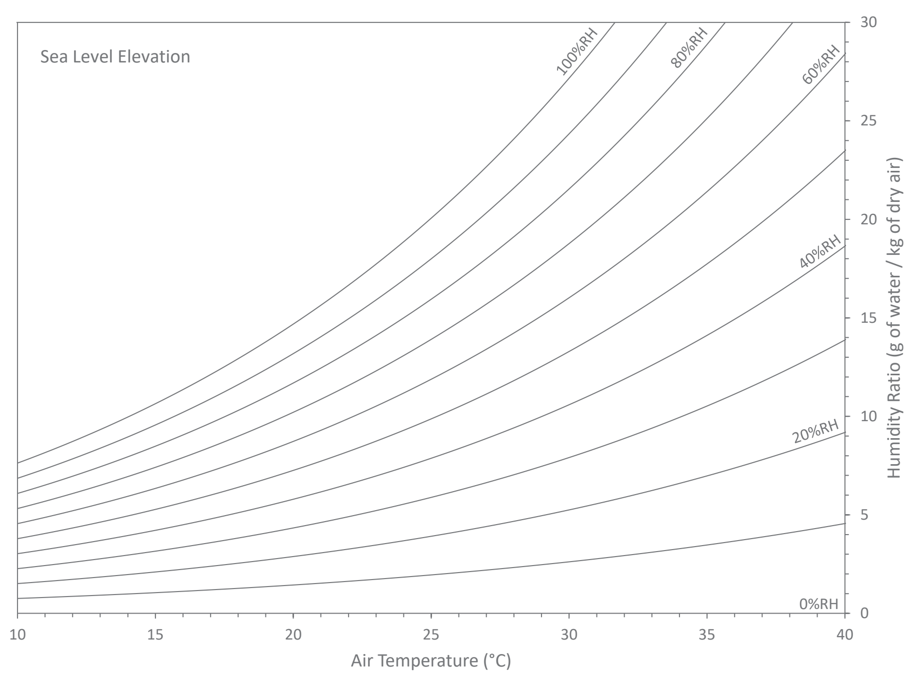


FIGURE 3.1A. Standard psychrometric chart for sea level elevation (chart 1). © ASHRAE, www.ashrae.org

FIGURE 3.1B. Simplified psychrometric chart for sea level elevation. Credit: Vincent Laudato Beltran



relative humidity will be near 100%. Relative humidity is shown on the psychrometric chart by isohume lines curving upward from left to right, with the uppermost curve representing the saturation line.

As observed in the standard version in figure 3.1a, other properties shown on the psychrometric chart include dew point temperature, wet bulb temperature, enthalpy, specific volume, and sensible heat ratio.

One use of the psychrometric chart is to determine graphically the properties of an air mass through the knowledge of only two variables—temperature and relative humidity are the most commonly measured—for a fixed barometric pressure or elevation. (Note that psychrometric charts prepared for sea-level elevation can be applied to elevations at or less than 600 meters; above this threshold, users should employ a psychrometric chart relevant to the elevation of the site.) The following sections also demonstrate how a psychrometric chart depicts an existing or target environment, as well as the outcome of applying psychrometric processes to alter an environment from an initial state point (defined by the initial set of environmental conditions) to a new state point.

The psychrometric chart can be an influential tool for visualizing temperature and relative humidity data in the context of environmental guidance for collection preservation and the psychrometric processes required to meet these environmental specifications. Further, familiarity with the psychrometric chart among technical staff can facilitate communication between facilities staff/HVAC engineers and collection care professionals, and guide collective decision-making on appropriate environmental management strategies.

Plotting Environmental Conditions

Paired measurements of temperature and humidity ratio can be plotted on a psychrometric chart. This dataset will produce a cluster of points that denote its environmental range, as well as regions of high and low density (contour lines can be plotted to better delineate regions of varying data density). Data subsets or separate datasets (e.g., seasonal, pre-/post-system installation, interior/exterior) can also be plotted to see how they compare temporally and/or spatially (fig. 3.2). Points representing statistical values obtained from a dataset can be shown on the psychrometric chart to describe the dispersion of data or define representative environmental conditions without presenting all data points.

Target Ranges of Environmental Conditions

The range of interior environmental conditions that are acceptable for collections conservation and/or thermal comfort can be illustrated on the psychrometric chart as environmental targets. The target and its boundaries can be defined by a set point or average value for temperature and relative humidity, bounded by acceptable limits in variations from these values. Alternatively, the environmental target can be defined by establishing maximum and minimum range limits.

While meeting the thresholds for the most precise levels of environmental control may be technically feasible, it is essential to balance the microbial, mechanical, and chemical risks to the collection and the building in which it is housed. The temperature and relative humidity conditions necessary to meet a narrow classification may not be advisable if the target conditions differ significantly from the historical means of temperature and relative humidity to which the object or collection was acclimatized. Further, use of

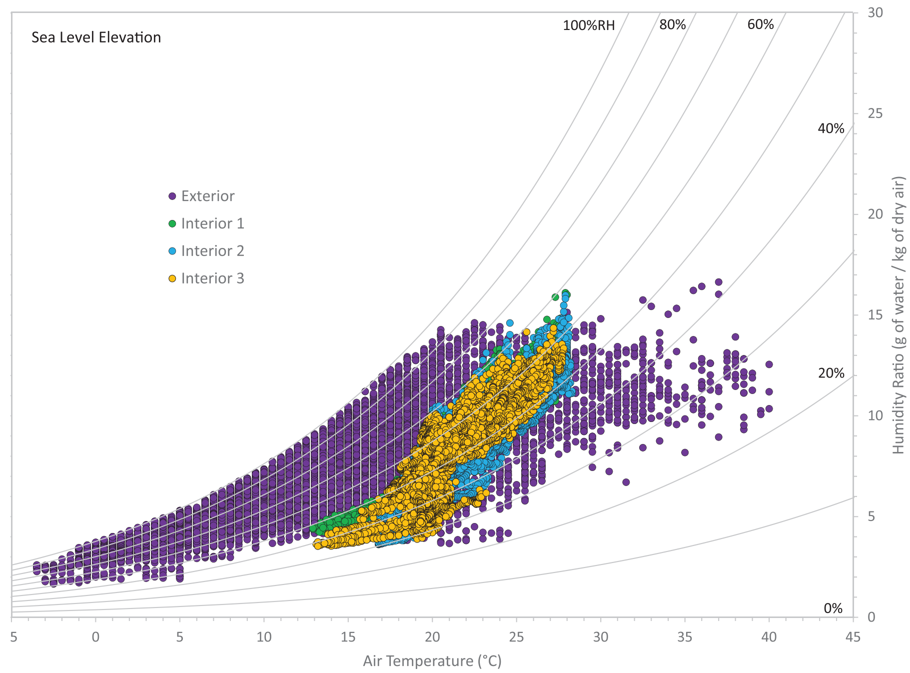


FIGURE 3.2. Psychrometric display of exterior and interior environmental data. Credit: Vincent Laudato Beltran

such a narrow strategy may ultimately prove to be economically and environmentally unsustainable, and may pose a risk of damage to the envelope of historic buildings. Depending on the damage potential from microbial, mechanical, and chemical risks, focus may be on environmental strategies that directly address the most severe risk, while accepting less precise environmental control with respect to secondary risks. Similarly, display cases can be used to establish specific microclimates for high vulnerability objects, while more robust objects remain subject to a wider environmental range. In practice, the selection of an appropriate environmental classification is also influenced by building envelope performance, opportunities for passive strategies, and complexity of the mechanical strategy. Figure 3.3 depicts two environmental control classes proposed by the temperature and relative humidity specifications in the 2019 ASHRAE chapter "Museum, Galleries, Archives, and Libraries," and based on an annual average of 42% RH and 70°F (21°C).

The psychrometric chart can be used to present the environmental conditions considered acceptable for thermal comfort, recognizing that the perception of comfort will vary among individuals. ANSI/ASHRAE's Standard 55-2020: Thermal Environmental Conditions for Human Occupancy defines psychrometric zones of thermal comfort based on laboratory and field surveys of occupant perceptions of the environment. In figure 3.4, acceptable thermal comfort zones are delineated on the psychrometric chart for a metabolic rate of 1.3 met, a clothing insulation factor of 0.65 clo, and air speeds of 0.1 m/s (using the analytical comfort zone method) or 0.5 m/s (using the elevated air speed comfort zone method). (Note that the x-axis in figure 3.4 is now defined as maximum operative temperature, which is 0.5 dry bulb temperature + 0.5 mean radiant temperature; mean radiant temperature represents the area-weighted average temperature of surrounding surfaces.) The use of elevated air speeds can enhance the cooling effect for occupants and will expand the thermal comfort zone by allowing for higher acceptable maximum operative temperatures.

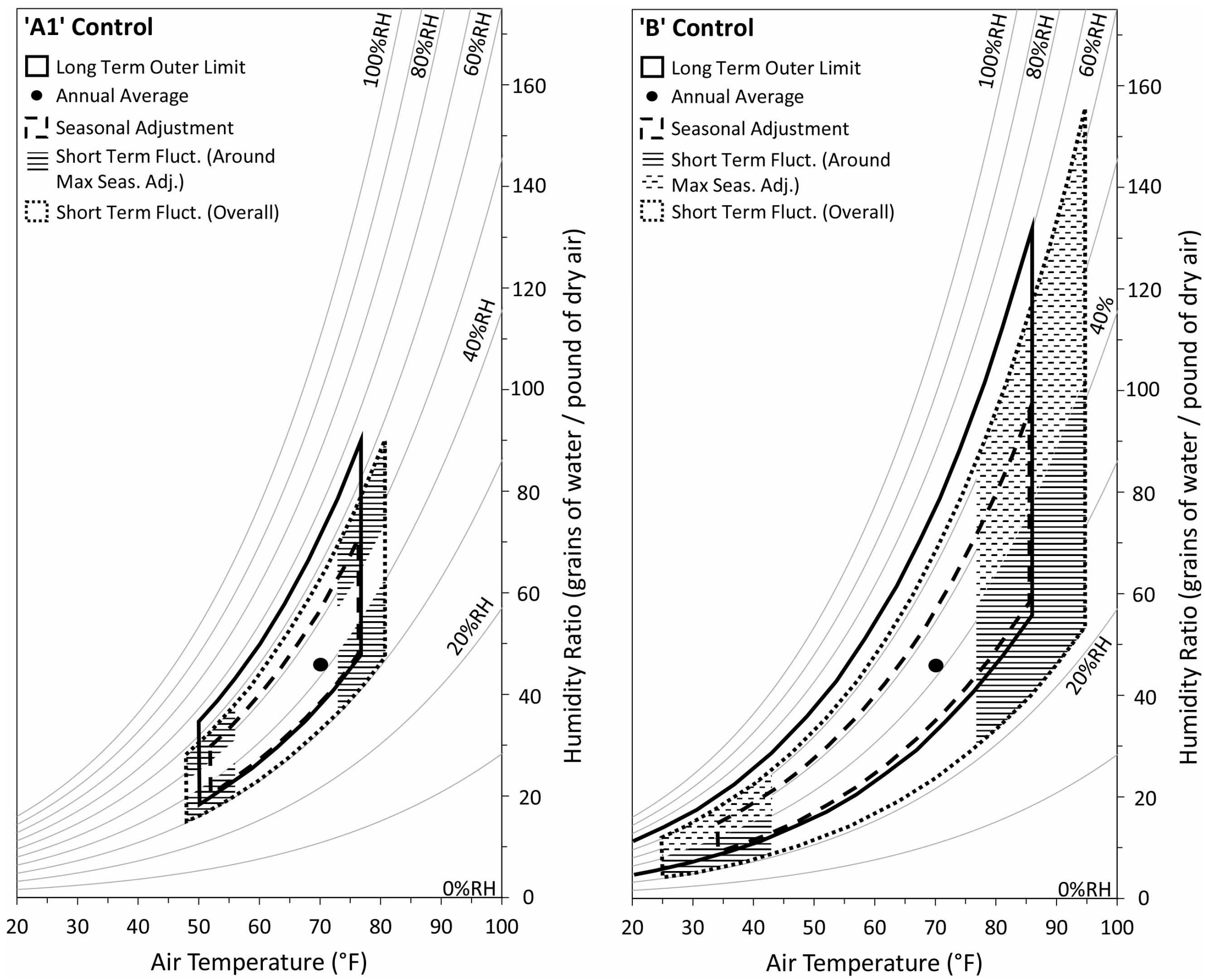


FIGURE 3.3. Environmental ranges of ASHRAE Class A1 (left) and B (right) environmental control based on annual averages of 42% RH and 70°F (21°C) (after ASHRAE 2019). Credit: Vincent Laudato Beltran

Displaying Psychrometric Processes

Psychrometric processes are depicted on the psychrometric chart by indicating an initial state point, defined by a set of environmental conditions, and the final state point following its application. As shown in figure 3.5, the net direction of change from the initial state point defines the overall psychrometric process. Horizontal and vertical changes of the state point denote changes in temperature and humidity ratio, respectively, while diagonal transitions represent a combination of the two adjacent processes. It should be noted that the actual psychrometric path taken by a nonmechanical or mechanical process may not be the straight line shown in the illustration. For the purposes of this technical note, these processes are illustrated simply as initial and final state points on the psychrometric charts, rather than as the actual process paths that might occur between the two state points.

When an initial environmental state is viewed on a psychrometric chart, the location of its initial state point can indicate limitations on the extent to which certain processes can be utilized. For example, while heating (shift to the right on the psychrometric chart) can be used to reduce relative humidity, its practical use

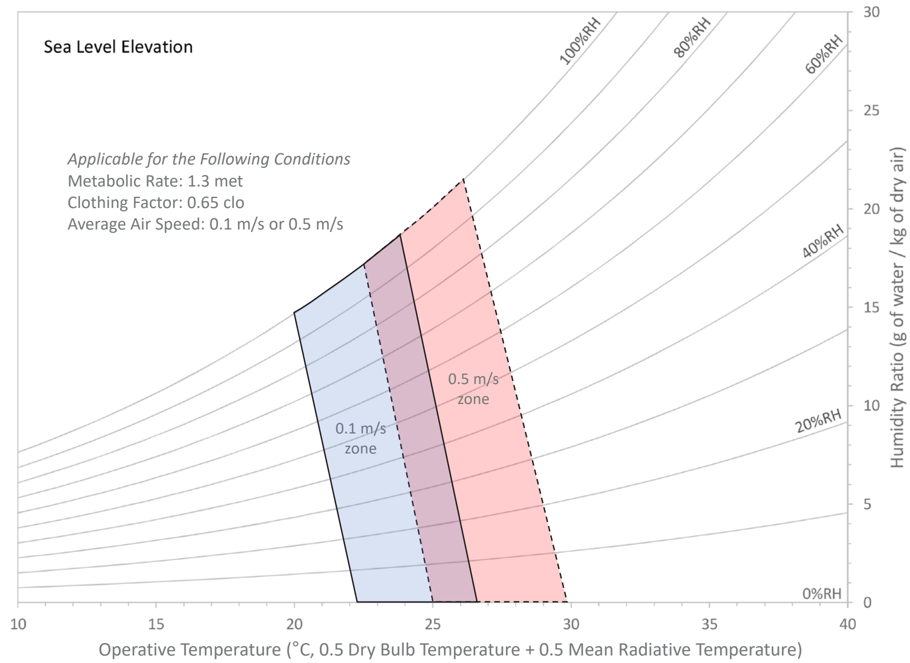


FIGURE 3.4. Acceptable occupant thermal comfort zones (after ANSI/ASHRAE 2021). Credit: Vincent Laudato Beltran

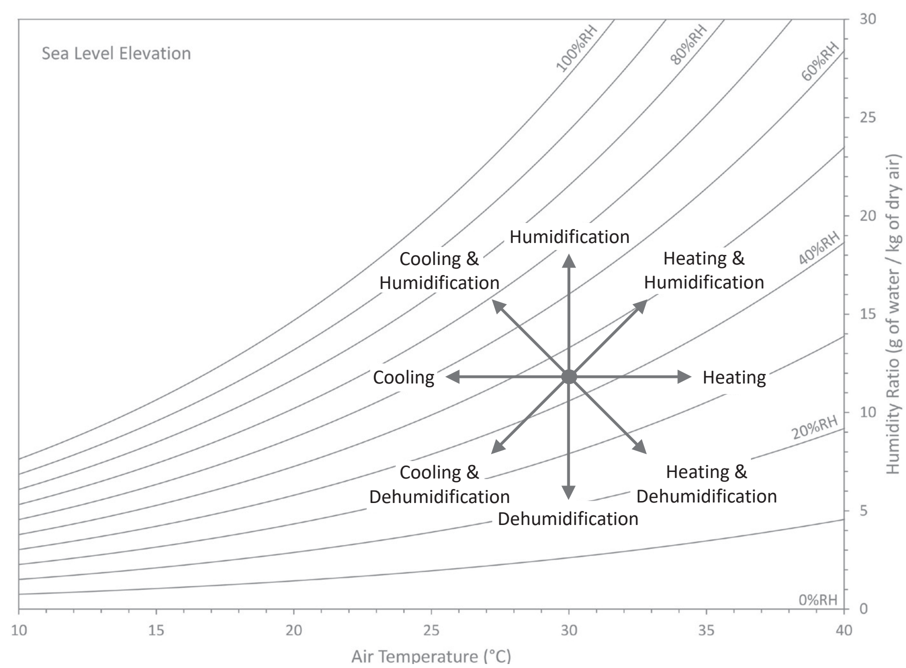


FIGURE 3.5. Directions of basic psychrometric processes with central circle representing the initial state point. Credit: Vincent Laudato Beltran

is limited by a threshold temperature above which the benefits of lower relative humidity are outweighed by other disadvantages (e.g., increased chemical deterioration, occupant dissatisfaction). Similarly, continued cooling (shift to the left) can lead to issues of condensation as conditions approach the saturation line (100% RH).

Psychrometric Strategies

There are two strategic approaches—nonmechanical and mechanical—to effecting change in an existing environment toward a target range of conditions. This section describes how both approaches can be presented on psychrometric charts.

Nonmechanical and Mechanical Strategies

Nonmechanical strategies are not psychrometric processes in the conventional engineering sense, but are methods that typically do not require energy and can be employed to reset the initial state point to more favorable conditions closer to, or within, the target zones. Nonmechanical strategies reduce the moisture and/or thermal energy gains to a space, can aid in limiting variations of relative humidity and temperature, and reduce energy consumption of mechanical environmental management strategies.

Examples of nonmechanical strategies include:

- Source moisture control
  - Gutters and downspouts
  - Intentional slopes and berms
  - Perimeter foundation drains
  - Joint sealants and weather stripping
- Source control of thermal energy
  - Lighter exterior colors or high emissivity coatings for exterior walls
  - Exterior awnings and shutters, and interior shutters and blinds
  - Light-filtering glazing or film (to existing glass)

In contrast, mechanical strategies consume energy and include the four basic mechanical processes—heating, cooling, dehumidification, and humidification—used in an environmental management system to modify the interior environment. Though not a psychrometric process, the mechanical process of ventilation is also described because of its ability to affect the interior environment.

Heating

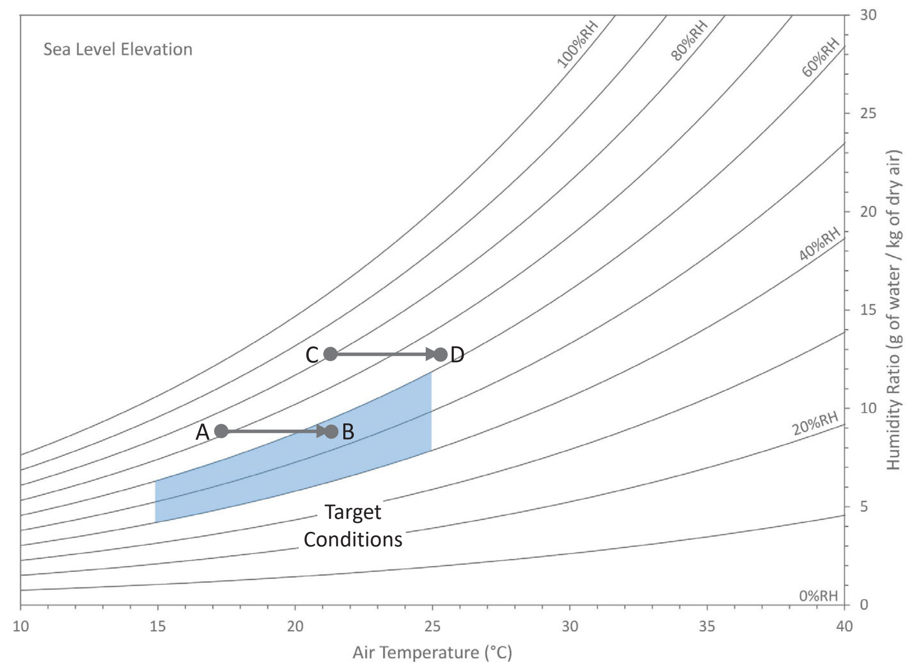
The process of heating warms the interior air and increases its capacity to hold water vapor, thereby reducing relative humidity. This psychrometric relationship is sometimes used intentionally to reduce relative humidity, a technique termed conservation heating or humidistatic heating (Staniforth and Hayes 1987). Since heating only serves to raise temperature, the humidity ratio of the air mass remains unchanged.

In figure 3.6, heating shifts the initial state point (A) to the final state point (B) within the environmental target range. While this psychrometric strategy may be counterintuitive in a hot climate, the use of limited heating can significantly lower relative humidity and protect against damage from microorganisms. Though heating also results in the shift from the initial state point C to the final state point D, the elevated humidity ratio of this air mass renders the heating process insufficient to bring the final state point into the target range of conditions. Thus, the use of additional psychrometric strategies or modified target conditions will be required.

Cooling

Cooling processes lower the air temperature, reducing the air's capacity to hold water vapor, and raise relative humidity. Cooling plays an important role in improving occupant thermal comfort in hot climates. However, in the absence of concurrent dehumidification, overcooling of an interior environment must be avoided, as this can raise relative humidity above target levels.

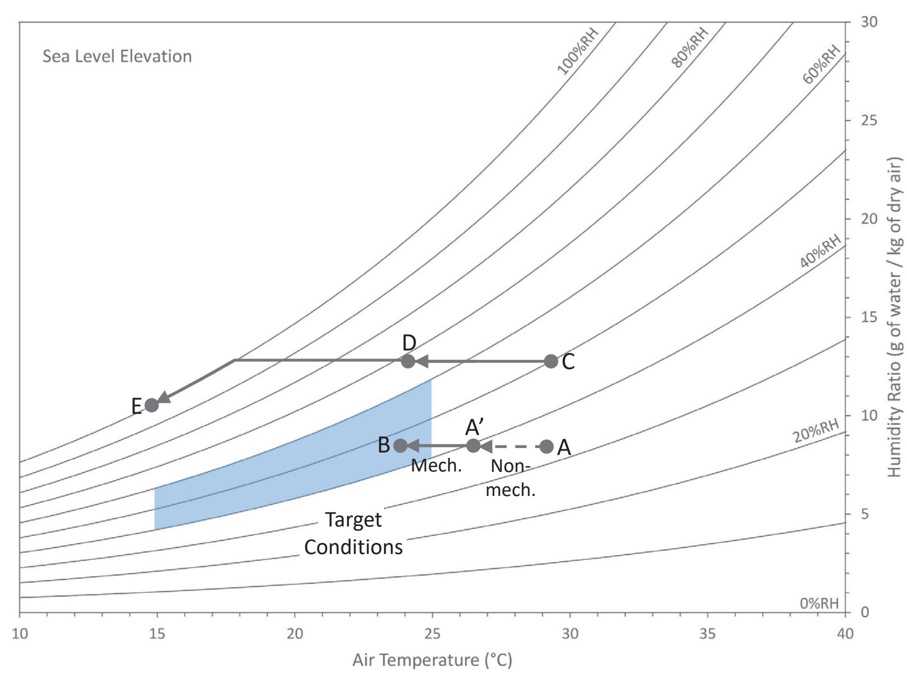
FIGURE 3.6. Implementation of a heating strategy. Credit: Vincent Laudato Beltran



Cooling will shift an initial state point to the left on the psychrometric chart, until saturation (100% RH) is reached. At saturation, continued cooling of an air mass moves the state point downward and to the left along the saturation line, lowering the humidity ratio of the air mass (process of dehumidification by cooling) until the target temperature is reached.

In figure 3.7, the A–A′–B process line shows the reset of initial interior conditions by nonmechanical source control of thermal energy (A–A′) followed by the application of mechanical cooling (A′–B), which brings the final state point within the environmental target range.

FIGURE 3.7. Implementation of a cooling strategy. Credit: Vincent Laudato Beltran



Cooling strategies for air masses with a high humidity ratio may be capable of satisfying the target temperature range, but unable to arrive within the target relative humidity range. In figure 3.7, the application of cooling processes the initial state point C to an intermediate state point D, which is outside of the target conditions. Further cooling of the intermediate state point D to the final state point E will result in dehumidification as moisture condenses from the air mass along the saturation curve, reducing both its humidity ratio and its temperature.

Dehumidification

Dehumidification removes moisture from the air, thereby reducing its humidity ratio and dew point temperature, and represents a key mechanical strategy for environmental management. As a consequence of dehumidification, relative humidity is decreased while temperature theoretically remains constant. Dehumidification is represented as a downward transition on the psychrometric chart. It should be noted that hot-humid air requires the removal of a larger amount of moisture than cool-humid air to achieve similar reductions in relative humidity; this is reflected on the psychrometric chart by the widening of isohumes (lines of constant relative humidity) with increasing temperature.

In figure 3.8, the A–A′–B process line shows the application of nonmechanical source moisture control (A–A′) followed by mechanical or desiccant dehumidification (A′–B). The dehumidification process shifts an intermediate state point (A′) to a final state point (B) within the environmental target range. As evidenced by the process from the initial state point C to the final state point D, the sole use of dehumidification for warm air masses may be insufficient to meet a specific environmental target range, necessitating the use of either additional psychrometric strategies or a modified target range of conditions.

Although figure 3.8 shows the dehumidification process as a straight-line state change without temperature change, the actual mechanical process path may be more complex. For example, dehumidification may be achieved by stepwise application of cooling and eating. In figure 3.7, the C–D–E process line shows an initial air mass (state point C) that is cooled to and along the saturation line (state point E), resulting in a reduction in both temperature and humidity ratio. Though not shown, it is common at this point to employ

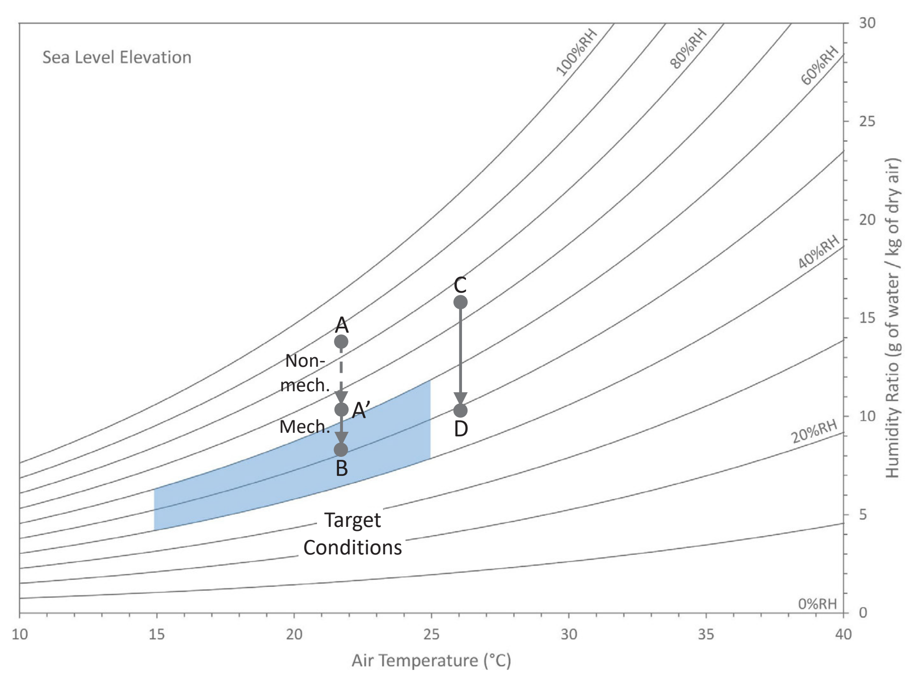


FIGURE 3.8. Implementation of a dehumidification strategy. Credit: Vincent Laudato Beltran

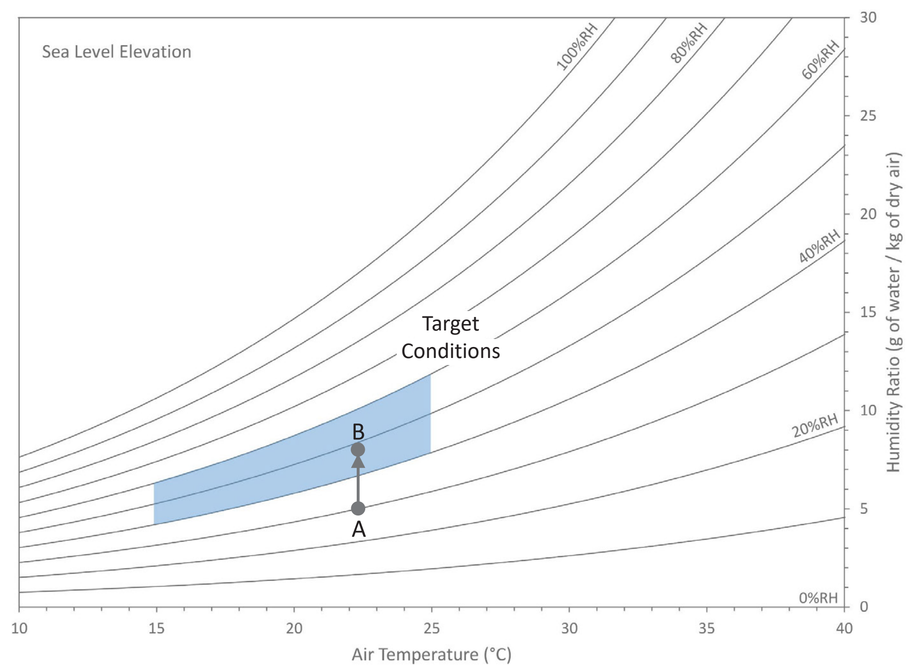
mechanical heating (or reheating), shifting the state point E to the right and bringing this air mass with a reduced humidity ratio within the target range.

Humidification

The process of humidification adds moisture to the air, increasing its relative humidity and humidity ratio while maintaining the same temperature. Humidification can be of particular importance during drier winter months in mixed and cold climates, when heating can result in low relative humidity conditions that may cause embrittlement or dimensional change in objects or result in occupant discomfort. On the psychrometric chart, this process results in an upward movement from an initial state point.

In figure 3.9, humidification shifts the initial air mass (state point A) to the final state point B within the environmental target range. In reality, the process of humidification will also affect the temperature of the air mass—evaporative humidification systems will slightly depress temperature, while steam humidification will slightly elevate temperature.

FIGURE 3.9. Implementation of a humidification strategy. Credit: Vincent Laudato Beltran



Ventilation: Dilution or Conservation Heating

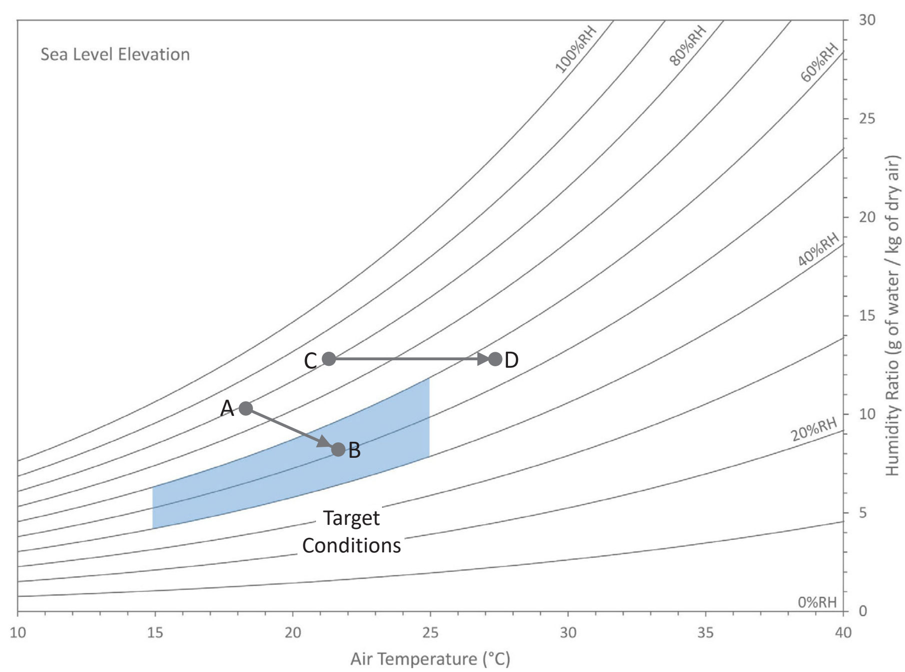
Ventilation is a process by which outside air is added to an inside space, displacing a portion of the existing air mass. Though not a psychrometric process, the mixing of interior and exterior air masses at different psychrometric states results in an interior air mass with environmental conditions between those of the initial air masses.

The ventilation process can be further categorized by its effect upon the interior environment. *Dilution ventilation* refers to the addition of lower humidity ratio air to a space in order to lower interior moisture content; in this case, the exterior and interior air masses have the same temperature but different humidity ratios. *Conservation heating ventilation* refers to the addition of warmer air to a cooler space in order to reduce relative humidity; the two mixing air masses have different temperatures but the same humidity ratio. While dilution ventilation and conservation heating ventilation should theoretically be illustrated on the psychrometric chart as vertical and horizontal lines, respectively, these exact circumstances rarely happen in practice, and the process lines will slope depending on differences in temperature and humidity ratio.

Ventilation is often achieved by mechanical means, such as fans, but can also be accomplished nonmechanically with natural ventilation, through either cross ventilation or stack effect. With either mechanical or nonmechanical strategies, the opportunity for dilution ventilation occurs when the exterior air has a lower humidity ratio than the interior air. The opportunity for conservation heating ventilation often occurs during the afternoon on clear, warm days.

Figure 3.10 illustrates the effects of ventilation on the psychrometric chart. Process line A–B represents dilution ventilation with the mixing of interior air (state point A) and exterior air (state point B) with different humidity ratios. With each successive air change, the initial interior state point A will shift closer to state point B, which resides within the target environmental conditions. Alternatively, the C–D process line indicates the potential limitations of ventilation as an environmental management strategy. In this example of conservation heating by ventilation, mixing of initially warm and high relative humidity interior air (initial state point C) with warmer and lower relative humidity exterior air (state point D) results in a shift toward state point D. Though the relative humidity of the interior air is decreased, conditions remain outside the environmental target range due to the high humidity ratio of both air masses.

FIGURE 3.10. Implementation of a ventilation strategy. Credit: Vincent Laudato Beltran



Limited use of conservation heating ventilation can result in a final state point that will require less subsequent mechanical dehumidification to achieve the target range of conditions. The effectiveness of ventilation is dependent on the seasonal or diurnal availability of exterior air with environmental conditions closer to or within the target range.

Summary

This technical note demonstrated how a psychrometric chart is used to depict a given environment as well as target ranges of environmental conditions for collections conservation and thermal comfort. Basic psychrometric processes used to alter the interior environment of buildings were described. Through the graphic presentation of these processes on the psychrometric chart, one can visualize how nonmechanical and mechanical strategies and their resulting change in interior environmental conditions relate to a nominal set of target ranges of conditions. Additionally, viewing these strategies on the psychrometric chart allows one to grasp the interdependence of the various environmental parameters and distinguish which parameters must be managed to achieve the target ranges.

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TECHNICAL NOTE 4: MUSEUMS AND THEIR EXTERIOR AND INTERIOR ENVIRONMENTS

Michael C. Henry, PE, RA

Introduction

The environmental conditions experienced by a building, and the occupants and objects inside the building, result from a complex interaction of natural climatic forces, site factors, building performance, building systems or services, occupancy, and use. By understanding how these forces and factors interact, we can identify measures to manage their impact on the interior environment, the building, and the collections. These measures will inform our preventive conservation strategies.

This technical note provides an overview of the interrelationship of the exterior forces and the factors that influence the interior environment of a museum building. However, this note is not intended to be a comprehensive treatment of these topics. Detailed technical guidance on climate and building envelope performance, and their effects on building interior environments, can be found in the 2019 ASHRAE chapter "Museum, Galleries, Archives, and Libraries."

Climatic Influences on the Building Environment

The documentation and characterization of climate and predictions of its daily manifestations as weather have long fascinated humankind. This interest continues to be necessary because climate and weather can determine our comfort/discomfort, our ability to conduct our activities, and our ability to satisfy our essential needs, such as food production.

Climate and weather are defined by measurable parameters of atmospheric conditions. These parameters include dry bulb temperature, moisture content as indicated by humidity ratio or dew point temperature (from which relative humidity is calculated), wind speed and direction, precipitation such as rain and snow, barometric pressure, and solar radiation. Over time, frequent measurement and statistical analysis of these variables yield sufficient data to identify relative differences in climate from season to season and from place to place. Typically, climatological information is presented as statistical summaries of empirical data for a specific parameter with time as the variable, for example, average monthly precipitation and mean daily high temperature (dry bulb). While helpful, statistical data do not convey the interrelationships of the various parameters that influence climate. As static values, the data do not indicate the extent to which the real-time values of these parameters, experienced as weather, are in a state of dynamic equilibrium.

For purposes of building design, climate is defined by the thermal and moisture (hygrothermal) loads that a climate imposes on a building. A good description of the characterization of climate established by *ASHRAE Standard 90.1-2016* is provided by Maekawa, Beltran, and Henry (2015). Currently, *ASHRAE Standard 169-2021* defines nine thermal categories (0 to 8) and three moisture categories (A to C), which are combined to classify distinct climate zones.

The thermal climate classification is determined by considering both annual heating loads (heating degree days, or HDD) and annual cooling loads (cooling degree days, or CDD). For example, Zone 3 climates have moderate annual heating and cooling loads that are nearly balanced while Zone 0 climates have high annual cooling loads and small annual heating loads. Moisture classifications of climates are determined by a more complicated sequence of quantitative criteria. These criteria include seasonal temperatures, annual precipitation, and seasonal distribution of precipitation.

The possible hygrothermal classifications for climate zones are listed in table 4.1.

TABLE 4.1.

Combined thermal and moisture climate zones (after ANSI/ASHRAE Standard 169-2021). Credit: Vincent Laudato Beltran

		Moisture Zone		
		A: Humid	B: Dry	C: Marine
Thermal Zone	0: Extremely Hot	0A: Extremely Hot-Humid	0B: Extremely Hot-Dry	
	1: Very Hot	1A: Very Hot-Humid	1B: Very Hot-Dry	
	2: Hot	2A: Hot-Humid	2B: Hot-Dry	
	3: Warm	3A: Warm-Humid	3B: Warm-Dry	3C: Warm-Marine
	4: Mixed	4A: Mixed-Humid	4B: Mixed-Dry	4C: Mixed-Marine
	5. Cool	5A: Cool-Humid	5B: Cool-Dry	5C: Cool-Marine
	6: Cold	6A: Cold-Humid	6B: Cold-Dry	
	7: Very Cold			
	8: Subarctic			

Figure 4.1 illustrates the current climate zones in the United States as defined by the ASHRAE climate classification. It should be noted that thermal Zone 0–Extremely Hot does not occur in the continental United States.

Figure 4.2 shows the current climate zones worldwide as defined by ASHRAE. For ease of comparison, table 4.2 provides a list of ASHRAE climate zones and examples of cities worldwide that are in each classification.

In preventive conservation, characterization of climate gives us clues as to the environmental management challenges we might expect with collections and buildings. For example, a Zone 2A Hot-Humid climate can be expected to host microorganisms and insects throughout the year, while the Zone 6B Cold-Dry climate might have a wide range of relative humidity and the potential for material desiccation due to extremely low relative humidity in winter. The Zone 4A Mixed-Humid climate would be expected to present thermal characteristics of both cool and warm seasons, with wide-ranging seasonal relative humidity.

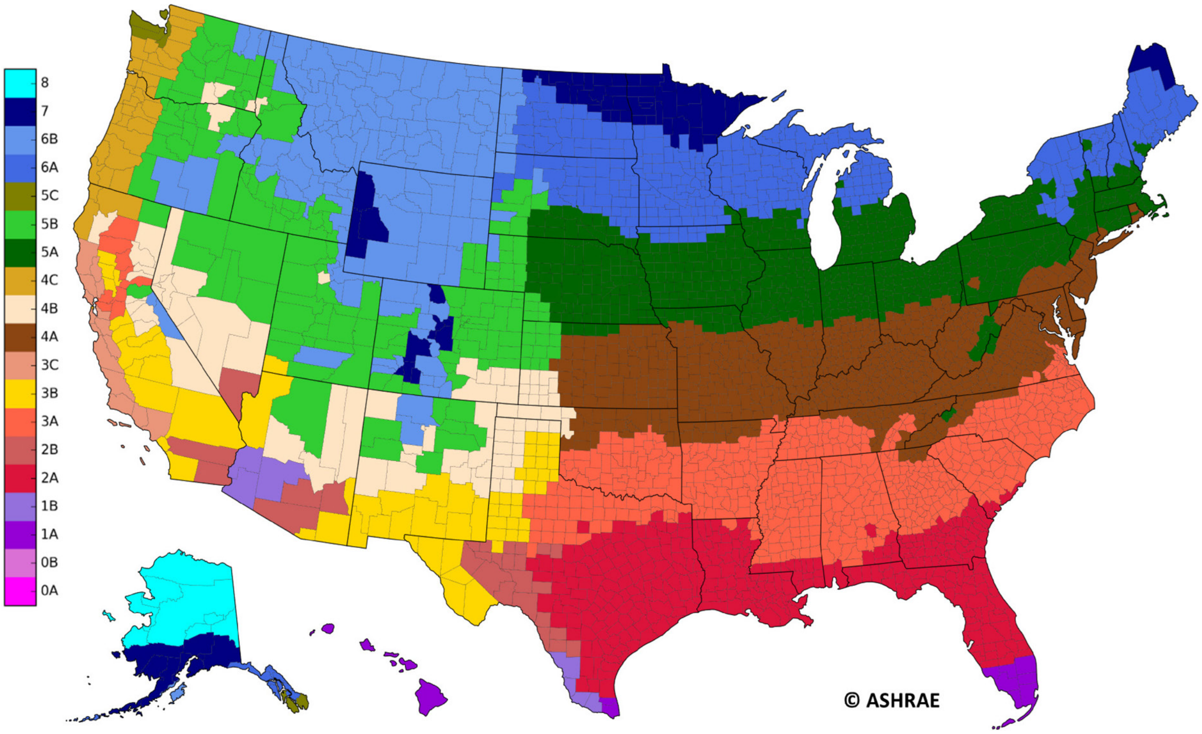


FIGURE 4.1. Climate zones for United States counties (ASHRAE Standard 169-2021). © ASHRAE, www.ashrae.org

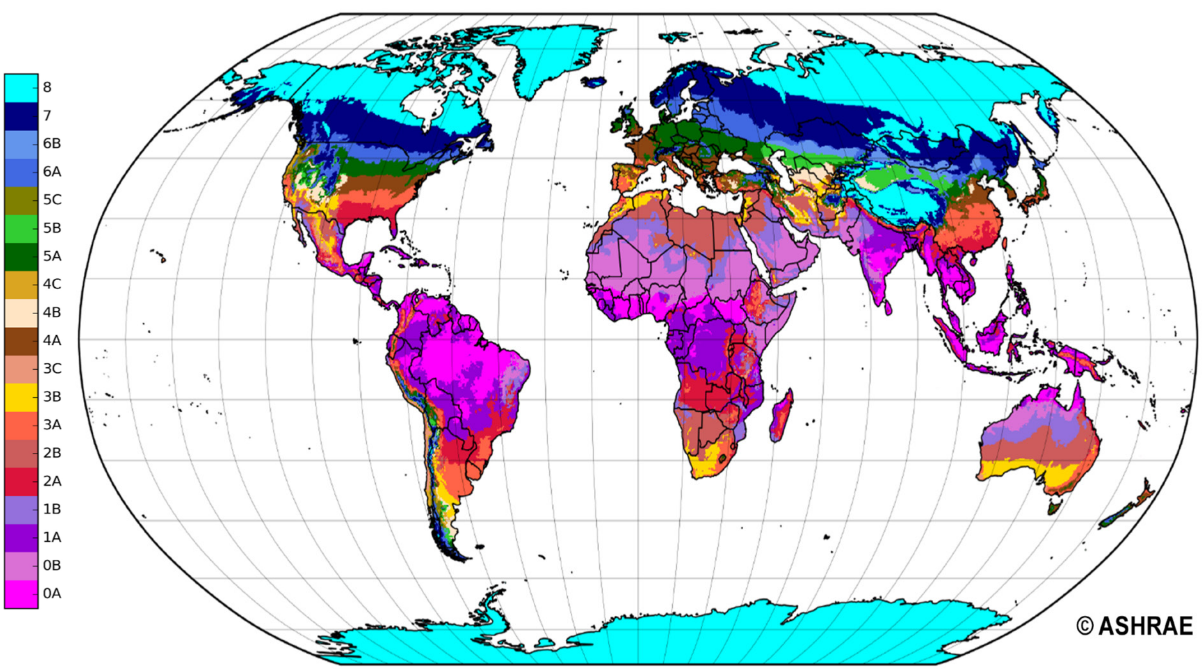


FIGURE 4.2. Climate zones worldwide (ASHRAE Standard 169-2021). © ASHRAE, www.ashrae.org

TABLE 4.2.
Climate zone classifications for select cities (after ANSI/ASHRAE Standard 169-2021). Credit: Vincent Laudato Beltran

Thermal Zone	Moisture Zone			No Moisture Zone Designation
	A: Humid	B: Dry	C: Marine	
0: Extremely Hot	Recife (Brazil) Bombay (India) Manila (Philippines)	Ahmedabad (India) Niamey (Niger) Riyadh (Saudi Arabia)		
1: Very Hot	Hanoi (Vietnam) Mombasa (Kenya) Miami (USA)	Luxor (Egypt) Lahore (Pakistan) Dakar (Senegal)		
2: Hot	Sao Paulo (Brazil) Haifa (Israel) Dallas (USA)	Cairo (Egypt) Lima (Peru) Phoenix (USA)		
3: Warm	Sydney (Australia) Shangai (China) Atlanta (USA)	Athens (Greece) Tehran (Iran) Los Angeles (USA)	Nairobi (Kenya) Cape Town (South Africa) San Francisco (USA)	
4: Mixed	Beijing (China) Paris (France) Philadelphia (USA)	Kabul (Afghanistan) Adelaide (Australia) Albuquerque (USA)	Brussels (Belgium) Santiago (Chile) Portland (USA)	
5. Cool	Toronto (Canada) Berlin (Germany) Chicago (USA)	Rio Gallegos (Argentina) Taiyuan (China) Denver (USA)	Esquel (Argentina) Corum (Turkey) Bremerton (USA)	
6: Cold	Oslo (Norway) St. Petersburg (Russia) Minneapolis (USA)	Chifeng (China) Bozeman (USA)		
7: Very Cold				Ulaanbaatar (Mongolia) Anchorage (USA)
8: Subarctic				Yellowknife (Canada) Fairbanks (USA)

In addition to hygrothermal loads, climate presents precipitation loads and wind loads, which will also affect the building and its interior environment. We can use these to assist in our management of buildings and their interior environments. For example, rainfall data are useful in understanding when bulk moisture problems might occur from storm water runoff. Wind data are helpful in understanding the potential for naturally ventilating a building as well as the potential for infiltration of outside air when the building is closed.

Figure 4.3 illustrates the rain exposure zones in North America.

In order to understand the effects of the climatic macroenvironment of a building and its collections, we must recognize the dynamic and synergistic aspects of individual climate loads. For example, wind and coincident precipitation will affect absorption of rain water by porous exterior materials. In another case, available solar radiation and wind will affect drying of the building surface and surrounding site.

Solar radiation, which includes visible, infrared, and ultraviolet regions of the electromagnetic spectrum, is of interest because it is a source of thermal energy and can also damage collections and building materials.

Anticipating Climate Change

Published climate data sets typically include the most recent 20 to 30 years of data and provide a historic perspective on what we might reasonably expect in climatic behavior at present. However, the historical data may obscure recent trends that are occurring as part of climate change. As a consequence, we must also consider climate change projections if we are to plan for future environmental risks to cultural heritage.

The United Nations Intergovernmental Panel on Climate Change has determined through science-based evidence that climate and the resultant weather are changing as a result of human activities such as consumption of fossil fuels and production of carbon dioxide (IPCC 2023). At a national level, countries have projected regional climate change and the implications for natural resources and human activities. Examples include the United States (USGCRP 2014), Australia (Climate Change In Australia 2023), and collectively the European Union (Climate Action 2023).

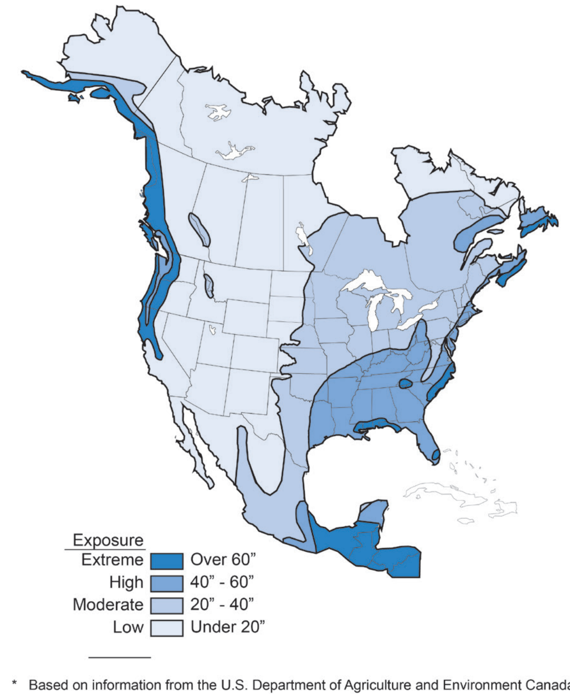


FIGURE 4.3.
Rain exposure zones in North America (Lstiburek 2016).

As stewards of cultural heritage, it is important that we take the long view with respect to the potential effects of climate change on built and moveable heritage. This is especially true when planning for improvements to building enclosures and systems where the expected service life of an improvement is sufficiently long that climate change will affect performance, efficiency, or functionality. Understanding the causes of climate change is also important if we are to implement environmental management strategies that reduce rather than increase the rate of anthropogenic climate change.

Physical Context and Its Influence on the Building Environment

Climate and weather provide the large natural forces that define the macroenvironment of buildings. These large-scale effects are amplified or diminished by the location of the building and its natural and human-made contexts.

In preventive conservation, it is important that we recognize how locational factors can moderate or amplify larger-scale climatic and weather effects, especially those effects that have a strong influence on the interior environment. Examples of the effects of location and its possible influence on the building environment include:

- topography, which influences wind and solar radiation;
- soil permeability and off-site watersheds, which influence surface water runoff and soil moisture; and,

- proximity to natural bodies of water, which can influence wind, temperature, atmospheric moisture, and solar radiation due to cloud cover.

Large-scale human activities can influence the local environment. Rural sites may be affected by nearby agricultural activities that might disperse soil particulates from disturbed fields, particulates from agricultural harvesting or burning, contamination from application of herbicides, pesticides and fertilizers, and irrigation residue/overspray. Sites in suburban environments may experience increased vehicular and industrial pollution, deposit of construction dust, and high surface water runoff due to over-development. Urban environments will experience many of the same issues as suburban sites, but may also be affected by elevated air temperatures (with their influence on relative humidity and precipitation) and wind blocking or intensification by surrounding buildings.

Local environmental factors may be well documented, especially those related to environmental conditions in urban areas, such as atmospheric pollution. Documentation on environmental factors in rural areas, such as those related to plowing, harvesting, or seasonal burning of agricultural fields, may not be available and we must rely on observation and targeted data gathering to identify these influences.

Large-scale human activity in the environment near a site may also be beneficial, such as introduction or improvement of infrastructure. The availability of water drainage systems, flood control, water supplies, information systems, and electrical power can be positive considerations when developing preventive conservation strategies for museum buildings and collections. However, we must also consider the consequences if infrastructure systems are interrupted by large-scale climate events such as hurricanes or snow storms.

Site-Specific Context and its Influence on the Building Environment

Each site and building exist within an intermediate exterior environment. At this level, seemingly small differences in the exterior environment may be sufficient to cause large differences between the various interior environments in a building. For example, in the southern hemisphere solar radiation on the north side of a building may cause spaces on that side to be warmer than those on the south side.

Early building design often addressed the site's influences on building performance and interior environment by exploiting opportunities for natural light, cooling breezes, and protection from winter winds. In many twentieth-century buildings, widespread use of mechanical systems for interior environmental management resulted in architectural designs based on closed envelopes without operable openings. As an outcome, many building designers did not account for the influences of building location and site features on environmental management because site influences could be offset by extra capacity and energy consumption of the mechanical systems. In the late twentieth century, the global effort to reduce a building's energy consumption and carbon emissions, a large part of which is for cooling and artificial lighting, reawakened interest in optimizing the energy-efficient opportunities of site-specific building design.

At the site-specific level, factors that affect building performance and interior environment can be readily quantified or documented, for example, building orientation and its effect on solar radiation, prevailing winds, and rain. Adjacent structures and enclosure walls can screen sunlight and wind. Buildings with reflective glazing can increase solar radiation on nearby buildings, increasing thermal loads. Site vegetation can shelter a building from sun and wind and atmospheric moisture. On-site and off-site surface water drainage and subsurface drainage systems can affect the moisture levels of soils, building materials, and the surrounding atmosphere.

Subsurface factors are difficult to observe directly, so information regarding these factors should be obtained from reliable sources, such as geotechnical studies. Site-specific subsurface factors that can significantly affect the interior moisture of a building include native and imported soils and their void fraction, permeability, and moisture retention. Subsurface infrastructure, whether abandoned or active, may affect soil moisture and localized groundwater. The possible effects of abandoned foundation structures on soil moisture should be considered.

Site-specific factors may increase or diminish the environmental effects of a location. For example, the environment surrounding a museum in an urban context may be expected to experience urban levels of vehicular pollution. If the site is at a busy traffic intersection, airborne pollutant levels will be higher because of the idling and acceleration of cars and trucks from the intersection. Conversely, if the site is buffered by an urban park or is in a heritage area of restricted vehicular traffic, airborne pollution levels may be slightly lower than the overall area.

Temporal Context and Its Influence on the Building Environment

Time is an important contextual consideration when working with historic buildings. The changes that have occurred over time inform our comprehension of the exterior environmental influences on a building and its interior environment. A building is initially designed for a specific use and set of conditions, such as the architectural program and the exterior climate. It may seem reasonable to assume that the original building design served its first use(s) satisfactorily, but over time changes may have occurred that have had a significant influence on the building and its environmental performance. These may include changes in use and occupancy or patterns in how the building has been operated. Changes may have been necessary to accommodate modern building systems or regulatory requirements such as universal access or safety codes.

Past changes in site and building configuration are relatively easy to determine, especially through documentation and comparative study of illustrations. With study, the effects of these changes on building environmental performance may also be identified.

In the absence of historical records or observable physical alterations, it may be difficult to discern the effects of changes in building use, occupancy, and function on the building. The change in a building's use from a fifteenth-century convent to a twentieth-century museum may result in the observable introduction of air conditioning due to increased occupant load and modern expectations for thermal comfort. However, a more subtle consequence would be that the temporary occupant load (visitors) increases, but the resident (staff) occupant load decreases, leaving fewer people to participate in the operation and maintenance of the museum building than when it operated as a convent.

Interaction of Exterior and Interior Environments

The building envelope is the material boundary between the interior environment and the exterior environment above and below ground, as shown in figure 4.4.

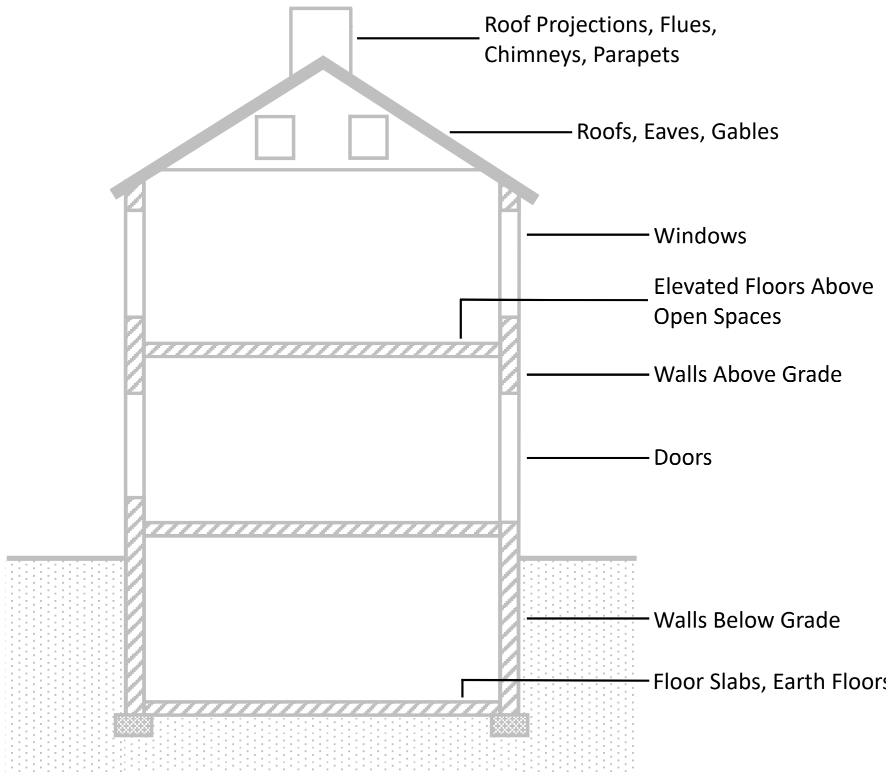


FIGURE 4.4. The building envelope. Credit: Michael C. Henry and Vincent Laudato Beltran

The exterior environment interacts with the building envelope, the building interior environment, and the contents and collections through:

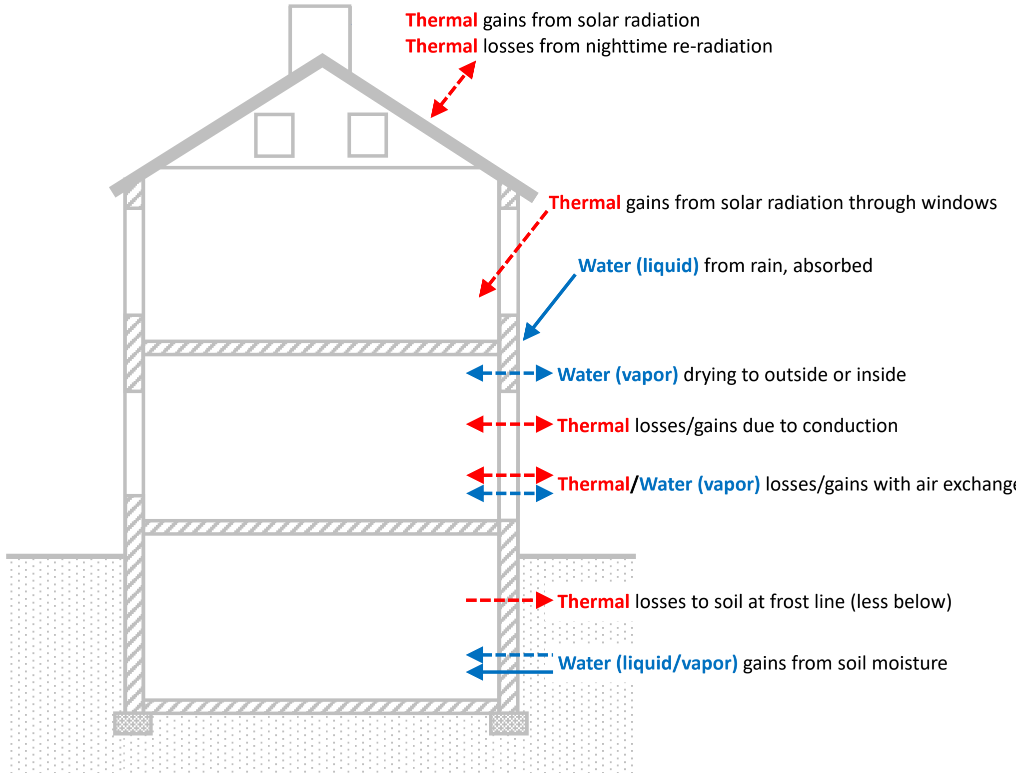
- mass transfer, involving the movement of air and moisture;
- momentum transfer, usually the pressure effects of wind; and
- energy transfer, involving heat gain or loss.

The transport processes are typically driven by differences in concentration, velocity, temperature, or potential or kinetic energy.

Figure 4.5 illustrates the external influences on the building envelope.

If the climatic conditions and the above differences remain unchanged, the processes of mass, momentum, and heat transfer would bring the exterior and interior conditions into static equilibrium. However, the exterior environment is dynamic, and as a result the effects on the interior environment are constantly changing.

FIGURE 4.5. External influences on the building envelope. Credit: Michael C. Henry and Vincent Laudato Beltran



In many buildings, the desired interior conditions are determined by the dual requirements for thermal comfort of the occupants (Maekawa, Beltran, and Henry 2015) and longevity of the building fabric. With museum collections, we are also concerned with achieving generally stable interior environmental conditions that are conducive to the preservation of the collections.

In order to manage the interior environmental conditions, we seek to understand and manage the transport of moisture (as vapor or liquid), air, thermal energy, and light between the exterior and interior.

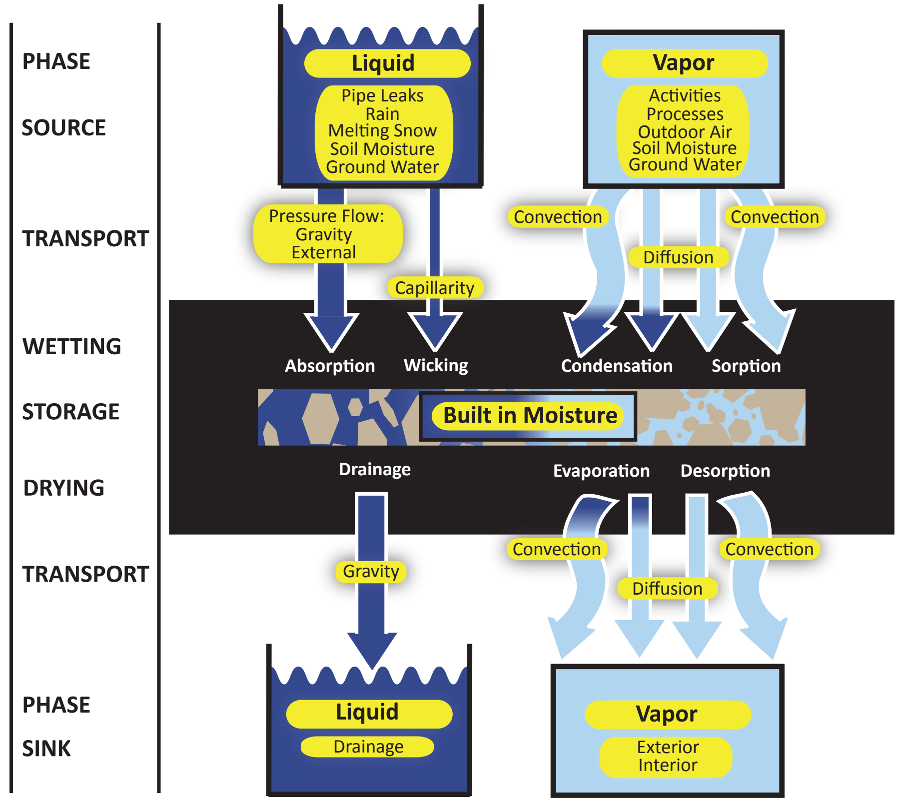
Of these mechanisms, moisture transport is the most complicated because it occurs with water in both liquid and vapor states. Moisture transport can take place as bulk flow of liquid, capillary flow of liquid in permeable materials, convective transport of moisture vapor with air, and diffusion of moisture vapor through air or permeable materials. Understanding these transport mechanisms enables us to correctly link cause and effect in interior environments so that we may identify and select the appropriate strategy for mitigation.

Figure 4.6 summarizes the sources of moisture and the modes of moisture transport encountered in a building.

Bulk Flow of Liquid Water

Water in its liquid state enters the building through large openings, small openings, and cracks, and through porous materials.

FIGURE 4.6. Interactions of moisture sources, flows, and building materials (after Straube 2002). Credit: Christine Beckman



Wind force can affect the movement of liquid water into a building and becomes particularly important with openings wider than 0.00039 in. [0.01 mm]. At openings of 0.0039 in. [0.1 mm], wind force effects on water flow are approximately equivalent to those from capillary suction. At openings of 0.020 in. [0.5 mm], wind forces dominate over capillary suction. Wind force is especially effective when water films flow over the length of a crack in the building fabric. The time frame for bulk flow may range from fractions of a second to hours.

Capillary Flow of Liquid Water

Capillary flow is the movement of water along the surface of a solid material as a result of a differential between the (higher) adhesive surface tension of the water/material interface and the (lower) cohesive surface tension of the water.

For surface tension to enable flow within a porous material, the size of the openings must be small. Small openings occur in mortars, porous brick, sedimentary stone, and the end grain of wood. The smaller the pore size, the greater the effects of capillary suction between interconnected pores. This can be seen in soils where the capillary rise of water varies greatly: coarse sand (2–5 cm); sand (12–35 cm); fine sand (35–70 cm); silts (70–150 cm); and clay (200–400 cm and higher).

The time frame for capillary flow to achieve 90% of maximum capillary height may be minutes for a sandy soil and days for a clay soil.

Convective Transport of Moisture Vapor in Air

Moisture vapor can be transported when there is air movement or convection. Convective transport between the building's exterior and interior occurs through large openings, such as windows, doors, chimneys, and shafts. Convective transport also occurs through small openings, such as expansion joints or material joints, through small crevices such as shrinkage cracks in bedding mortar or concrete, and through permeable porous materials and assemblies.

Convective velocities through a window or door opening can be 7.33 ft. per second (2.24 m per second) for a 5 miles per hour (8 km per hour) breeze. For the same breeze, convective velocities for infiltration through a framed exterior wall assembly may be less than 0.002 ft. per minute (0.06 cm per minute).

Static pressures due to wind will vary by location at the exterior surfaces of the building and within the assemblies of the building envelope and will generally result in windward infiltration and leeward exfiltration.

Within the building, convective transport can occur vertically due to stack effect and solar heat gain or horizontally due to exterior static pressure differentials and solar heat gain. In the absence of wind-induced static pressures, stack effect will dominate, with infiltration in lower levels and exfiltration in upper levels. Convective transport can also occur between conditioned spaces because of imbalances in pressure or between conditioned and unconditioned spaces due to air leakage in supply and return ducts.

Moisture Vapor Adsorption and Diffusion

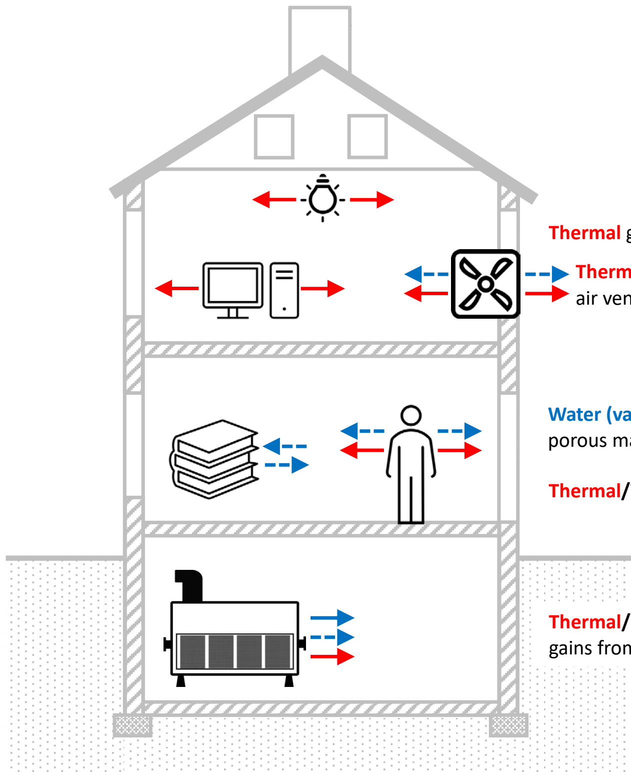
Near sea level, the atmosphere is a mixture of "dry air" and a variable amount of moisture vapor (about 1%). Dry air is composed of nitrogen (about 78%), oxygen (about 21%), argon (about 0.9%), carbon dioxide (0.04%), and other gases in trace amounts. Water vapor behaves as a gas and the water molecule is a very small bipolar molecule (less than 0.3 nanometers; a human hair is about 80,000 to 100,000 nanometers thick). Because of its small size and bipolarity, the water vapor molecule is easily adsorbed by porous materials. At a given temperature, the equilibrium moisture content of a porous material will depend on the material and the relative humidity of the surrounding air.

In a space at constant temperature without air movement, water vapor molecules will disperse throughout space by diffusion until the amount of moisture vapor and the water vapor pressure are the same at any given location in the space. At sea level and 68°F (20°C) and 100% relative humidity, water exerts a partial vapor pressure of 0.334 psi (2.3 kPa). For comparison, at the same conditions the other gases in the air exert 11.313 psi (78 kPa) for nitrogen, 3.046 psi (21 kPa) for oxygen, and 0.131 psi (0.9 kPa) for argon, with a total atmospheric pressure of 14.823 psi (102.2 kPa).

Internal Thermal and Moisture Loads

The use and occupancy of a building will directly affect the interior environment by introducing both thermal and moisture loads. Typical sources of internal thermal and moisture loads are illustrated in figure 4.7.

FIGURE 4.7. Internal thermal and moisture loads from people and equipment. Credit: Michael C. Henry and Vincent Laudato Beltran



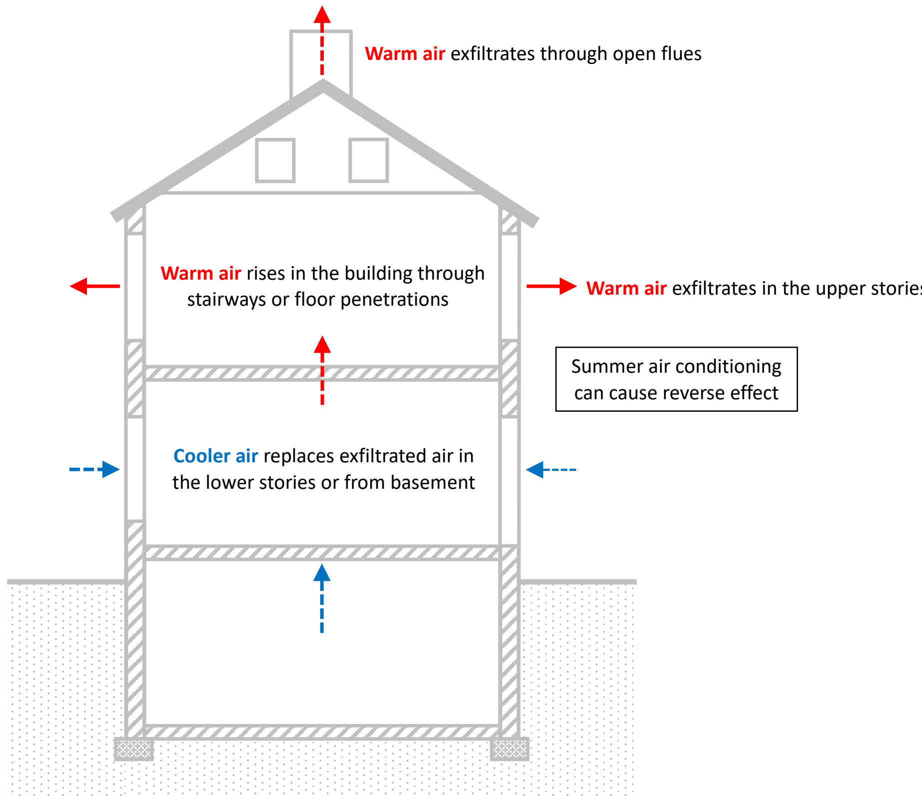
Understanding a Building's Environmental Comportment

In addition to the exchange of mass, momentum, and energy between the exterior and interior environments through the building envelope, the interior building environment is affected by a number of other factors. These include the exterior building form, building height, and overall proportions, which affect exposure to wind, rain, and natural light. The organization of interior spaces and interior horizontal and vertical communication of spaces will both affect air and moisture vapor movement within the building. Thermal and moisture influences include thermal mass of the building materials (which affects the building's inertial thermal response to atmospheric temperature change) and moisture storage capacity of the building fabric (which affects the building's inertial moisture response to atmospheric moisture change).

The end result of these factors is the overall environmental comportment or behavior of the building in response to its exterior environment. Figure 4.8 illustrates the movement of air and moisture vapor in a building due to stack effect.

Quantified evaluation of these building characteristics and comportment can be done by either monitoring or computer modeling; both are time consuming and may be cost prohibitive relative to other needs. For the purposes of identifying preventive conservation strategies, it may be sufficient to evaluate these characteristics on a qualitative basis, deferring quantitative analysis and modeling for specific problem solving or for validation of specific strategies. Qualitative evaluation of the hygrothermal behavior or comportment of a building can be informed by observing the building's configuration and factors such as the ratio of exterior surface area to floor area or volume, which can suggest responsiveness to exterior environmental changes. Exterior exposure and patterns of building weathering, water runoff, and material

FIGURE 4.8. Stack effect. Credit: Michael C. Henry and Vincent Laudato Beltran



saturation, as well as the effects of wind and light on the interior and exterior, are also informative. Inside the building, indications of stagnation or movement of interior air can be helpful.

The above observations can be supplemented by spot measurements or short-duration monitoring of temperature, relative humidity, and dew point temperature of spaces to comparatively assess the interior environmental behavior. Examination of wall, floor/ceiling, and roof assemblies and materials will allow comparative estimates of thermal mass and moisture capacity based on published data.

Based on our observations and previous experience with other buildings, we can characterize the overall comportment of a building with respect to exterior environmental change and interior environmental response. Understanding a building's comportment and its implications for the interior environment should inform our selection of nonmechanical and mechanical environmental management strategies for preventive conservation.

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PART 2: ANALYSIS AND UNCERTAINTIES

Introduction

The beginning of the 2010s witnessed the emergence of several interim guidelines and guiding principles advocating for flexible or broader parameters of temperature and relative humidity in order to save energy and reduce the carbon emission of museums. Inherent in these guidance documents was the idea that "the issue of collection and material environmental requirements is complex, and conservators/conservation scientists should actively seek to explain and unpack these complexities" (IIC/ICOM-CC 2014)

The four technical notes grouped in part 2 begin to "unpack these complexities", which, as we will see, go far beyond the materiality of the objects. The first technical note, "Physical Responses of Hygroscopic Material to Climate" by Michał Łukomski, provides an overview of basic mechanical and physical concepts—such as stress-strain curves, yield point, Young's modulus, hysteresis effect, and moisture coefficient of expansion—that are necessary to explain the properties of hygroscopic materials and to understand how environmentally induced stresses lead to physical failure. This, in turn, allows us to better understand the allowable environmental fluctuations that a particular object can endure without experiencing irreversible deformation or failure.

A critical overview of standards and guidelines is then offered by Joel Taylor in the technical note "Standards and Guidelines for Climate in Preventive Conservation." The author explains defining features of standards and guidelines, and identifies similarities and differences in their conceptions, objectives, and applications. In addition to material behavior, environmental recommendations must consider other contextual factors, such as human comfort, equipment capability, artifact use, and energy consumption. In the face of these complexities (and a dose of uncertainty avoidance and risk aversion, to be explored in part 3), recommended parameters for collection environments during the past several decades relied upon a "stable is safe" prescriptive route. Taylor identifies a more collaborative, context- and process-based trend in recent guidance.

The application of standards and guidelines that take context into account, however, implies that this context is known and understood. Defining this context is aided by monitoring environmental parameters and the resulting collection response. The final two technical notes in part 2 stress the importance of data collection and analysis to reach an informed decision. Michael C. Henry reviews "Environmental Monitoring and Diagnostics for Museums" as a tool that helps unpack the complexities of correlating causes and effects in the deterioration of collections and buildings, and orients environmental management strategies. The processes of defining a problem and then planning, designing, deploying, and maintaining a monitoring program are carefully explained. This is followed by the crucial step of analysis, which transforms collected data into actionable knowledge that can inform decision makers.

In the technical note "Analysis and Visualization of Environmental Data," Vincent Laudato Beltran further explores the analysis step, introducing basic statistical analysis concepts (numerical indices, data subsets) and common graphical techniques for presenting temperature and RH (time-series, probability distribution plots, and psychrometric charts). At the core of this technical note is the fact that data analysis and visualization not only help distinguish relationships and trends, but also support the critical step of communicating these data-driven narratives to an interdisciplinary team, facilitating the application of context- and process-based approaches promoted by recent museum environmental guidance.

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TECHNICAL NOTE 5: PHYSICAL RESPONSES OF HYGROSCOPIC MATERIAL TO CLIMATE

Michał Łukomski

Introduction

Collection preservation requires understanding properties of materials—their changes and interactions in response to external conditions. The allowable environmental fluctuations for a particular object can be determined by examining the independent response of each of the materials constituting an object, understanding the effects of the composite nature of the object on each material's response, and then comparing the worst-case responses with the critical stress or deformation a particular material can endure.

This chapter presents an overview of the information necessary to analyze and understand the mechanics of physical changes in objects. The presented material is illustrated by the properties of wood and the ground layer. Decorated wood is most vulnerable and at the same time most frequently found in museum collections of various kinds. Wood itself is particularly complicated. It is inhomogeneous, time dependent, and highly responsive to changes in temperature and humidity, and as such is an ideal example of hygroscopic material at risk of mechanical damage caused by improper climatic conditions.

> *Physical damage* is the failure of materials under the action of loads caused by external conditions. These conditions may include external forces as well as temperature and humidity variations.
>
> *Material failure* is the loss of load-carrying capacity of a material involving cracking (in a brittle state) or permanent deformation (in a ductile state). Both are recognized as "damage" in the cultural heritage field.

Response to External Forces

Force is any (inter)action that causes a change in an object's motion or, if the object is restrained and cannot move, its deformation. Forces can result from many factors, such as changes in temperature and relative humidity, gravity, hitting/dropping an object, or stretching/bending a material during construction or conservation.

The mechanical properties of materials are defined by their response to external forces and are described using stress and strain (fig. 5.1).

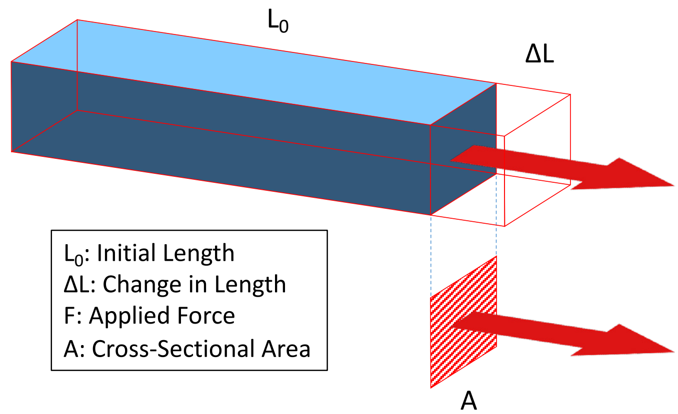


FIGURE 5.1. Deformation caused by external force. Credit: Michał Łukomski

Stress (σ) is defined as the force (F) per unit area of a material (A): $\sigma = F/A$.

Strain (ε) is a measure of relative deformation: $\varepsilon = \Delta L/L_0$.

The relationship between the stress and strain that a particular material displays is known as that particular material's stress-strain curve. Figure 5.2 shows an example of such a curve for a material exhibiting elastic-plastic behavior. It is unique for each material and is found by deforming a sample of material at a constant rate, and measuring the corresponding load at different time intervals (or different extensions). These load-displacement values are used, along with the sample dimensions, to calculate stress and strain. The purpose of this conversion is to eliminate the effect of the sample size. For example, in a comparative test on a sample with twice the cross-sectional area, the measured force will double; however, stress remains the same.

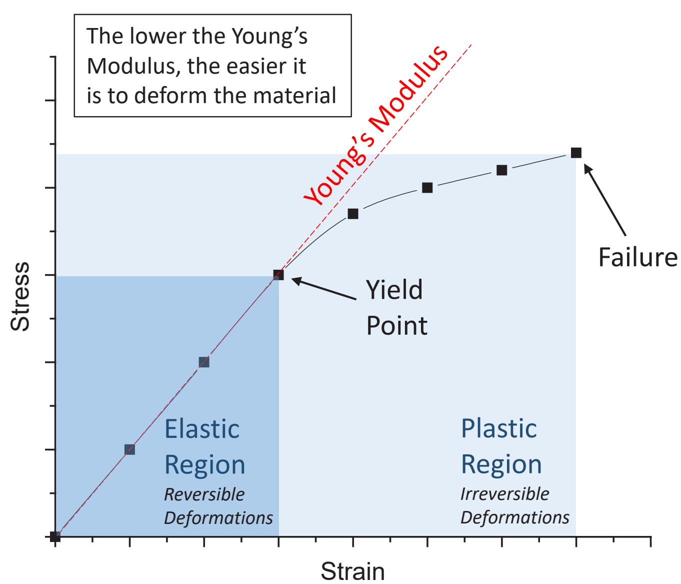


FIGURE 5.2. Stress-strain curve showing elastic-plastic material behavior. Credit: Michał Łukomski

In figure 5.2, the yield point defines the limit of linear relation between stresses and strains—the so-called elastic region. In this region, the stiffness of a material is defined by the Young's modulus (an elastic modulus), where stress is proportional to strain. As long as a material remains in the elastic region, all deformations are reversible and there is no risk of irreversible change.

Above the yield point, stress results in irreversible deformation. Changes of material in the plastic region are permanent. The failure point indicates the stress and strain at which the material finally breaks.

Toughness of the material is related to the area under the stress-strain curve. In order to be tough, a material must be both strong and ductile. For example, brittle materials (like ceramics), which are strong but have limited ductility, are not tough; conversely, very ductile materials with low strengths are also not tough.

The stress-strain curves of materials vary widely due to different types of material behavior, and also individual sensitivities to various factors. For example, tensile tests conducted on the same material may produce significantly different results under varied environmental conditions and rates of loading. Many materials exhibit significantly different behavior under slow and fast loading. Time-dependent properties, such as stress relaxation and creep, are due to the specific molecular structure of the materials. These commonly observed phenomena are especially pronounced in both natural and synthetic-based polymer materials (fig. 5.3).

Stress relaxation is a decrease in stress in response to constant deformation generated in the material.

Creep is an increase of deformation under the influence of mechanical stresses still below the yield point of the material.

To illustrate time-dependent (visco-elastic) material behavior, figure 5.4 shows the stress-strain curves obtained for wood subjected to loading at different rates. Due to relaxation processes, the Young's modulus in a slow test is significantly lower than in a fast test.

To complicate matters, the stress-strain curves of many organic materials vary with temperature and moisture content, and their respective dimensional changes are a further consideration. It should be noted that even rapid humidity fluctuations usually result in slow response of objects due to limited diffusion of moisture vapor through materials.

Material Response to Moisture

Sorption

A hygroscopic material has the ability to adsorb and store moisture from the surrounding air. When the relative humidity (RH) changes, a difference in the water vapor pressure causes the material to adsorb or desorb moisture to reach equilibrium. As a result, the material changes by expanding or contracting in volume, becoming sticky, or otherwise becoming altered. The list of hygroscopic materials is long:

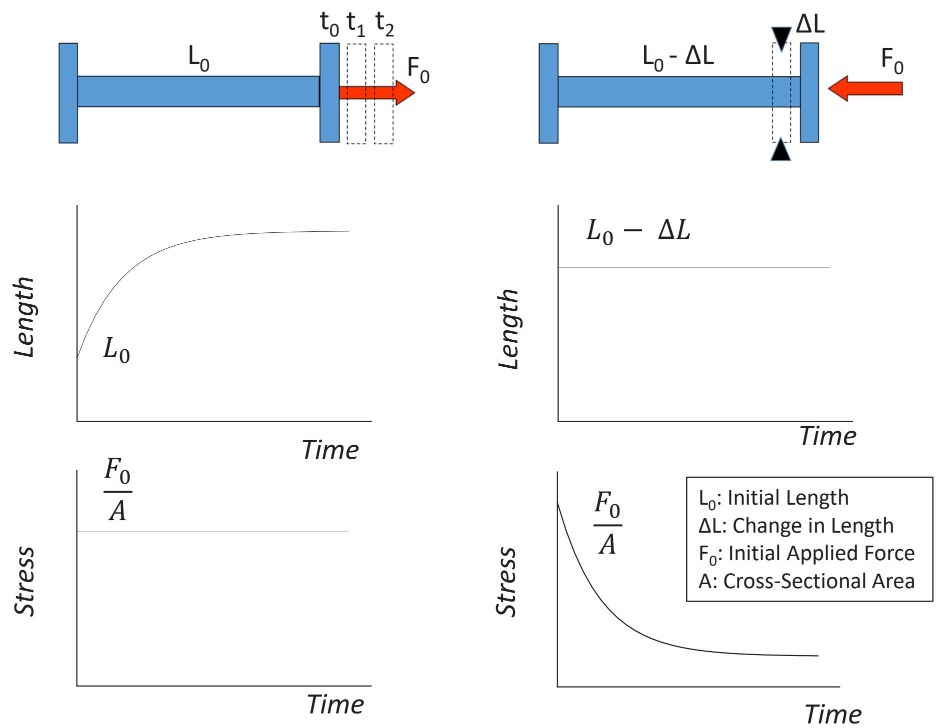


FIGURE 5.3. Creep (left) and stress relaxation (right). The left image shows a constant applied force with length increasing over time, while the right image shows an initial application of force resulting in a change in length that is then fixed. Credit: Michał Łukomski

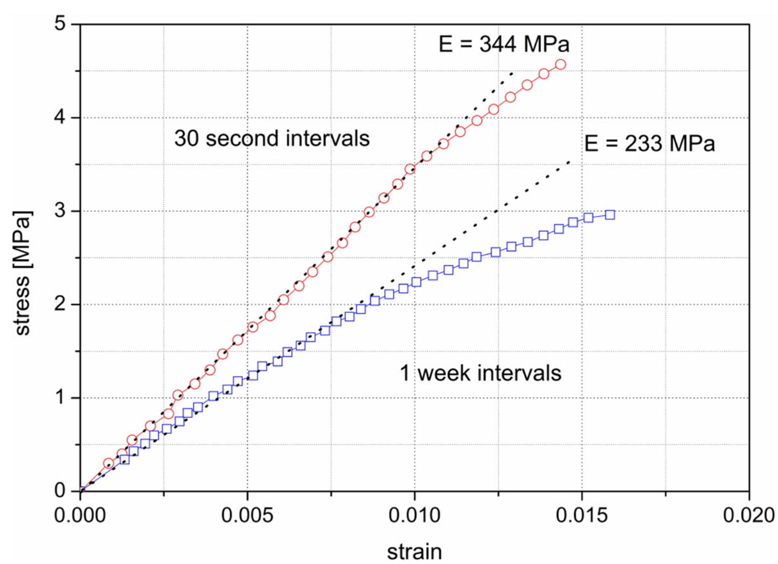


FIGURE 5.4. The effect of rates of loading on the stress-strain relationship at 50% RH and 23°C (73°F) for tangentially cut poplar (Bratasz 2013, experimental data provided by Marion Mecklenburg).

paper, cotton, wood, nylon, polycarbonate, sugars, and many more. Water vapor sorption may be based on adsorption (creation of a water film on the surface of the adsorbent) and absorption (when the water molecules enter the bulk of the material).

Hygroscopic materials gain moisture when relative humidity is high and they lose moisture when the surrounding air is dry. The moisture content in a material exposed to a given temperature and RH eventually attains a constant level—the equilibrium moisture content (EMC). The relationships between the RH and EMC at constant temperatures are termed water adsorption or desorption isotherms and for many organic materials they are described by an S-shaped curve (sigmoid function).

Moisture sorption isotherm is a curve representing the relationship between water content and equilibrium relative humidity of a material. For each relative humidity value, a sorption isotherm indicates the corresponding water content value at a given constant temperature. Because of the complexity of sorption processes, the isotherms are not determined by calculation, but are recorded experimentally for each material.

In figure 5.5 a distinct hysteresis effect is observed, that is, a higher moisture content during desorption when compared with that during adsorption at any given RH value. This phenomenon, common in hygroscopic materials, may have different origins and extents depending on the type of material and its microstructure. Hysteresis is usually associated with capillary condensation in the structure of the material.

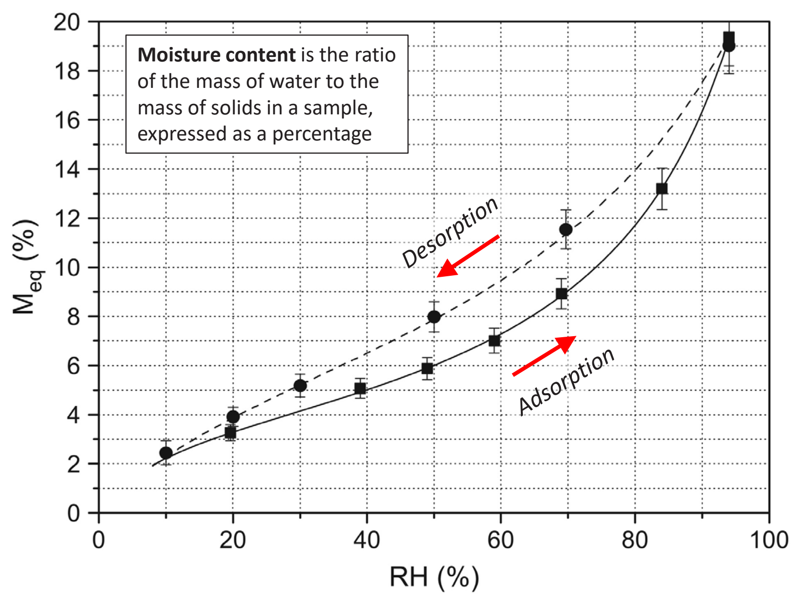


FIGURE 5.5. Adsorption and desorption isotherms of water vapor for lime wood at 24°C (75°F) (Rachwał et al. 2012a).

Moisture Coefficient of Expansion

Changes in moisture content result in the materials' dimensional response. Materials shrink as they lose moisture and swell when they gain moisture.

The moisture coefficient of expansion (y) is defined as a relative change in dimension (strain, $\Delta\varepsilon$) divided by the change in relative humidity (ΔRH) causing this change.

$$y = \Delta\varepsilon / \Delta RH \left[\frac{1}{\%}\right],$$

where strain: $\Delta\varepsilon = \Delta x / x_1$

The symbols used in this equation are described in figure 5.6.

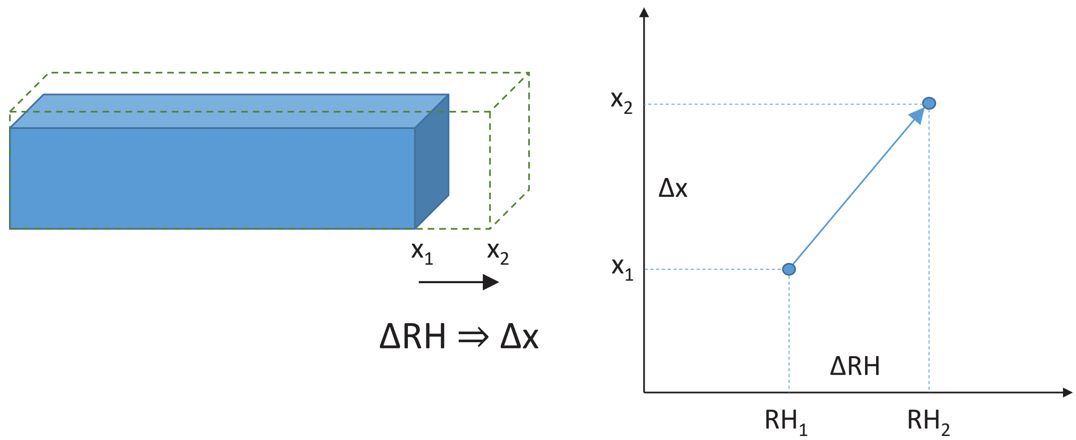


FIGURE 5.6. Dimensional response caused by change in relative humidity. Credit: Michał Łukomski

Due to hysteresis, the moisture coefficient of expansion has different values for the adsorption and desorption curves of the sorption isotherm. Such ambiguity is not present when the moisture coefficient of expansion is defined as a function of moisture content instead of relative humidity. However, since moisture content in a particular object is difficult to measure and values vary over time and with position of the sensor, it is not commonly used.

Moisture-related dimensional change can be complicated in materials of anisotropic structure (as illustrated in figure 5.7). Wood is a good example of a very common yet complex material (Forest Products Laboratory 2002). It has three principal anatomical axes: longitudinal or parallel to grain, radial, and tangential. For most practical purposes, wood can be considered dimensionally stable parallel to its grain. The most pronounced moisture response is in the tangential direction and the response in the radial direction is approximately two times smaller (fig. 5.7). As the graph below shows, wood has an evident hysteresis in dimensional response to humidity variations.

Due to hysteresis, the moisture coefficient of expansion depends on the type of process (adsorption or desorption) and the magnitude of RH change. This is illustrated for lime wood in figure 5.8, where a large humidity cycle is followed by a small humidity cycle: in the large cycle, the relative humidity is increased from 0% to 95% (denoted on the figure by the number 1) and decreased from 95% to 40% (2); in the small cycle, the relative humidity is increased from 40% to 70% (3) and decreased from 70% to 40% (4). The moisture coefficients of expansion were determined as slopes of the adsorption curves for both cycles at 50% RH. It can be seen that the value of the moisture coefficient of expansion for the smaller cycle (y_2) is significantly lower than that of the large cycle (y_1), and variations of relative humidity around an average value result in a much smaller dimensional change than those that can be predicted from measuring the moisture coefficient of expansion on the basis of the full sorption isotherm.

Response Time—Time to Reach a New Equilibrium

The dimensional response of a material in interaction with moisture vapor is not instantaneous. Water diffusion in a material depends upon the material's type, its density/porosity, its moisture content, and the speed at which the air is moving around the material. Dimensional response is also strongly influenced by temperature, increasing and decreasing with respective increases and decreases of temperature.

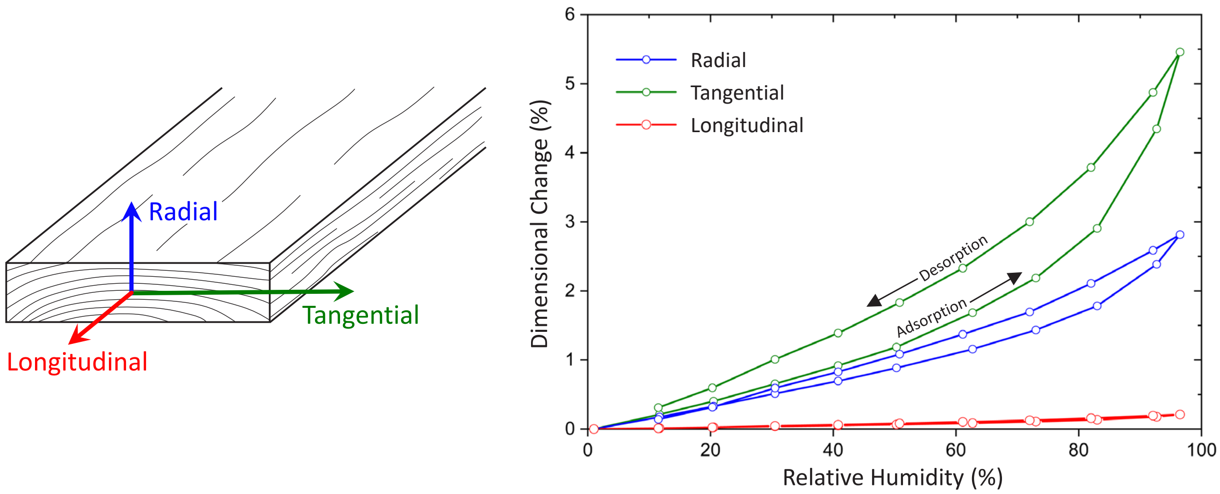


FIGURE 5.7. Dimensional response of lime wood to changes in relative humidity. Credit: Michał Łukomski

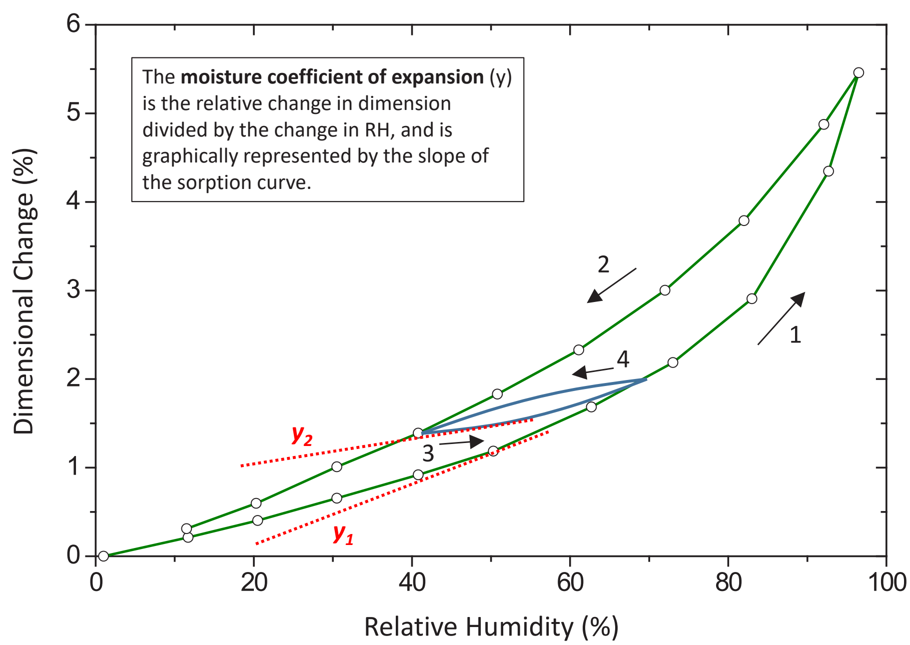


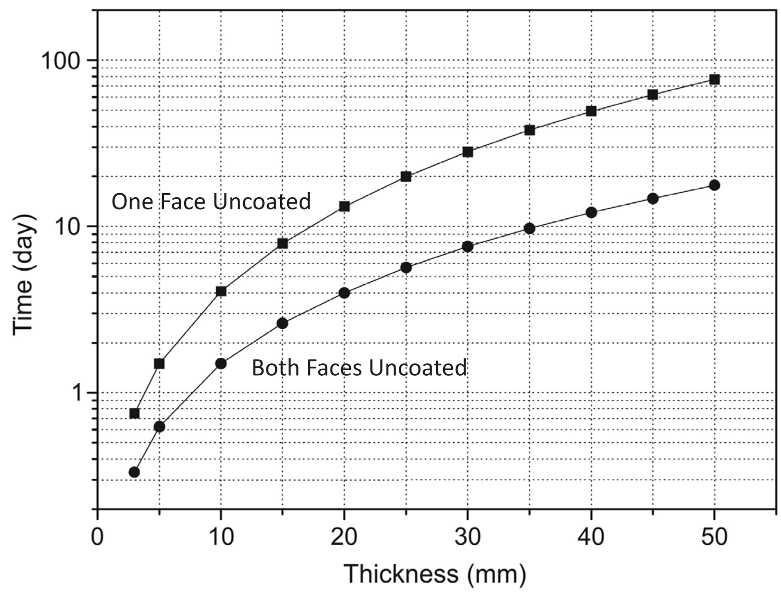
FIGURE 5.8. Moisture coefficient of expansion for adsorption curves at two different humidity cycles. Credit: Michał Łukomski

Water vapor transport depends on the structure of the material. Wood is characterized by three different diffusion coefficients corresponding to the anatomical axes: longitudinal, radial, and tangential. Diffusion in the longitudinal direction is about ten to fifteen times faster than radial or tangential diffusion, and radial diffusion is somewhat faster than tangential diffusion.

The shape and size of an object is crucial to understanding its time response. A thick, bulky object will respond more slowly to a change of relative humidity in the air than a thin object made with the same material. At a given depth from the surface, they will respond at the same rate; however, a thicker object will take longer to reach moisture equilibrium with the surrounding air. Response time is also dependent upon the availability of surface area for moisture exchange. Objects coated with a layer of lower vapor permeability will exchange moisture vapor with the surrounding air more slowly than uncoated objects and thus will be less affected by RH fluctuations. This is illustrated in figure 5.9 by the response time of wooden panels of different thicknesses with one or two surfaces available for moisture vapor exchange. Panels are subjected to 35–70% RH change.

Figure 5.9 shows the relationship between the panel thickness and the time it takes for a panel to reach 63.2% of its final (asymptotic) dimensional response. This value is mathematically derived from the time constant of a panel response. Note that the time corresponding to 95% of total asymptotic response is three times greater than the time presented in figure 5.9.

FIGURE 5.9. Response time of panels with one face (■) and both faces (●) uncoated and subjected to a steep relative humidity change from 35% to 70% as a function of panel thickness (Rachwał et al. 2012a).



Response to Temperature

All materials respond dimensionally to changes of temperature. This response is typically faster and much smaller than change induced by relative humidity. Also, hysteresis is negligible when analyzing changes induced by variations of temperature.

The thermal coefficient of expansion is defined analogously to the moisture coefficient of expansion:

The thermal coefficient of expansion (α) is defined as the relative change in dimension (strain, $\Delta\varepsilon$) divided by the change of temperature (ΔT) causing this change.

$\alpha = \Delta\varepsilon / \Delta T \left[\frac{1}{K}\right]$,

where $\Delta\varepsilon = \Delta x / x_1$.

Symbols used in the equation are described in figure 5.10.

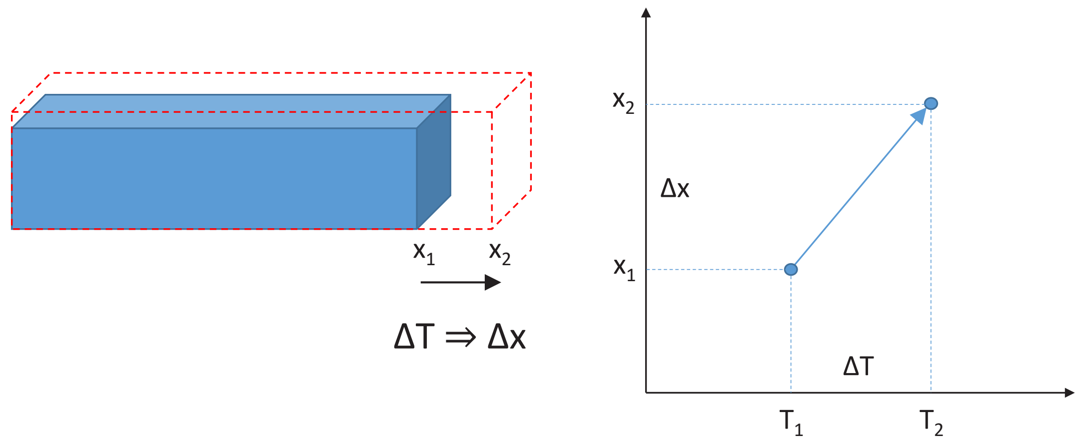


FIGURE 5.10. Dimensional response caused by change in temperature. Credit: Michał Łukomski

In most hygroscopic materials, the thermal conductivity is a few orders of magnitude higher than that of water vapor, and the dimensional response caused by temperature variations is much smaller than the response caused by relative humidity variations. Therefore, the response of wood to moderate temperature variations occurring in real-world display conditions should be considered instantaneous and the risk related to thermally induced dimensional change is negligible.

However, altering temperature can still have a significant effect on the long-term stability of collections. Elevated temperatures increase the rate of the chemical processes that promote deterioration and, in the case of artistic paints, low temperatures leads to change from a flexible to a brittle state.

How Changes in Relative Humidity and Temperature Cause Dimensional Change

Internal stresses will not occur with unconstrained objects fabricated from a single material that are exposed to slow changes in relative humidity and temperature. However, when constrained materials, such as veneers on furniture, experience these changes, stresses will appear because of the constraints. Materials constituting art objects can be fully constrained (when blocked by a rigid frame or construction) or partially constrained (when connected to a material with a different coefficient of expansion).

Bulky objects can experience internal stresses and constraints as the moisture vapor diffusion through the material is not instantaneous; this uneven moisture distribution causes uneven dimensional response. Gradients of moisture content in a material may also result from covering parts of the object with coatings that have different permeability.

A direct link exists between moisture-/temperature-related swelling/shrinking of an object and the deformation (strain) caused by external forces. Two situations are presented in figure 5.11. The mathematical link between temperature-/moisture-induced swelling and strain resulting from the application of stress is discussed in this chapter's appendix.

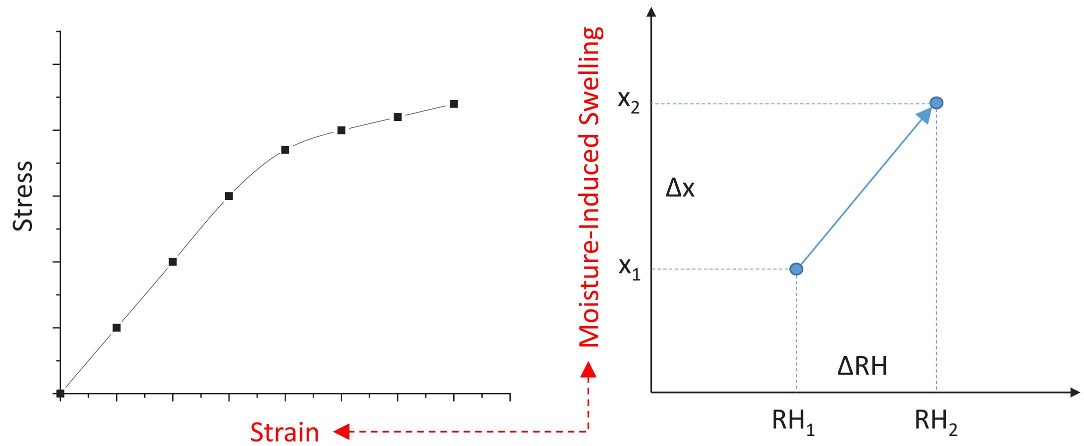


FIGURE 5.11. Dimensional response of material caused by increasing stress (left) and increasing relative humidity (right). Credit: Michał Łukomski

Changes in temperature and relative humidity can result in dimensional response and the development of stresses if deformation is constrained. But behavior of materials depends on both the amplitude of change and the absolute values of the starting and ending T/RH levels. Glue-based materials experience transition from a brittle to a ductile (jelly-like) state in high relative humidity. For gesso, such transition happens around 75% RH. Above this RH level, gesso easily deforms. As a result, the strain leading to fracture becomes an order of magnitude greater than in the brittle state (fig. 5.12).

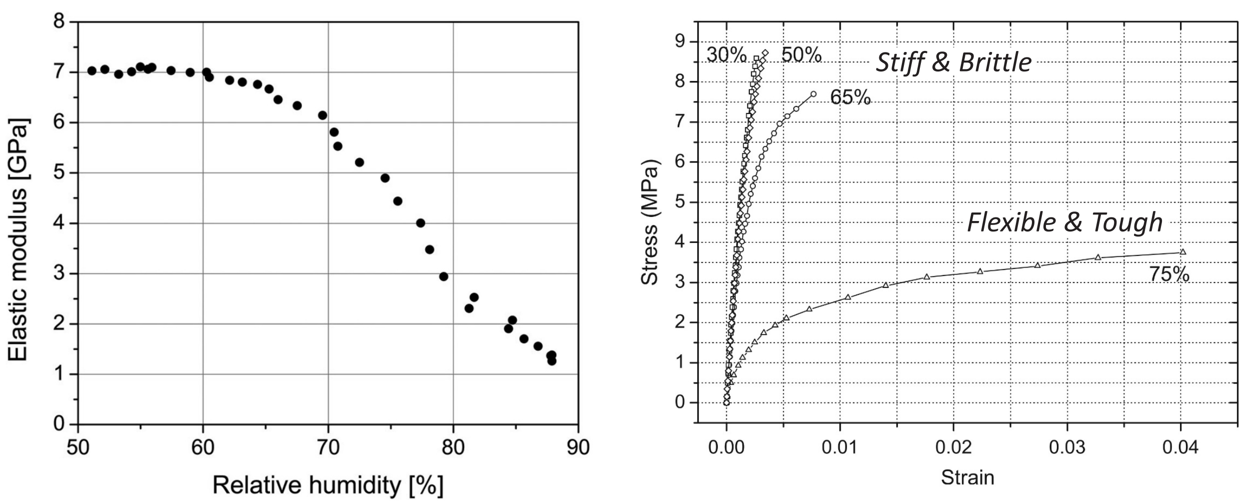


FIGURE 5.12. The modulus of elasticity of the gesso plotted as a function of relative humidity (left, Krzemeien et al. 2016), and the stress–strain curves for the gesso tested at various relative humidity values (right, Rachwał et al. 2012b).

Change in temperature can also influence properties of materials when the temperature crosses the glass transition temperature, or T_g. The glass transition is the reversible change in amorphous materials from a hard and relatively brittle "glassy" state into a viscous or rubbery state as the temperature increases. For paints, glass transition temperatures are below room temperature, whereas for most other materials, the glass transition temperature is higher than room temperature. Lowering the temperature below glass transition for paints should be avoided, because they become increasingly fragile in this temperature range.

Conclusions

Understanding how environmentally induced stresses and deformation are developed in different materials is necessary to properly assess the needs of the collection and mitigate risks of irreversible change. By relating the differing moisture coefficients of expansions for artistic materials at various levels of T and RH, it is possible to determine the extent of climatic fluctuations an object can endure without experiencing irreversible deformation or failure.

Mechanical properties of artistic materials depend on external factors such as temperature and relative humidity, external loads, fatigue, and chemical and biological degradation. Therefore, quantitative determination of those properties is a complex process requiring use of specialized laboratory equipment and following precise measuring protocols.

However, a great number of materials relevant for the cultural heritage field have already been precisely characterized. Mechanical properties of wood, animal glue, gesso, different paints, paper, canvas, and the like (published in conservation or material science literature) can be used for analyzing the risk of climate-induced physical damage for the collection. Even when measured on materials that only mimic historic ones, the resulting information is relevant for a wide class of materials. The important characteristics of physical change outlined in this technical note provide insight into how that information can be interpreted.

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Appendix

The relation between moisture-/temperature-related swelling and shrinking of an object and its deformation (strain) is caused by exerted stress.

Young's modulus (E) is a ratio of the stress acting on a substance ($\Delta\sigma$) to the strain produced ($\Delta\varepsilon$):
$E = \Delta\sigma / \Delta\varepsilon$,
which gives: $\Delta\sigma = E\Delta\varepsilon$.

The moisture coefficient of expansion (y) is a strain ($\Delta\varepsilon$) divided by change of relative humidity (ΔRH):
$y = \Delta\varepsilon / \Delta RH$,
which gives: $\Delta\varepsilon = y\Delta RH$.

The thermal coefficient of expansion (α) is a strain ($\Delta\varepsilon$) divided by change of temperature (ΔT):
$\alpha = \Delta\varepsilon / \Delta T$,
which gives: $\Delta\varepsilon = \alpha\Delta T$.

By combining the above equations, we can find:

1. Stress in restrained material resulting from change of relative humidity: $\Delta\sigma = E\Delta\varepsilon = Ey\Delta RH$
2. Stress in restrained material resulting from change of temperature: $\Delta\sigma = E\Delta\varepsilon = E\alpha\Delta T$

Both stresses are expressed by Young's modulus (E), which characterizes stiffness of the material and can be determined in mechanical testing.

TECHNICAL NOTE 6: STANDARDS AND GUIDELINES FOR CLIMATE IN PREVENTIVE CONSERVATION

Joel Taylor

Introduction

Standards and guidelines for climate control in conservation have been at the center of the debate about collection preservation and international loans (Michalski 2016). Although they have been the subject of various conferences (e.g., Plus/Minus Dilemma, 2010), their goals, qualities, and implications are not always clear to those involved in the application, nor are the outcomes always consensus agreements (Bickersteth 2016). Standards are often regarded as a means of raising low-level practice, but they can also result in compromising on an innovation or stand in for careful consideration of actual conditions, collections "needs," and potential operations (Padfield 1994). This alone underlines the challenge of developing standards and guidelines that work for different parties.

In preventive conservation, they have not always been positively regarded, with Padfield and Johnsen (1996) stating that, "standards have an authority that encourages acquiescence without deeper consideration, particularly by administrators who have little knowledge of the experimental or experiential basis for the standard." Given their influence, and criticisms of them, it is worth examining the nature of standards more closely.

This technical note reviews some of the contextual factors that have led to the emergence and shaping of standards and guidelines in conservation, and why they can result in contrasting guidance. Examining the context surrounding existing (and occasionally withdrawn) standards and guidelines reveals historic influences, different approaches and assumptions, and motivations that have led to the creation of conservation guidance and policy. It also shows why standards have evolved over time and clarifies the need for periodic review.

This technical note will discuss standards and guidelines related to temperature and relative humidity. Although temperature and relative humidity are rarely the greatest risks a collection faces, these topics have prompted the most discussion in the conservation field and shown the most variation in different contexts and over time.

What Are Standards and Guidelines?

Standards and guidelines are not interchangeable terms, but have similar qualities and involve crossover in their creation and application. A standard is a means of measuring status or performance for evaluation.

They are usually established by consensus and approved by a recognized body with the aim of providing guidance or actions that can be repeated or followed to promote order and good practice in a given context. A guideline is a principle or recommendation that may come from a small group or an individual. Guidelines are often the result of an individual or specific group responding to an emergent need for direction on a specific matter.

Guidelines in the context of collection preservation are not designed to be mandatory, but compliance may be mandatory depending on the application. Applications can include the construction of a new building or specifications for a loan agreement, wherein standards and guidelines are used as reference points. Similarly, application can include a non-mandatory suggestion to follow an existing standard, so use and function can overlap in practice.

In this context, both function as documents that regulate behavior or action, but some distinctions in their creation should be noted:

1. Guidance may be informal or contextual, such as Garry Thomson's early guidance on museum specifications (1986) but can become a de-facto standard for the field. They are often the product of a single author or institution (e.g., Canadian Conservation Institute, Grattan and Michalski 2017).
2. Guidelines from a professional body (ASHRAE, ICOM-CC/IIC, AICCM) may represent a stance that has been reviewed and commented on by peers. They are often responses to changes in the field.
3. Standards from a standards organization (e.g., EN15757: 2010, BS EN16893: 2018) are commissioned works that regularly feature a range of authors and undergo a form of public review.

Standards are designed to maintain the quality of a service or activity. Because different people or institutions apply them, there is a tendency toward unambiguous, clear, and comprehensive information that rests on a degree of professional consensus. For this to be achieved, a measurable quantity or quality is often included. Standards do not necessarily reflect the cutting edge of the field, since they are the result of collective discussion (and compromise) and focus on accepted practice rather than unproven ideas. Guidelines tend to focus more on the nuance of a specific topic to make recommendations for best practice. They do not imply accountability, and do not represent an authorizing or regulatory body. Guidelines can require high-level interpretation and application, since consensus or compliance to a behavior or set of parameters may not be the primary aim of their creation. Within this spectrum are various guidelines produced by professional bodies, which may respond to the need for greater consensus, clarity, or the dissemination of new information within the profession.

With these distinctions outlined, the note will refer to standards in a broad sense for purposes of brevity, unless referring to a specific document.

Kinds of Standards

Despite their many similar qualities, standards can vary in a number of ways. Standards in conservation tend to be the following:

- Measurement standards: a prescriptive specification with an unambiguous pass/fail quality, such as a fixed set point and range found in a climate specifications.
- Process standards: methods to carry out a process in a measurable way, so quality can be controlled and results compared if necessary, such as standards to calculate a moving average for relative humidity (CEN 2010), or procedures and instruments to measure humidity (CEN 2012).
- Performance standards: standards or guidelines that indicate different ways to achieve a result; these can vary with context. Performance standards are often harder to measure than a simple

measurement standard. The 2019 ASHRAE Handbook—HVAC Applications present different levels of performance based on context and needs, and often offer different ways to meet those needs.

Standards can vary for a number of reasons, which indicate the contextual features that contribute to the creation of any standard or guideline. Ashley-Smith (2006) pointed out a number of qualities related to conservation as a series of word pairs on which a standard or guideline can be located (table 6.1). Each word pair represents an index that helps characterize different qualities of conservation standards.

TABLE 6.1.
Paired words (antonyms) indicating the characteristics of a standard's contents (after Ashley-Smith 2006).

Qualities of Standards		
Universal	———	Local
General	———	Specific
Coercion	———	Guidance
Performance	———	Need
Evangelism	———	Cost Awareness
Certainty	———	Risk
Fixed Numbers	———	General Directions

Standards can also have different levels, which vary in scope and detail. For example, the European Norms (CEN) had three different layers of detail (Johnsen 2013)—from general specifications to standards related to specific activities to standards that support techniques required to meet broader standards (process standards). Some bodies even release support documents for interpreting standards, such as the *Guide to the Interpretation of BS 5454: 2000: Recommendations for the Storage and Exhibition of Archival Documents* (Kitching, Edgar, and Milford 2001).

Their application can also have a significant impact on how standards or guidelines are understood and implemented. It is common to see their inclusion in grant stipulations and contracts, indicating a reward or a penalty for (non)compliance that is not stated in the standard itself. These applications may never have been intended by the creators of the standard.

The Anatomy of a Standard: Influences on Standards and Guidelines

The differences outlined above already show the extent of variation that can exist in the narrow topic of climate specification, but there are a number of inter-related influences that can help explain how standards are created. They provide insight into the context surrounding these authoritative documents, as well as how to interpret them in practice.

Why

Why is a standard a standard? The specifics of the guidance, and why it has been created in the chosen form, can result from a variety of factors. Below are common motivations that individually or collectively can necessitate guidance.

- Controlling quality
- Formalizing an agreement
- Promoting understanding
- Providing a framework for action
- Disseminating new knowledge
- Fostering communication—with external contractors within the field and between disciplines
- Building consensus, including chosen terminology

The discussion above indicates that the choice for a standard or a guideline has implications as to how those motivations might be delivered. The type of document can also greatly impact its use, but is influenced by a series of other factors as well.

The motivations for creating a standard can also provide insight into its context. The European Norm standards (CEN) were developed after several years of European Commission funding of conservation science research as a means to transfer that knowledge into policy and practice. The ICOM-CC/IIC declaration on standards resulted from an identified need in the field to review and unify professional consensus, and "was driven by the social responsibility of reducing non-renewable energy consumption and creating a sustainable future" (Kirby Atkinson 2016).

By Whom and for Whom

The recognized bodies that create standards and guidelines may also have methods of working and approaches that affect the nature and scope of the developed document. A CEN standard must be completed in three years from inception to publication, which can impact how the process is managed and how consultation is employed. Defining a narrow scope in order to achieve a predefined target can determine who is well placed to contribute to the standard. In the case of CEN, the experts—some invited, some volunteers—represented European institutions. Although the standards are available for public comment, which is not the case for many guidelines, who is invited and eligible to contribute will have a significant influence on the outcome.

Those who do contribute do not always agree. The majority of standards are the product of committees or groups with different interests, professional backgrounds, and personalities. The guidance that is developed is the product of consensus, but can potentially lead to compromise or an emphasis on well-established guidance rather than emergent or cutting-edge knowledge.

The "Environmental Guidelines – IIC and ICOM-CC Declaration" included the recognition of several interim guidelines (IIC/ICOM-CC 2014) after significant and vocal debate within and outside of the conservation field. A stated aim of the fixed numbers that were promoted in that declaration was to resolve variation in international loans, rather than to establish a universal prescription for collection preservation. However, the declaration noted that not all of the interim standards were related to loans, which caused confusion among the conservation community about the international guidance (Bickersteth 2016).

A related aspect to the make-up for those writing standards is the professional interests that arise from these contexts. Standards are written in language that is intended to be neutral, which can often (though perhaps unintentionally) mask professional interests. A test devised to identify professional interests in conservation ethics considers who is best prepared to enact the recommendations by Muñoz Viñas (2013), who reflected on an early definition of conservation from 1947 (after Staniforth 2000) that required "understanding and controlling of agencies of deterioration." By considering those involved in collection preservation at the time—art historians, conservators, and chemists—he asked which group was best prepared to "understand agencies of deterioration." The chemist was considered best prepared to understand them, and the chemist and conservator best prepared to control them. This corresponds to what he referred to as the "scientific turn" of object conservation at that time (Muñoz Viñas 2005).

When examining the recommendations and specifications of standards and guidelines, similar patterns can emerge. Those best prepared to understand and carry out the recommendations of Benchmarks (Resource 2002) are collection managers and conservators; those best prepared to carry out recommendations of ASHRAE guidance are conservators and engineers; and those best prepared to carry out guidance from IIC/ICOM-CC 2014 declaration are conservators and registrars. The conservator may often be a continual presence, but allied professions vary in the extent to which they are able to position their activities in relation to the particular guidance.

Guidance for the ASHRAE chapter "Museums, Galleries, Archives, and Libraries" includes a step process for examining and addressing environments. A diagram of the process features a table (ASHRAE 2019, 24.3) with rows corresponding to each step that recommends which stakeholders might lead, be consulted, or be informed at each stage of the process. This is an attempt to avoid the drawbacks of one discipline dominating a process, or the limitations of all stakeholders being equally engaged in each step.

The promotion of communication through interoperability (e.g., same-measurement units), commensurability, or a common language can help set the stage for constructive collaboration between different disciplines. Understanding the audiences that use the standard helps develop a common ground.

"It is true that our profession [object conservation] has a lot of books, conference proceedings and journals. Yet their wisdom is in a format not easily conveyed to others such as colleagues, clients or contractors" (Leigh 2016).

What Standards Can Represent: Context

The scope of standards or guidelines can impact how effectively recommendations or specifications can be implemented. Standards and guidelines are often written for a particular country or region, even if their implementation might extend beyond that scope. The range of conditions within a country, however, can still vary considerably. One example of a typical loan standard is set-point ranges of 45–55% RH, 19–22°C (66–72°F). This represents the box on the psychrometric chart in figure 6.1. This is plotted against the average temperature and RH for January and July in different cities around the world that correspond to different climate zones.

Although this standard often corresponds to international loan agreements, the figure illustrates the diverse conditions that can surround a standard created for the purpose of international travel. A local climate can diverge from prescriptive numbers, so what might be considered "appropriate" for permanent and temporary exhibitions can vary considerably. The comparatively sustainable implementation of HVAC systems with set points based on a local climate is easier for some institutions than others. Deciding on a set of numbers that can be recognized by a national or international body and account for a specific climate within a nation (or beyond) is a considerable challenge.

The moderate 50% RH is more suitable to some regions than others. Padfield points out that even moderation can still lead to the effects more commonly associated with extreme climates. "A 50% RH standard is high enough to cause condensation to buildings in cool climates yet low enough to cause damage to objects that have attained a stress-free condition at a high relative humidity in a church or historic house" (Padfield 1994, 191). Over time, professionals have increasingly recognized the fuel costs required to deliver the suggested ranges.

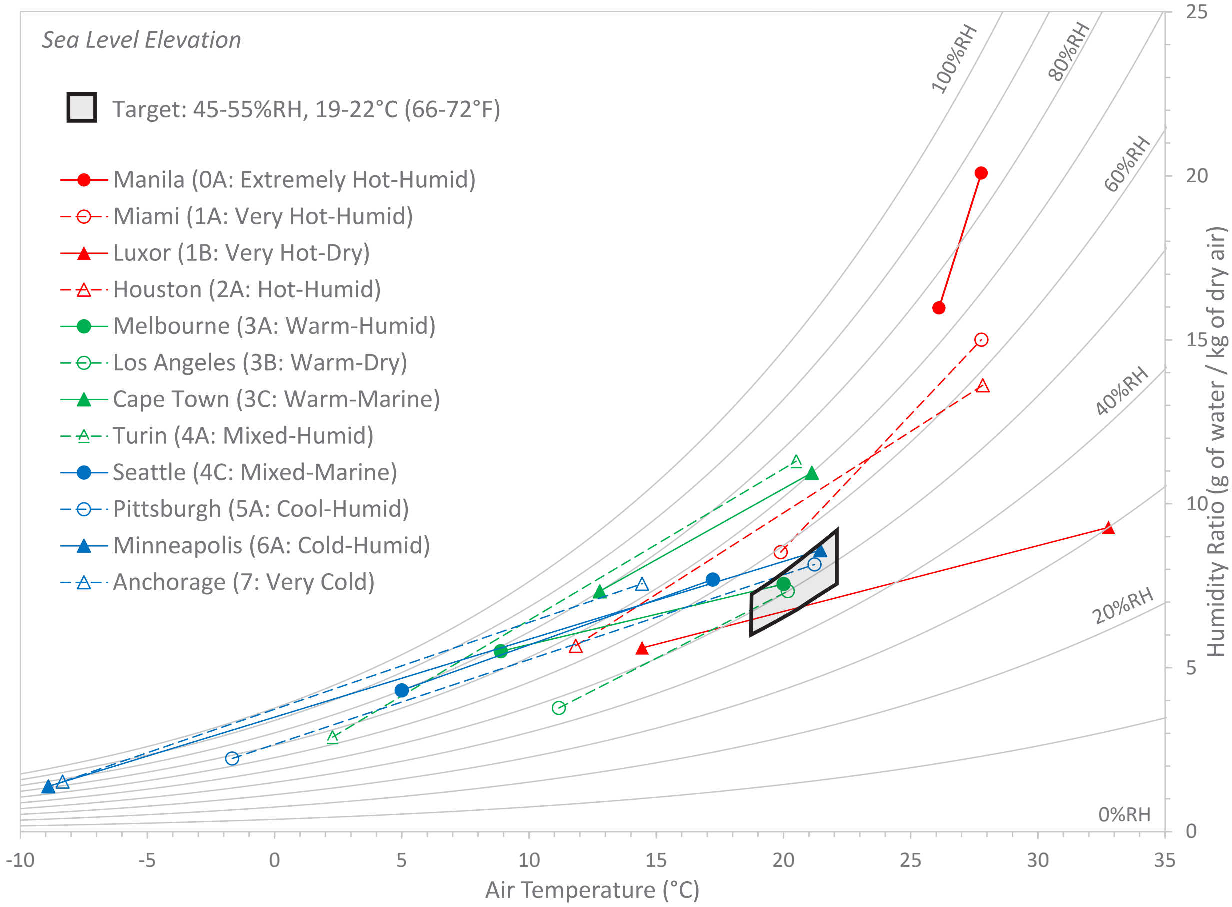


FIGURE 6.1. A psychrometric chart showing the temperature and relative humidity in January and July for cities in different climate zones, many of which can be found in a single country (Taylor and Boersma 2018; formatted: Vincent Laudato Beltran).

Existing Knowledge

All standards require a knowledge base that informs the final recommendations. Many uncertainties and unknown factors contribute to changes in the properties of historic material. Heritage conservation is a small field in comparison with many other professions, and in some cases evidence must be found in those other fields. The guidance for biological threat of mold came from data in the food industry (ASHRAE 2019). Pollution guidance in collection preservation was initially based on data from the World Health Organization. The knowledge required to provide guidance for preservation does not always exist in the desired form. Industrial standards based on repeatable testing of new materials or fields that face similar problems can provide some supportive evidence, but the purpose of the industrial standard may be unrelated to that of the conservation guidance. There are also knowledge gaps that cannot be met by other fields. Standards operate on the platform of best practice, which is constantly evolving and often incomplete or uneven. Several standards and guidelines (e.g., CEN, ASHRAE) are periodically revised.

Damage Mechanisms

In heritage preservation terms, the expected deterioration mechanism can also greatly impact the rationale for applying a standard, and its consequences. An example of this is two documents released for the preservation of archives in the year 2000: one was guidance for determining temperature and relative humidity (RH) set points for archives in Canada developed for the Canadian Conservation Institute

(Michalski 2000), the other a standard for archive preservation in the UK that included temperature and RH - BS 5454: 2000 (BSI 2000). Despite the same kinds of collections involved, several differences can be noted: the kind of document, the geographical location, and the scope of the guidance. A particular difference, however, was the approach to deterioration mechanisms, which focused on fluctuations and physical damage (BSI 2000) and reaction rates and chemical damage (Michalski 2000).

For standard *BS 5454:2000*, the temperature for accessible archives was required to be between 17° and 18°C (62.6°F and 64.4°F), ± 1°C (1.8°F), with RH at a fixed point between 45 and 60%, with fluctuations of ± 5%. Air conditioning was recommended. The climate was designed to be moderate and very stable, which accounted for mechanisms like expansion and contraction that would lead to physical change. Despite the moderate UK climate, the prescriptive and narrow set point meant that the standard was difficult to achieve outside purpose-built locations. Archives that do not comply to the standard could lose recognition and support. A noted criticism was that loose sheets of paper would be more affected by chemical deterioration than by fluctuation (Pretzel 2005), implying that the tight specifications would not have significant impact on preservation.

No fixed set point was in the CCI guideline. The guidance approached preservation in terms of chemical deterioration being most important, and considered equivalent "expected lifetimes" for different temperatures and RH levels that corresponded to the chemical equivalent of 20˚C (68˚F) and 50% RH. This meant that the tight values were used as a reference point, rather than a fixed target (fig. 6.2). Temperature and RH were not considered in isolation as a result. Guidance on RH fluctuation varied with the kind of material (± 5% tiny damage to vulnerable material, ± 40% small damage to low vulnerability material), to account for items that were not loose-leaf archival documents. Allowing for large variations that resulted in the same rate of chemical deterioration meant that different climates could follow the guidance pragmatically: the cold and dry weather that is common in Canada could be an advantage rather than a hindrance. All RH standards/guidelines include fluctuation in some form, but the extent to which this is emphasized varies.

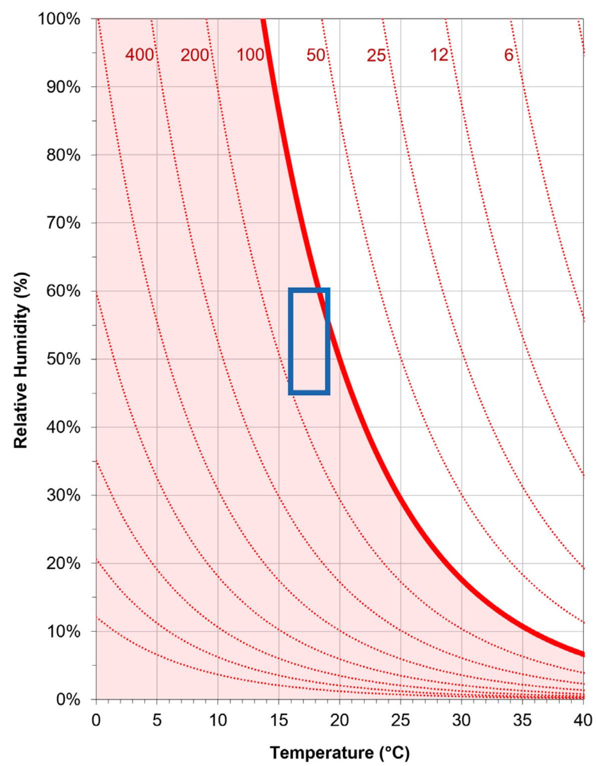


FIGURE 6.2. A depiction of the target ranges for BS 5454:2000 (blue box) and CCI guidance based on permanence calculations (area shaded pink). The red line at the edge of the pink area denotes broadly equivalent chemical deterioration to the area in the blue box, with much of the pink area providing better conditions for chemical preservation (after Ashley-Smith 2018; Pretzel 2005).

Approaches to Concepts

Preservation may be considered in different ways, which can lead to varied ideas about how its guidance should be expressed and what steps an institution might take to meet recommendations. Theoretical approaches to expressing damage can also involve different assumptions.

The European standard *EN 15757* differs from a number of specifications that deal with set points and ranges in that recommendations are based on historical averages, rather than expected change (fig. 6.3). This approach does not involve reference to material properties, testing on mock-ups or new materials, or assumptions about the presence or absence of materials in a collection. It is based on the "proofing" principle that any cracking that a collection has sustained while housed in a given environment is not likely to occur if future fluctuations do not exceed the historic ones. This is based on practical information that is directly related to the immediate climate and collection, rather than on testing, but there is not yet significant evidence to support this common sense approach. Caveats exist: changes to the environment, changes to objects (e.g., repairs or conservation treatments), and material responses to repeated humidity cycles. However, the approach simplifies many of the decisions involved in preservation of mixed materials for permanent collections and storage while making fewer assumptions about the collection.

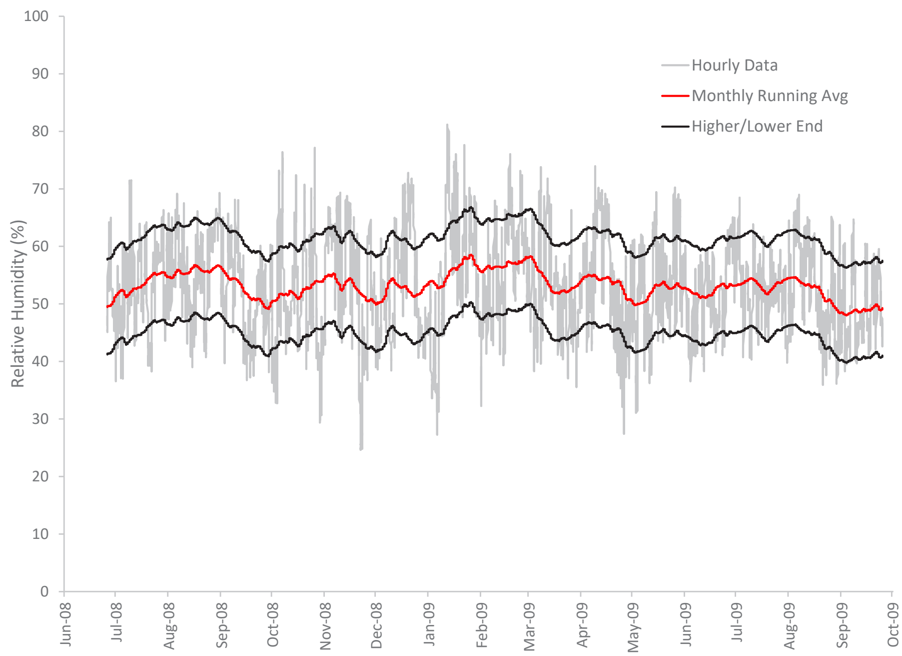


FIGURE 6.3. A moving average and one standard deviation for one year of data plotted for EN 15757:2010. Credit: Joel Taylor

The different approaches have different characteristics and implications. How these recommendations are met, and what is required to meet them, also varies.

What Is Achievable in Terms of Control

Recommendations and specifications are often written with an idea of how the phenomenon might be controlled as well as what specifications might be preferable. A desirable situation in preservation terms might be to have no pollution, which is requested in standard *BS5454:2000*, or no RH fluctuation, but this is hardly achievable. Since the advent of HVAC in museums, set points have often been used to define RH levels (Michalski 2016), initially based on best guesses in the absence of specific knowledge about collection preservation. Maintaining those set points without variation was and remains an unfeasible task, so technological limitations are the main obstacle to achieving this goal.

Using the best available technology as a benchmark, however, leads to the implication that values outside the specification can result in damage (or that no damage will occur within them), when there is no evidence that this is the case. "The standard specification of ± 4 or 5% in RH control is based more on what we can reasonably expect the equipment to do than on any deep knowledge of the effect of small variations on the exhibit" (Thomson 1986, 118).

Other approaches to guidelines that incorporate concepts of control include pragmatic ones, such as those of the National Trust (UK), custodians of historic houses without HVAC. By basing specifications on "conservation heating," humidistatic control utilizes heaters to vary temperature as a means to achieve a stable, moderate relative humidity. During the winter, when houses are closed, temperature specifications need not be based on human comfort. Taking advantage of the moderate, often damp UK climate and the closed operating period allowed the institutional guidance to relax temperature control, to achieve a cost-effective management of relative humidity.

Application

Returning to the matter of applying standards and guidelines, recommendations cannot relate to collection or object preservation alone. Other factors, such as human comfort, which has its own standards and guidelines, must be accounted for in display contexts. These factors are not always directly related to preservation.

How Objects Are Used

As well as collection preservation, standards need to incorporate additional factors, some of which are indirectly connected to heritage preservation. Standards for lighting in museums have rarely been based on the objects themselves, but rather on the point at which color differentiation of those objects becomes obscured. In order for objects to be displayed, some relative humidity, and therefore slow chemical deterioration, is necessary. Access to collection objects requires climate standards for human comfort, such as ASHRAE Standard 55, to be observed, as well as minimum requirements for the ratio of fresh air entering an air-conditioned space to recycled air (ASHRAE 2016).

The expected or intended use of a collection might well have a significant impact on its expected lifetime or the kinds of values that are elicited from it. Distinctions are often made within standards and guidelines about storage and display, but there are additional variations and caveats.

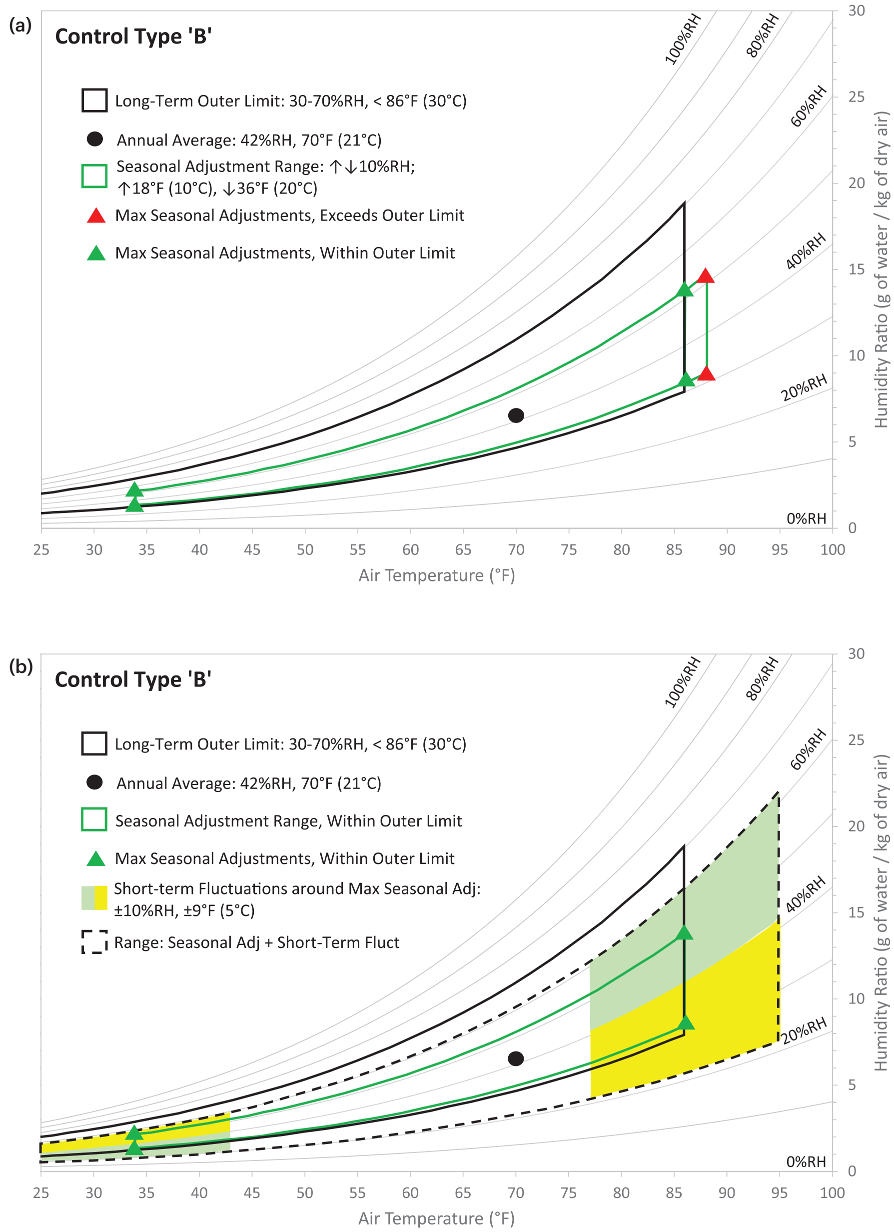
Flexibility

As well as incorporating factors outside of preservation, such as comfort, into climate specifications, there is also the possibility of misapplication, or lack of guidance that represents the specific context in question. Even early attempts to provide summative advice (Thomson 1986) included specific references to the reasoning involved in order to avoid oversimplification. The application of specifications, however, has not always corresponded to the rationale behind them. Figure 6.1 illustrates the kind of situation possible when guidance is applied outside of its intended context.

"A set of fixed points for different materials is wrong but … an agreed procedure for arriving at a sensible specification is worth discussing" (Padfield 1994, 194). The practical implications involve more work, but conservation activities based around expected collection preservation rather than the climate itself can add needed contextual relevance.

Essential to applying guidance is the extent to which published guidance can correspond with the specific application. The chapter "Museums, Galleries, Archives, and Libraries" in the 2019 *ASHRAE Handbook—HVAC Applications* is an example of changes to the guidance that had greater emphasis on process and context. The starting point for determining climate specification changed from 50% RH, with increasing levels of fluctuation, to the historical climate average for the specific collection. Figure 6.4 depicts the climate range for control type B (ASHRAE 2019). The historical average for temperature and RH (the black dot) can be anywhere within both rectangles without significantly increasing risk (fig. 6.4a). With limits for specific damage thresholds, a broad range that could vary between seasons becomes identifiable. From this, tolerances for short-term fluctuations can be configured (fig. 6.4b).

FIGURE 6.4. Psychrometric charts depicting Control Class B based on (a) annual average, long-term outer limit and seasonal adjustment; and (b) short-term fluctuation (after ASHRAE 2019). Credit: Vincent Laudato Beltran



Conclusion

Examining the history of guidance and standards (Michalski 2016), as well as their qualities, illustrates that rigid, narrow specifications are difficult to sustain across a wide range of contexts. Given the variety of factors involved in standards, however, discussion about "relaxing" or "tightening" them may seem limiting.

The assignment of numbers or ranges alone passes over the many contextual factors that give rise to those recommendations, which will vary in relevance from institution to institution.

For international guidance and standards on loans, moderation has often prevailed, with differences of opinion on the range around a moderate band (Bickersteth 2016). Tendencies to practice caution when moving an object from a moderate environment to a climate zone that is humid or dry often arise (often less than when moving objects from dry or humid climate zones to moderate ones), which can further affect resources and management. Analyzing data and understanding the needs of the collections, however, can present opportunities to account for movement between different climatic zones that do not involve moderate climates, or objects coming from outside moderate zones.

As Hatchfield (2011) suggests, recognizing that most collection objects will not sustain damage within a fairly broad range of RH and temperature is a good first step, then customizing for the outliers. "As environmental parameters are broadened, a more individualized approach is needed to protect the most sensitive objects" (Hatchfield 2011, 51).

Trends toward more collaborative, context-sensitive approaches to guidance (e.g., PAS 198: 2012, BS-EN 16893: 2018, ASHRAE 2019) provide more opportunity for guidance to be interpreted with greater sensitivity and, ideally, transparency.

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TECHNICAL NOTE 7: ENVIRONMENTAL MONITORING AND DIAGNOSTICS FOR MUSEUMS

Michael C. Henry, PE, RA

> When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind.—*William Thomson, Lord Kelvin*

Introduction

We monitor by collecting data at defined intervals in order to identify trends in a variable of interest. The time-based trends can provide us with insights into the behavior of a system, such as an interior environment, or perhaps a process or activity.

There are three typical objectives for monitoring in stewardship of cultural heritage: diagnostic, collection management and validation/performance. Diagnostic monitoring is used to correlate trends in one or more causal factors with the trends in, or evidence of, the process or system of deterioration or damage in a site, building, or object. Collection management monitoring is used to document the conditions to which an object or a collection has been exposed. Validation or performance monitoring is used to confirm the predicted or desired performance system or process, such as the environmental management system or the visitor experience and its quality. The objectives for each of the above types of monitoring typically include the collection of data and may include alerts when certain thresholds are exceeded by the measured variables.

This technical note provides strategic guidance for diagnostic monitoring for cultural heritage, including collections of museums, galleries, archives, and libraries, and the historic and non-historic buildings that house the collections. It is focused on diagnostic monitoring for problems in deterioration or environmental management, but the principles contained in the note can be applied to investigating and monitoring issues, such as visitor flows through a museum. Various monitoring terms are included in the glossary at the end of this publication.

This technical note reviews Diagnostic Monitoring as a problem-solving tool and addresses the following topics:

- Diagnostic monitoring in cultural heritage
- Problem identification and diagnostic thinking
- Basics of measurement
- Planning a diagnostic monitoring program
- Design and selection of the monitoring system
- Deploying and maintaining the monitoring system
- Analyzing the monitoring data and the presenting the results

Diagnostic Monitoring in Cultural Heritage

Diagnostic monitoring is essential for correct identification of causal factors of deterioration or damage to buildings and collections and for assessing the effectiveness of interventive or preventive conservation strategies. Monitoring can sharpen the focus on a problem by quantifying variables that elude qualitative description, or for measuring changes or rates of change that are too small for direct visual observation. Monitoring over extended time, such as a full year of seasons, expands the window of data collection and observation across a range of causal conditions and their variations.

Making sense of the collected monitoring data requires an understanding of measurement theory, instrument specifications, and statistics. Understanding of the process being monitored is also required. For example, environmental monitoring requires knowledge of psychrometrics, the transport of air, moisture and thermal energy, and the moisture content characteristics of materials.

Diagnostic monitoring programs should be designed to answer a specific set of questions or concerns; uninformed, directionless monitoring will yield irrelevant data. Monitoring should generate data that are both useful and reliable; otherwise, the data may lead to erroneous conclusions. Unnecessary monitoring may not put a building or collection in direct risk, but unnecessary or misdirected monitoring can divert valuable time and financial resources from implementation of effective preventive or interventive strategies to resolve an identified problem.

The objectives of a monitoring program, and how the monitoring data are to be used, will greatly influence the type and location of the measurements, the selection of monitoring devices and monitoring software, and the placement of sensors. The objectives of the monitoring program must be clearly defined before the system is designed or purchased. This is best accomplished by applying diagnostic thinking before embarking on the development of a monitoring program or selection of the monitoring devices.

Problem Identification and Diagnostic Thinking

A problem in conservation of cultural heritage may be identified when an object or historic building fabric exhibits accelerated deterioration or damage. For example, the deterioration may appear to be caused by environmental factors such as extreme high or low relative humidity/temperature conditions, fluctuations in relative humidity/temperature, or exposure to light or ultraviolet radiation. Some problems with environmental management may be relatively simple to identify and resolve, such as a room becoming too cold because sunlight strikes a thermostat and the thermostat does not sense that heating of the room air is required.

In reality, the deterioration of an object or building fabric usually results from a large system of interacting factors: the exterior climate, sunlight, the building envelope including operable elements such as doors and windows, occupants and their activities, equipment and lighting, and the HVAC equipment. Because of this complexity, and the resultant dynamic behavior of the environment, correctly identifying and resolving many conservation problems requires an analytical approach to identifying the causal factors. Properly designed, diagnostic monitoring can provide data that show how parts of the overall system behave and the relationship of those systemic behaviors to causal factors.

In practice, the diagnostic process is often iterative and rarely linear. Watt (2007) sets out a decision-making flow chart for diagnosis of building pathologies. This process is applicable to deterioration cultural heritage problems generally and is less linear than methods in other possible guidance documents, such as the guidance in ASCE 30 (2014).

In cultural heritage, the challenging problems in deterioration of fixed or moveable property are complex and involve multi-variant causal factors. Some factors may be interrelated, such as the amount of rain, soil moisture, and foundation moisture, but other factors may be independent yet result in the same or similar forms of deterioration or damage. These problems do not lend themselves to heuristic solutions and require a consciously analytical approach to diagnosis by the heritage professional.

Croskerry (2009) has studied the medical diagnostic process in emergency situations and illustrated a model for diagnostic thinking in medicine that alternates between two cognitive processes, System 1 (intuitive-heuristic) and System 2 (analytic), as shown in figure 7.1. In this model, the presence, or lack, of information influences the diagnostician's thinking. Croskerry (2003) also listed the potential traps in System 1 (intuitive-heuristic) thinking, citing the potential to arrive at an erroneous diagnosis due to biases or predispositions in the medical diagnostician's thought processes. Examples of diagnostic predispositions described by Croskerry include: "unpacking principle," "confirmation bias," and "ignoring negative evidence."

An important outcome of research on the diagnostic process is that, as diagnosticians of a problem, we need to be conscious of our own thinking (meta-cognition) to understand our thinking processes, so we can improve our ability to correctly analyze and diagnose problems.

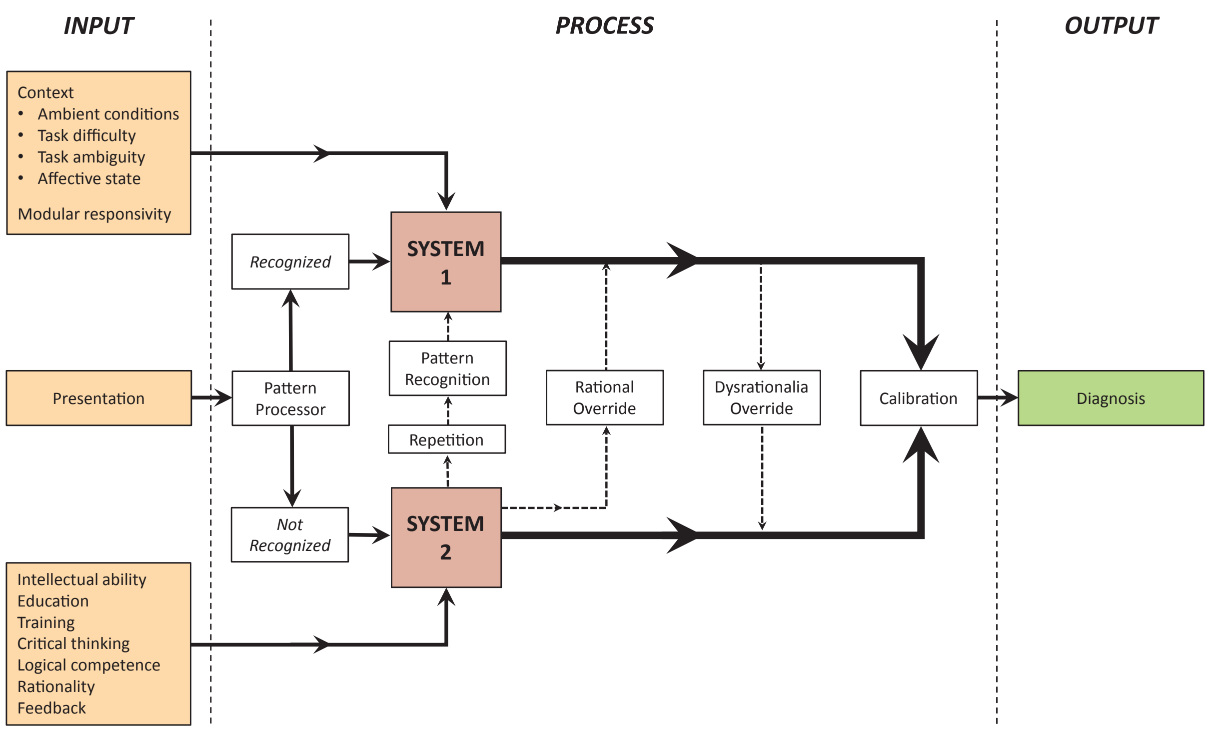

FIGURE 7.1. Diagnostic thinking model (after Croskerry 2009).

Drawing from Croskerry and Watt, diagnosing problems in environmental management in cultural heritage would include the following essential actions:

- Understand the climate and environmental context of the building and object.
- Review documentation pertaining to the design, construction, and alteration of the building, the building envelope, and systems.
- Review documentation on the object, its origin, its current condition, and its history of damage and treatment.
- Review available documentation of mechanical system performance, including data.
- Qualitatively assess the potential hygrothermal performance of the building envelope.
- Clarify and define the actual problem, not just the symptomatic evidence.
- Identify potential factors that might contribute to the problem.
- Develop multiple working hypotheses (Chamberlin 1897) as to the potential cause(s) of the problem, the processes that are enabled by the causal factors, and the observable results of the processes.
- Identify the data and information that are needed to prove/disprove the working hypotheses.

Basics of Measurement

Monitoring is the process of measuring key parameters at set time intervals in order to identify trends or behaviors of a system; in this use, examples of a "system" would include a process of deterioration or HVAC system. Monitoring data can provide insights as to possible correlations between cause and effect and identify causal factors of a problem. Therefore it is important that the measurements are accurate and precise and that the resolution of the measurements is small enough to reveal meaningful differences in the data within the time frame of the monitoring interval.

Qualitative information collected by monitoring can be useful if it is based on a common standard, such as the Blue Scale Fading Cards that are used to assess exposure to light. In the absence of a standard, qualitative information is likely to be of limited use in making meaningful comparisons over time. For example, observations of an environment's thermal and moisture conditions may be characterized by observers as "hot," "cold," "temperate," "damp," "saturated," or "dry." These characterizations would be of limited use because they are based on individual sensations that are influenced by physiological and psychological factors in addition to actual environmental conditions.

For basic measurements or simple comparisons, a handheld device such as a light meter or hygro-thermometer may be sufficient provided that random error by the operator is minimized. For measurements taken at multiple locations on frequent intervals, automated measurements and data collection are preferred due to reduced random error and more efficient use of staff time.

ASHRAE (2021) provides a technical discussion of measurement, errors, and uncertainty in measurement, and identifies the types of instruments used to measure environmental conditions. The glossary at the end of this publication provides definitions of terms encountered in measurement and monitoring.

Planning a Diagnostic Monitoring Program

Planning for a diagnostic monitoring program requires consideration of:

- establishing variables to be monitored;
- determining the frequency of measurement and the duration of data collection; and
- budgeting for the monitoring program.

Establishing Environmental Monitoring Parameters

After the hypotheses for a problem have been defined, the variables to be measured can be identified and the necessary parameters for the monitoring program can be established. Depending on the hypotheses, diagnostic monitoring may involve measurement of a several potential causal factors in the process of deterioration. For diagnostic monitoring of collections environments, these variables may include temperature, relative humidity, dew point temperature, daylight, ultraviolet radiation, vibration, and movement or displacement. In diagnostic monitoring of environmental management systems, the hypothesized causal factors may also be external to the building, such as precipitation, wind, soil moisture, solar radiation and atmospheric temperature, relative humidity, and dew point, as well as equipment operation and cycling.

The numerical range of each of the variables to be monitored can be determined by taking spot readings, conducting short-term monitoring, or reviewing available exterior climate and interior environmental data. The service conditions in which the instrument must take measurements are factors as well. For exterior relative humidity conditions, for example, a relative humidity sensor may experience condensation on the sensor surface that can cause errors in subsequent measurements. In some exterior exposures, high service temperature may affect instrument accuracy or battery life.

Determination of the necessary measurement accuracy should take into consideration the difference in a monitored variable that will be significant to proving/disproving a working hypothesis. For instance, if the accuracy of a relative humidity data logger is ± 3% RH, a difference in measurement of less than 6% RH between two devices cannot be considered significant unless the devices demonstrated a constant difference (offset) over the entire measurement range for the same condition.

Precision—the relative agreement between successive measurements for a fixed variable—is important if we need to draw conclusions from differences in values taken with the same instrument in a space at the same time, or at a specific location over one or more intervals in time.

Determining the Frequency of Measurement

The duration between recorded measurements should be sufficiently small to establish overall trends while capturing fluctuations that might be of diagnostic interest. The significance in the magnitude or duration of short-term fluctuations will depend on the hygric or thermal response time of the object(s) of interest as well as the cycle time for certain HVAC system operations, such as air-conditioning compressors. If the monitoring interval is too long, changes in the measured variable will be missed and critical information about the behavior of the mechanical system may not be captured. If the monitoring interval is too short, large quantities of irrelevant data will be generated.

ASHRAE (2019) and the Canadian Conservation Institute (2017) provide guidance for risks to objects and assemblies based on the magnitude and duration of relative humidity and temperature fluctuations. This guidance can be used to determine the necessary monitoring parameters with respect to measurement intervals or frequency.

The number of variables and the measurement intervals will result in the volume of data generated by the monitoring program. A monitoring program can generate a large volume of data, and unnecessarily large volumes of data can increase the staff time required for data downloads, storage, retrieval, and analysis. Therefore the estimated volume of data should be considered as part of the development of the monitoring program. Extraneous and unnecessary data may obscure the vital information needed to understand the cause/effect relationship of the problem at hand.

Initial Budgeting for the Monitoring Program

The budget for the monitoring program should realistically address the costs of monitoring system design, procurement and delivery of hardware and software, installation, calibration, and maintenance of systems, data collection and storage, and data analysis and presentation. Developing an initial budget that encompasses all of these potential costs is a good reality check as to what is feasible to undertake in a monitoring program. The initial budget should be revised and updated as the specifics of the monitoring system evolve.

Design and Selection of the Monitoring System

Monitoring can be undertaken by two basic types of equipment, standalone data loggers and communicating data loggers with multiple sensors (fig. 7.2).

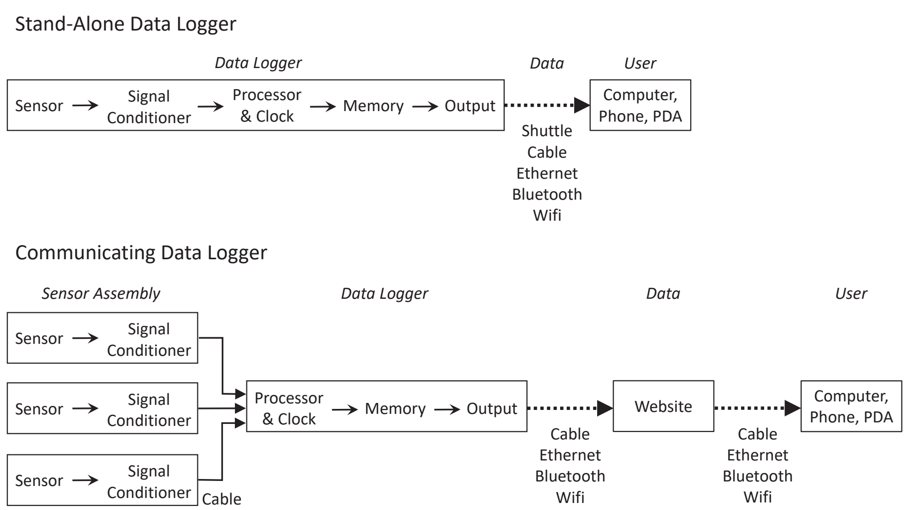

FIGURE 7.2. Schematic diagrams of a standalone data logger (above) and a communicating data logger (below). Credit: Michael C. Henry and Vincent Laudato Beltran

The standalone data logger is typically capable of measuring and recording temperature and relative humidity measurements with all the necessary data logger functions contained within the device. Some standalone data loggers can receive digital or analog signals from multiple sensors and store the data. Standalone data loggers may have a screen that displays the current values of the measured variables, battery capacity, and available memory. The data stored in a standalone data logger must be downloaded periodically by a staff member to a computer or similar device for analysis and viewing as a trend; the frequency of downloading will depend on memory capacity of the data logger and the measurement interval. Data may be downloaded directly to a computer by cable connection or Wi-Fi, or via an intermediate memory device such as a smartphone or data shuttle.

The standalone data loggers are small, easily relocated, and usually unencumbered by power or signal cables. Standalone data loggers can be stolen unless fastened to the building or exhibit case. The variables that can be measured by standalone data loggers are limited.

Communicating data loggers can automatically upload data to a website at regular intervals using a cable or Wi-Fi connection to a local area network or via a built-in cellular communication module. Communicating data logger systems can serve multiple sensor channels. Sensors may transmit data to the data logger through hardwired cables or wireless networks with low signal strength. The use of low-power wireless sensors inside buildings may be limited by the thickness and materials of walls, floors, and ceilings.

Communicating data loggers can serve a variety of digital and analog sensors, and measurements can include variables such as soil moisture, infrared temperature, surface temperature, barometric pressure, and organic vapors, in addition to temperature and relative humidity (fig. 7.3). Communicating data loggers with built-in Wi-Fi or cellular data modules can upload data to a website at designated intervals. The website can be accessed for near real-time trend viewing and for alarm functions on personal devices such as smartphones and computers.

FIGURE 7.3. A communicating data logger, solar power panel, and weather sensors. Photo: Michael C. Henry

In addition to answering the fundamental question of standalone versus communicating data loggers, design of the monitoring system and selection of the data logger(s) and sensors to implement the monitoring program should consider other factors:

- Quality and types of measurements to be made
- Service conditions and available electrical power
- Data logger software

The Quality and Types of Measurements

The performance specifications for the instrument system must satisfy the requirements of the monitoring program with respect to accuracy, precision, resolution, and sensitivity. The variables to be measured will depend on the hypotheses as to the cause(s) of the problem.

At a minimum, the monitoring system should be capable of monitoring temperature, relative humidity, and dew point temperature. Dew point temperature, an indication of the air's moisture content, is a critically important variable in the diagnostic process because it can be used to determine the origin of moisture vapor sources or if moisture vapor migrates between spaces. Typically, dew point temperature is not measured directly but is calculated by the data logger software based on temperature and relative humidity. Data logger software that does not provide dew point temperature data is inconvenient for diagnostics of environmental issues, requiring the user to calculate dew point temperature separately.

More complex diagnostic programs may require measurement of variables such as the on/off state of mechanical equipment, the open/closed state of exterior or interior doors, moisture content of soil under the floor, differential pressure between interior and exterior, daylight (solar radiation), or non-contact surface temperature of a collection object. For ease of use and efficient analysis of data, it is important to select a monitoring system that is capable of measuring all of the necessary variables within a single family of data-logging devices and software.

Service Condition and Available Electrical Power

The monitoring system must be able to perform reliably and accurately within a range of service conditions.

Devices used for exterior monitoring will be subjected to more extreme conditions than devices used inside the building. Exterior devices should be fitted with enclosures that are water-, rain-, and moisture-vapor tight. Connections in cables must be fitted with seals and installed with drip loops so that water does not seep past the seal. Some interior locations, such as wet basements, should be treated as exterior installations because of the prospect of condensation on electronics.

All electronic devices will need a reliable source of power. Standalone data loggers usually have internal batteries for power, but exterior service conditions can shorten battery life or cause voltage to drop below the level needed for the logger. Communicating data loggers, with multiple analog and digital sensors and Wi-Fi/cellular modules, consume more power than standalone units without communications capabilities. The communicating units are fitted with batteries that must be charged and will need typical line voltage power. If mounted outside, a small solar panel may be sufficient to keep the battery charged.

Data Logger Software

Data logger manufacturers develop their own proprietary software for formatting the data. The manufacturer's software may provide simple trend-graphing of data, but the visual and technical quality of the graphics may be limited.

Ideally, the manufacturer's software should allow for combining different datasets from multiple data loggers or sensors (from the same manufacturer) into a single graph for ease of comparison. Other software features should include the ability to customize trend line colors and styles, adjust the value range of the graph axes, and switch between systems of measurement units (Celsius to Fahrenheit, for example). The data logger software should provide the option to export data in other formats, such as .csv (comma separated values) for use in software such as Microsoft Excel or for uploading to specialized software such as eClimateNotebook (Image Permanence Institute 2023) for analysis.

Because operating software on personal computers is frequently updated, it is important that the data logger manufacturer is sufficiently robust that the manufacturer can provide updates to the data logger software over the expected service life of the monitoring system.

Deploying and Maintaining the Monitoring System

As is the case with any system, monitoring systems must be managed and maintained in order to obtain expected results. As part of implementing a monitoring program and maintaining a monitoring system, museum staff should:

- establish responsibility for training in the operation of software or devices;
- assign responsibility for answering questions and troubleshooting problems after start up;
- establish a plan for maintenance, including battery replacement and annual checks for device accuracy; and
- determine what spare parts, such as sensors or batteries, are needed to avoid interruptions in data.

Accuracy and consistency of data are essential if monitoring results are to be used to differentiate causal factors of deterioration or damage. For this reason, the deployment of sensors and standalone data loggers requires planning and care (fig. 7.4). Placement of sensors and standalone data loggers should include consideration of their exposure to theft, shock, pressure, or mechanical damage. These devices should be isolated from spurious or extraneous influences on measurements that are not part of the investigation, such as drafts, reflected sunlight, or heat from exhibit lighting and lighting ballasts. Although they must be protected from the public, standalone data loggers should be accessible to staff for periodic data downloads and battery replacement.

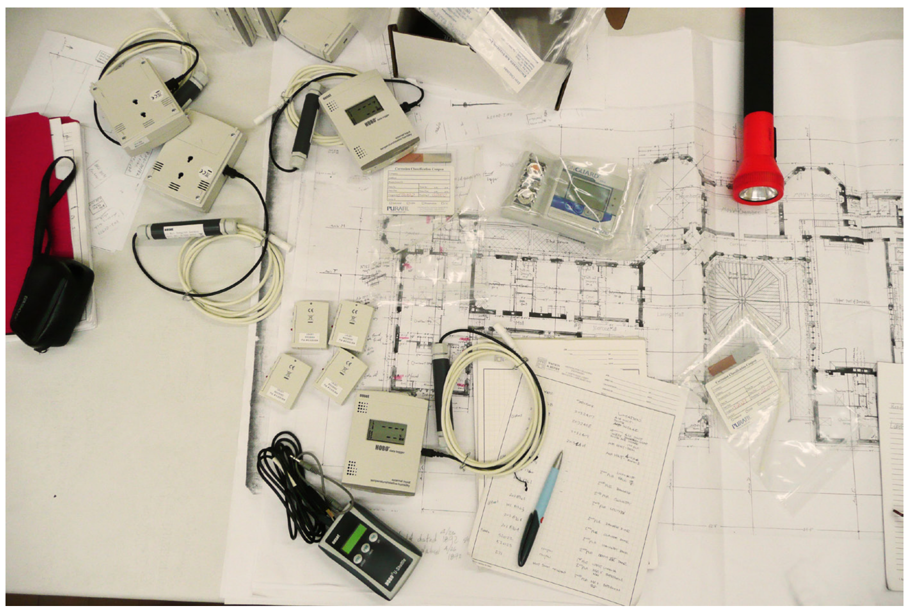

FIGURE 7.4. Preparing to deploy a monitoring system. Photo: Michael C. Henry

Over time, the accuracy of measurement devices may degrade due to drift or sensor contamination. It may be impractical to check devices in monitoring systems with a three-point calibration as used for laboratory or scientific instruments. All measurement devices in a monitoring system should be periodically checked for accuracy. This can be done by using a high accuracy handheld meter to compare results *in situ*, or by doing a bench comparison of devices in a controlled space. In either instance, differences in readings should be noted, and if a device performs outside the acceptable accuracy range, it should be repaired or replaced.

The integrity of the monitoring data collected is essential for confirmation of the diagnostic hypotheses. To ensure data integrity, planning for data collection and compilation should address the capture, downloading, file-naming protocols, organization, and retention of the data that was originally downloaded.

Analyzing the Monitoring Data and Presenting the Results

The monitoring data must be analyzed and interpreted to determine whether the initial hypotheses have been confirmed or validated and if not, why. The analysis should also address unanticipated results.

Data presentation and results should visually demonstrate causality in a comprehensible and efficient format. Tufte (1997, 2006) provides extensive review of effective and ineffective methods for displaying quantitative information, adhering to the metaprinciple that the design of presentations of information must be derived from the cognitive tasks that the presentation informs. Tufte's basic principles for graphical display of information may be summarized as such:

- Display all data on a consistent and uniform graphic scale.
- Make comparisons.
- Show causality.
- Show multivariant information.
- Integrate word, number, and image in a single space.
- Document sources.

Summary

A well-designed diagnostic monitoring program can be useful in analyzing and correcting a problem or condition in conservation of cultural heritage.

Diagnostic monitoring programs require a commitment of financial and staff resources. Poorly designed diagnostic monitoring programs can result in large volumes of irrelevant data. Therefore it is essential that monitoring programs be thoughtfully designed and that the program is preceded by:

- disciplined and thorough assessment of the building and collections and their conditions;
- formation of diagnostic hypotheses that identify the possible causal factors of the observed condition;
- identification of the variables to be monitored to prove/disprove the hypotheses;
- selection of devices and equipment appropriate for the desired data, the conditions of the building and the financial and staff resources available for the undertaking, using the simplest, rather than most complex, available technology; and
- rigorous and consistent implementation of the monitoring program and analysis of the results.

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TECHNICAL NOTE 8: ANALYSIS AND VISUALIZATION OF ENVIRONMENTAL DATA

Vincent Laudato Beltran

Introduction

The collection and analysis of environmental data seek to answer underlying questions about existing environmental conditions. In the museum context, emphasis is placed on the collection of interior air temperature and relative humidity data, but information for other environmental variables, such as light, occupancy, vibration, and pollution, may also prove helpful. The collection of data constitutes fulfillment of environmental monitoring criteria, but the analysis and interpretation of this data are critical for supporting decision-making regarding environmental management.

The purposes for collecting environmental data can include the following:

- Comparisons of current environmental conditions to recommended guidance and/or loan conditions for the collection (and occupants)
- Assessment of a building's ability to moderate thermal and moisture loads from the exterior climate
- Identification of potential seasonal extremes that may pose a risk to a collection
- Guidance in prioritizing and developing environmental management strategies (nonmechanical or mechanical)
- Establishment of benchmark environmental conditions before implementation of environmental management strategies to allow for a post-implementation assessment

Following the collection of environmental data, exploratory analysis distinguishes relationships or trends in the dataset, compares results to prior conditions and/or existing guidance in the field, and produces tabular and visual representations of the data. The use of clear and succinct data visualizations is particularly important when presenting environmental monitoring results to an interdisciplinary team—conservator, curator, facilities and maintenance staff, engineer, architect, and director—with varying levels of expertise in the subject matter. Different audiences may require different levels of data interpretation, which is reflected in the choice of visualizations. The sharing of information will establish awareness of the current environmental conditions and, if its preservation state is to be improved upon, promote discussion of appropriate nonmechanical and mechanical measures to bridge the gap between current and target conditions.

Statistical Analysis

Statistics provide a framework with which one can organize, analyze, interpret, and present raw data. The use of numerical indices such as an average or standard deviation allow for a quantitative summary of the data. Note that raw data denotes the original source information (e.g., hourly temperature or relative humidity data taken directly from the data logger), which contrasts with data processed to facilitate analysis.

Numerical Indices

Various numerical indices or measures can be used to statistically characterize a dataset. Two index types are measures of central tendency, which seek to describe the middle of a dataset, and measures of dispersion, which examine the spread of data within a dataset.

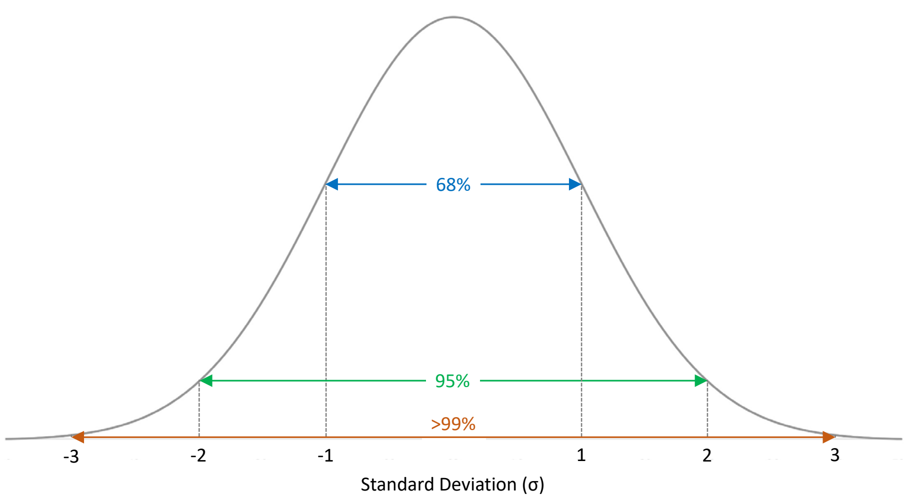
Common measures of central tendency include the following:

- Mean: the "average" value of the data, arithmetic mean is typically used (i.e., sum of all values divided by the number of values)
- Median: the middle number when ranked in order of magnitude, relatively unaffected by extreme scores or skewed distributions

Common measures of dispersion include the following (note that the first two describe spread about the mean, while the latter two define specific intervals of interest):

- Variance (σ^2): average squared difference between observations and the mean value; differences are squared to account for negative deviations from the mean, but this makes comparison to the mean value less obvious
- Standard deviation (σ): square root of the variance, allowing it to be expressed in the same units as the original variable (e.g., mean); assuming a normal distribution, $\pm1\sigma$, $\pm2\sigma$, and $\pm3\sigma$ encompass 68%, 95%, and 99% of the values, respectively (fig. 8.1)
- Range: difference between maximum and minimum values
- Interquartile range (IQR): difference between the third quartile (Q3) and first quartile (Q1) of the dataset, which will be elaborated upon shortly; assuming a normal distribution, the range encompassed by Q3 + (1.5 x IQR) and Q1 – (1.5 x IQR) is roughly equivalent to $\pm3\sigma$ or 99% of the values

FIGURE 8.1. A normally distributed curve with standard deviations overlain.



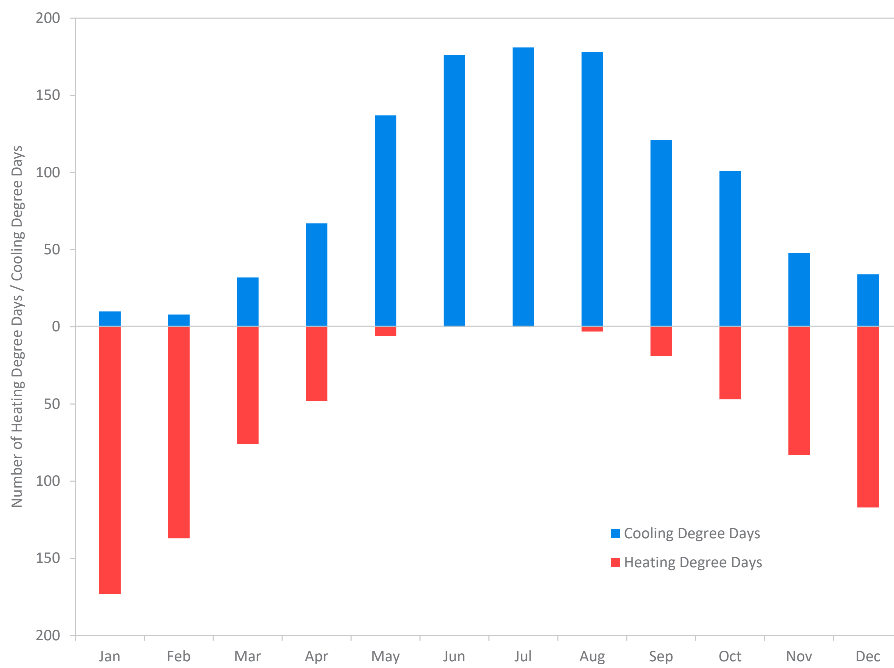
The IQR is anchored by the concept of probability distribution that describes how likely a value is to occur in a dataset. A probability distribution can be divided into quantiles, which are contiguous intervals containing equal proportions of the dataset. Divisions of a dataset into four quantiles are referred to as quartiles (i.e., each interval contains 25% of the dataset), and divisions into 100 quantiles are called percentiles (i.e., each interval contains 1% of the dataset). Thus, the third and first quartiles, whose difference defines the IQR, can also be described as the 75th and 25th percentiles, respectively, while the median is the 50th percentile. These divisions will form the basis of box plots, which will be described later.

The definition of a percentile is the value below which a given percentage of the dataset falls. For instance, if the 75th percentile of air temperature data in a storage space is 23°C, this indicates that 75% of the temperature data are below 23°C and 25% are above 23°C. If data are collected continuously during the monitoring period, the percentile also denotes the percentage of time that values are above and below a specific threshold. Conversely, one can use the probability distribution of a dataset to estimate the percentile for a specific value, such as a mold germination threshold of 65% RH. If the relative humidity value of 65% is associated with the 90th percentile of the humidity dataset, then 90% and 10% of the data are below and above 65% RH, respectively.

Data Subsets

While statistics can be used to characterize an overall dataset, application to specific subsets of raw data can be instructive. A common comparison for a museum gallery or storage space is to examine seasonal environmental data, which illuminate transitory risks of damage to a collection that might be masked in a statistical analysis of an annual dataset. Thus, environmental analysis often calls for the examination of at least one year of data. Further, the partitioning of environmental data should be based on seasonal trends for the exterior climate. For example, temperate regions may have a four-season climate (spring, summer, autumn, winter), while warmer and more humid climates may only experience a two- or three-season climate (dry, monsoon, cool). Seasonal distinctions can be made more apparent by examining location-specific engineering metrics (e.g., Engineering Weather Data 2000) such as heating and cooling degree days or mean ventilation and infiltration loads over the course of an average year (fig. 8.2).

FIGURE 8.2. Heating and cooling degree days recorded over one year.



The response time of cultural heritage objects to changing environmental conditions in a gallery or storage space can also inform how one might statistically process the data. Temperature equilibration of objects typically occurs in a matter of hours due to a relatively rapid thermal response of the constituent materials. (Due to the potential exposure to more extreme temperatures and the use of insulation materials, the thermal equilibration of crated objects following transport may be extended.) In contrast, the full equilibration of massive hygroscopic objects, such as furniture, to shifts in relative humidity may take up to several days, weeks, or even months. Thus, the slower moisture response of a massive object may necessitate processing the relative humidity data in a way that better reflects the object's effective exposure conditions. In this case, application of a moving average for weekly or monthly relative humidity may be a more relevant metric with respect to full object response. A moving average calculates the mean value for a defined window of time that is then shifted forward over the entire dataset, smoothing out the short-term variability present in the raw data and emphasizing trends over an extended period.

Data Classification

The 1978 publication of *The Museum Environment* by Garry Thomson underscored the concept of environmental management as a means of preventive conservation. While Thomson's work is often cited as an influential factor in the prescriptive adoption of 50 ± 5% RH and 21 ± 2°C (70 ± 4°F) as standard museum conditions, in reality the book describes a nuanced range of interior environmental conditions appropriate within the context of various climate zones and building and collection types. Research and practice on the topic of the museum environment have continued to progress and, since Thomson's seminal contribution, an evolving series of environmental guidelines have been developed.

These guidelines provide an opportunity to assess the preservation state of specific museum environments by comparison to temperature and relative humidity criteria, and can supplement the statistical characterization of the environmental dataset. These criteria can be applied to the overall dataset or to subsets comparing seasonal risks or periods before and after implementation of management strategies. While continued research and experience are certain to lead to further refinements (or the creation of new guidance), protocols for evaluating interior museum environments have been set forth by several recent publications. These include, but are not limited to:

- *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* (BSI 2018);
- "Museums, Galleries, Archives, and Libraries," chapter 24 in the 2019 *ASHRAE Handbook—HVAC Applications*;
- *Environmental Management for Collections: Alternative Conservation Strategies for Hot and Humid Climates* (Maekawa, Beltran, and Henry 2015).

Intended as a move toward risk-based assessment and away from the use of prescriptive standards, *BS EN 16893:2018* visually presents the relative risks of temperature and relative humidity-induced damage as a sliding scale (table 8.1). Collection risks are defined in terms of chemical sensitivity for temperature, and chemical sensitivity, mechanical sensitivity, and mold risk for relative humidity. Further, awareness of the sensitivity of one's own collection materials to changes in reaction rates (chemical risk due to temperature) and hydrolysis (chemical risk due to relative humidity) is needed to apply the appropriate high, moderate, or low sensitivity scales. The specification also presents seasonal energy considerations as it relates to various target temperature and relative humidity conditions.

Acknowledging its primary audience of HVAC engineers, environmental specifications from ASHRAE's 2019 chapter "Museums, Galleries, Archives, and Libraries" are geared toward the design parameters of HVAC systems, such as annual average, long-term limits, seasonable adjustments, and short-term fluctuations (table 8.2). The resulting environmental control classes are defined by variations in these design parameters.

TABLE 8.1.

Relative risk of damage and deterioration for relative humidity from BS EN 16893:2018. Permission to reproduce extracts from British Standards is granted by BSI Standards Limited (BSI). No other use of this material is permitted. British Standards can be obtained from BSI Knowledge knowledge.bsigroup.com

Risk factors		Relative humidity % (0 10 20 30 40 50 60 70 80 90 100)
Chemical stability [1]	High sensitivity to hydrolysis [2]	
	Medium sensitivity to hydrolysis [3]	Some inorganic materials, such as metals, will benefit from relative humidity below 30% [4]
	Low sensitivity to hydrolysis [5]	
Mechanical stability [6]	Safe range for most non composite, non constrained hygroscopic items to avoid mechanical damage	Organic materials can become less flexible, increasing the risk of damage mainly by mishandling; Above 70%, stability decreases in some materials, e.g. wood
Risk of mould [7]	Risk of mould germination at 20 °C	
	Risk of mould growth	
Energy considerations [8]	Reduced energy demand for humidification in winter-spring	
	Reduced energy demand for dehumidification in summer-autumn	

KEY

1) Chemical stability: these ranges show higher relative humidity leading to accelerated moisture-induced chemical degradation rates, indicated by the gradation from green to red.

2) High sensitivity to hydrolysis: materials with a relatively high presence of hydrolysis-sensitive chemical groups within the polymer chain, e.g. leather and textiles previously acidified by pollution, cellulose acetate and nitrate film.

3) Moderate sensitivity to hydrolysis: materials with a relatively moderate presence of hydrolysis-sensitive chemical groups within the polymer chain, e.g. some wood pulp papers.

4) Examples of inorganic materials that need lower RH levels than organic materials include archaeological iron, copper and lead, historical steels, copper alloys, zinc, tin, pewter, lead, salt laden stone, salt laden ceramics, stone with expanding clay materials. These may need dry stores or microclimate packaging.

5) Low sensitivity to hydrolysis: materials with a relatively low presence of hydrolysis-sensitive chemical groups within the polymer chain, e.g. rag paper, polyester film.

6) Mechanical stability: the area shown in yellow indicates the range within which the risk of physical damage is higher, whilst the area shown in green indicates the range within which the risk of physical damage is lower. In the area below 30% RH, the risk of damage to organic materials by mishandling is increased despite the reduced rate of chemical degradation. In the area above 70% RH, for some materials e.g. wood, mechanical stability decreases.

7) Risk of mould: the areas shown in grey indicate a precautionary upper limit of 65% RH to avoid mould germination at 20 °C. The gradation to darker grey indicates increasing risk of mould growth and faster germination times. Note also that mould germination and growth are also temperature dependent.

8) Local climate will affect energy considerations and achievement of safe RH ranges for the collection.

TABLE 8.2.

Temperature and relative humidity specifications for collections in buildings (not shown are specifications for temporary exhibition spaces and unstable materials) (ASHRAE 2019, figure 13A). Figures, tables, and sections mentioned in the footnotes can be found in ASHRAE 2019. © ASHRAE, www.ashrae.org

Type of Collection and Building	Type of Control	Long-Term Outer Limits[a]	Annual Averages	Seasonal Adjustments from Annual Average[b]	Short-Term Fluctuations plus Space Gradients[c]	Collection Benefits and Risks[d]
Museums, Galleries, Archives and Libraries in modern purpose-built buildings or purpose-built rooms **Temperature at or near human comfort**	**AA** Precision control, no seasonal changes to relative humidity	≥35% rh ≤65% rh ≥10°C ≤25°C	For permanent collections: historic annual average of relative humidity and temperature. In public display areas, human comfort temperatures can apply.	No change to relative humidity Increase by 5 K; Decrease by 5 K	±5% rh, ±2 K	Mold germination and growth, and rapid corrosion avoided. No risk of mechanical damage to most artifacts and paintings. Some metals, glasses, and minerals may degrade if rh exceeds a critical value. Chemically unstable objects deteriorate significantly within decades at 20°C, twice as fast each 5 K higher.
	A1 Precision control, seasonal changes in temperature and relative humidity	≥35% rh ≤65% rh ≥10°C ≤25°C		Increase by 10% rh. Decrease by 10% rh. Increase by 5 K; Decrease by 10 K	±5% rh, ±2 K	Mold germination and growth, and rapid corrosion avoided. No mechanical risk to most artifacts, paintings, photographs, and books; small risk of mechanical damage to high-vulnerability artifact. (Current knowledge considers the specifications A1 and A2 as causing the same low risk of mechanical damage to vulnerable collections. Slow seasonal adjustment of 10% rh is estimated to cause the same mechanical risk as rapid fluctuations of 5% rh, because of significant stress relaxation occurring within three months of a slow transition.)
	A2 Precision control, seasonal changes in temperature only	≥35% rh ≤65% rh ≥10°C ≤25°C		No change to relative humidity. Increase by 5 K; Decrease by 10 K	±10% rh, ±2 K	Chemically unstable objects deteriorate significantly within decades at 20°C, twice as fast each 5 K higher.
Museums, galleries, archives, and libraries needing to reduce stress on their building (e.g., historic house museums), depending on climate zone[e]	**B** Limited control, seasonal changes in relative humidity and large seasonal changes in temperature.[f]	≥30% rh ≤70% rh ≤30°C	For permanent collection: historic annual average of relative humidity and temperature.	Increase by 10% rh Decrease by 10% rh Increase by 10 K Decrease by up to 20 K	±10% rh, ±5 K	Mold germination and growth, and rapid corrosion avoided. Chemical deterioration halts during cool winter periods No risk of mechanical damage to many artifacts and most books. Tiny risk to most paintings, most photographs, some artifacts, some books. Moderate risk to high-vulnerability artifacts. Objects made with flexible paints and plastics that become brittle when cold, such as paintings on canvas, need special care when handling in cold temperatures. Chemically unstable objects deteriorate significantly within decades at 20°C, twice as fast each 5 K higher.
	C Prevent relative humidity extremes (damp or desiccation) and prevent high temperature extremes.	≥25% rh ≤75% rh ≤40°C[g]	Within 25% to 75% rh year-round. Temperature usually below 25°C		Not continually above 65% rh for longer than *X* days.[h] Temperature rarely over 30°C	Chemical deterioration halts during cool winter periods. Mold germination and growth, and rapid corrosion avoided. Tiny risk of mechanical damage to many artifacts and most books; moderate risk to most paintings, most photographs, some artifacts, some books; high risk to high-vulnerability artifacts Even greater care is needed than provided in B when handling objects made with flexible paints and plastics that become brittle when cold, such as paintings on canvas. Chemically unstable objects deteriorate significantly within decades at 20°C, twice as fast each 5 K higher.
Collections in open structured buildings, historic houses	**D** Prevent very high relative humidity (dampness)	≤75% rh	Relative humidity reliably below 75% rh		Not continually above 65% rh for longer than *X* days.[h]	Chemically unstable objects deteriorate significantly within decades at 20°C, and twice as fast each 5 K higher. Conversely, cool winter season can extend their life. Mold germination and growth, and rapid corrosion avoided. High risk of sudden or cumulative mechanical damage to most artifacts and paintings because of low-humidity fracture; but avoids high-humidity delamination and deformations, especially in veneers, paintings, paper, and photographs.

[a] Long-term limits apply to combination of selected annual average plus selected seasonal adjustments. See Figure 15 for examples on a psychrometric chart.

[b] Rate of seasonal adjustments in relative humidity set point should not exceed the short-term fluctuation limit each 30 days, and the rate for temperature adjustment should not exceed the short-term fluctuation limit each 7 days (e.g., for A1, a seasonal adjustment can be no faster than 5% rh change per 30 days and 2 K change per 30 days).

[c] Short-term fluctuation means any fluctuation shorter than the times specified in footnote b for rate of seasonal adjustment (i.e., 30 days for relative humidity fluctuations, 7 days for temperature fluctuations). Space gradient refers to the differential in relative humidity or temperature between any two locations where objects are permitted to be placed in the controlled space (designers can specify out-of-limit locations, such as a specific distance to exterior walls and supply vents).

[d] See Table 3 for examples of objects in each sensitivity category, and Table 5 for lifetimes of objects at various temperatures.

[e] Microclimates (enclosures, packaging) can achieve the same relative humidity control as type AA or A in a much less controlled space (e.g., B, C, or D), and with much greater long-term reliability. See the section on Response Times of Artifacts.

[f] Long-term risk (≥10 years) of mechanical damage because of relative humidity fluctuations is dominated by the probability of extreme events such as system overload or failure in winter. Control type B with high reliability is less risk to collections than AA or A with poor reliability.

[g] An upper temperature limit is provided for a mixed collection that may contain objects with waxy materials that deform irreversibly beginning at ~40°C. This limit is set more cautiously for type B control, 30°C than type C control.

[h] From Figure 3, mold germination becomes very slow, but not impossible, in the range of 75 to 65% rh.

Classes AA, A1, and A2 represent varying degrees of precision environmental control for purpose-built buildings and rooms, while class B offers more limited control appropriate for historic house museums. Classes C and D seek to mitigate high-risk extremes, with class D focusing on dampness. The specification describes general collections risks and benefits associated with each control class, linking the conservation concerns of the museum professional with the system requirements used by the HVAC engineer. The 2019 edition of this chapter represented a significant revision from prior versions—among the refinements were an emphasis on a permanent collection's historic environment as initial set points rather than nominal values of 50% RH and 70˚F (21˚C) and a decoupling of environmental specifications for permanent collections and temporary loans.

The classification protocol set forth in the book *Environmental Management for Collections: Alternative Preservation Strategies for Hot and Humid Climates* (Maekawa, Beltran, and Henry 2015) is ostensibly geared toward climate zones subject to high moisture loads and high thermal energy. However, it remains useful in defining relative risks of damage when applied to interior environmental data from any climate zone. This protocol is presented as a tool to analyze environmental data based on the calculation of specific statistical parameters that roughly align with the short-term and seasonal temperature and humidity specifications from ASHRAE's chapter "Museums, Galleries, Archives, and Libraries" (table 8.3). Risk categories are segregated by microbial (humidity), mechanical, and chemical risk (temperature), and a range of risk classes are defined for each. The hot and humid classification protocol emphasizes the mechanical and chemical risk when deviating from an object's historical mean temperature and relative humidity. This also highlights the challenge of maintaining prescriptive museum environmental conditions (50% RH, 70°F or 21°C) in a gallery or storage space that resides in a nontemperate climate, and harks back to Garry Thomson's recommendation that the existing climate and the nature of the building and collection be reflected in the choice of interior environmental conditions.

Data Visualization

The graphical representation of environmental data should be guided by the needs of the researcher, who may be a conservator, a collection manager, a scientist, a curator, an engineer, or a financial manager. Whether the focus is on the exploratory analysis of short-term fluctuations, long-term trends, frequency or probability distributions, or psychrometric processes, the nature of the desired analysis will dictate the visualization type. In turn, when summarizing the results of the environmental monitoring for an interdisciplinary team, it is important to use data visualizations that are clearly presented and easily understood. In his book *The Visual Display of Quantitative Information* (2001), Edward R. Tufte states that graphical displays should do the following:

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

Common graphical techniques will be discussed, but of course a variety of visual choices exist beyond what will be shown here—papers by Pretzel (2011) and Henderson, Baars, and Hopkins (2017) provide excellent examples of novel methods of data analysis and visualization. Further, numerous software packages may be used to calculate different variables (e.g., moving average, range, humidity ratio, dew point temperature) and generate a range of plots. The visualizations shown here originated with datasets consisting of date,

TABLE 8.3.
Conservation environment classification-hot and humid protocol showing humidity and temperature criteria for mixed collections in hot and humid climates (Maekawa, Beltran, and Henry 2015).

		Relative Humidity (%RH)			Air Temperature (°C)		
Category	**Specific Risk**	**Parameter**	**Criteria**	**Class**	**Parameter**	**Criteria**	**Class**
Microbial Risk[1] (Dominant risk in hot and humid climates)	Germination Threshold	97.5 Percentile (P97.5)	$x \le 65$ $65 < x \le 70$ $70 < x \le 75$ $x > 75$	A[6] B C F	*Microbial activity will typically remain dormant at temperatures above 40°C*		
Mechanical Risk[2,3] (Overall class determined by lowest class of any specific mechanical risk)	Short-Term Variation	Rolling 24-Hr Variation, 95th Percentile (P95)	$\Delta 0 \le x \le \Delta 10$ $\Delta 10 < x \le \Delta 20$ $x > \Delta 20$	a b f	Rolling 24-Hr Variation, 95th Percentile (P95)	$\Delta 0 \le x \le \Delta 4$ $\Delta 4 < x \le \Delta 10$ $x > \Delta 10$	a b f
	Seasonal Variation	Absolute Difference in Seasonal Means (Means ≤ 70%RH)[5]	$\Delta 0 \le x \le \Delta 10$ $\Delta 10 < x \le \Delta 20$ $x > \Delta 20$	a b f	Absolute Difference in Seasonal Means	$\Delta 0 \le x \le \Delta 10$ $\Delta 10 < x \le \Delta 20$ $x > \Delta 20$	a b f
	Deviation from Historical Mean	Absolute Difference between Annual and Historical Mean	$\Delta 0 \le x \le \Delta 10$ $\Delta 10 < x \le \Delta 20$ $x > \Delta 20$	a b f	Absolute Difference between Annual and Historical Mean	$\Delta 0 \le x \le \Delta 10$ $\Delta 10 < x \le \Delta 20$ $x > \Delta 20$	a b f
Chemical Risk[4]	Deviation from Historical Mean	*Consider condensation risk at high humidity and depressed surface temperatures*			Difference between Annual and Historical Mean	$x > \Delta 5$ $\Delta 3 < x \le \Delta 5$ $\Delta{-3} \le x \le \Delta 3$ $\Delta{-5} \le x < \Delta{-3}$ $x < \Delta{-5}$	++ + 0 – – –

NOTES

1. While adherence to Class C criteria will typically limit most microbial activity, meeting criteria for Class A or B will further extend time period until mold germination and restrict growth.

2. Due to variations in material response times to humidity and temperature fluctuations and construction techniques, the risk of mechanical damage is object-specific.

3. If deliquescent salts present, one must maintain relative humidity below deliquescence point to limit risk of salt-related mechanical damage.

4. Chemically unstable collections should be stored in cold (-20°C) or cool (10°C) conditions, while only stable metal collections treated-against corrosion or with natural patina may be stored at conditions above 60%RH.

5. If seasonally mean humidity exceeds 70%RH, mechanical risk due to seasonal humidity variation is assigned to Class f. Above 70%RH, small shifts in humidity can result in large changes in a material's equilibrium moisture content and may lead to irreversible dimensional change.

6. Though a lower humidity limit is not given for Class A microbial risk, the maintenance of an excessively low humidity condition may introduce mechanical risk by deviating far from the historical humidity mean.

CLASS DESIGNATIONS AND RISK LEVELS

Microbial Class: A - No Risk, B - Low Risk, C - Moderate Risk, F - High Risk

Mechanical Class: a - No Risk, b - Moderate Risk, f - High Risk

Chemical Class: ++ - Significantly Increased Risk, + - Moderately Increased Risk, 0 - Similar Risk, - - Moderately Reduced Risk,
-- - Significantly Reduced Risk

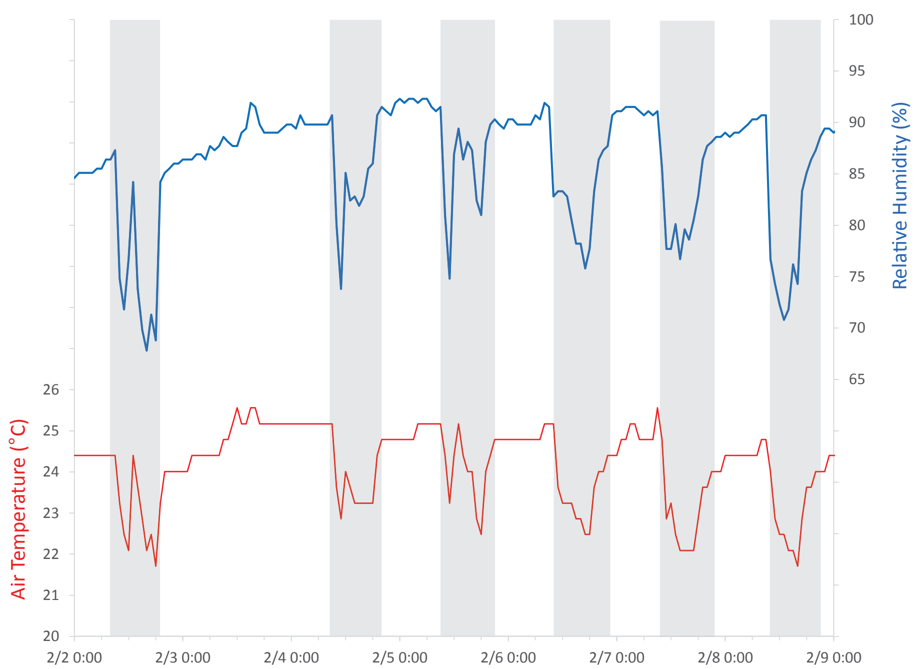
Sample Overall Classification: An overall classification of Bb+ means the collection environment poses a low microbial risk, a moderate mechanical risk, and a moderately increased chemical risk.

time, air temperature, and relative humidity, and were created by the *GCI Excel Tools*, a suite of Excel modules (software chosen for its wide accessibility) developed as didactic material for the GCI course *Preserving Collections in the Age of Sustainability*.

Time Series Plots

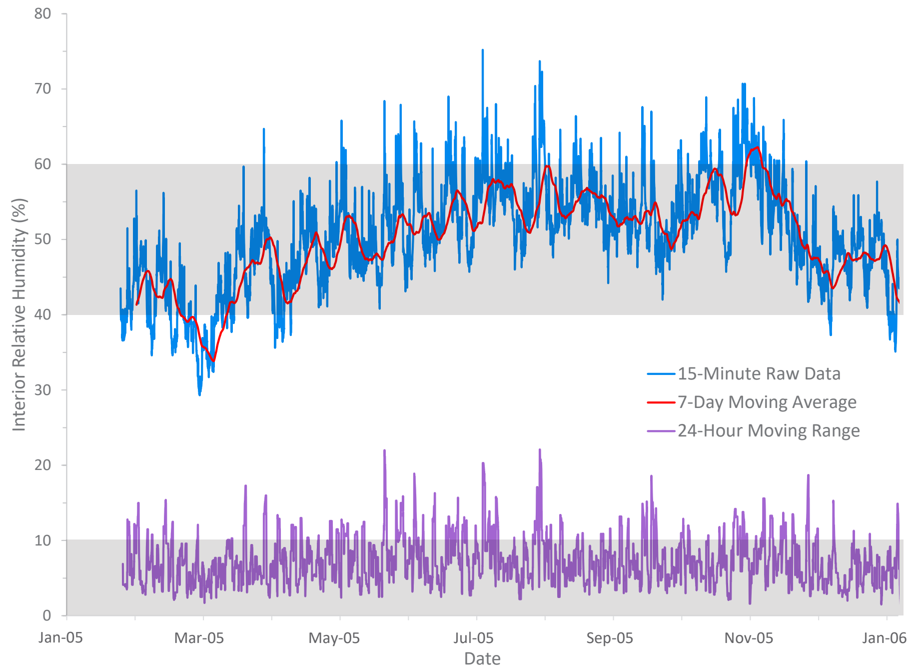
Since environmental data is ordered in time, initial visualizations typically explore the dataset through the use of time series plots, which show time on the horizontal axis and the variable of interest on the vertical axis. By plotting raw data as overlapping time series, one can compare the behavior of different variables. This is particularly useful when examining narrow time windows (e.g., one week), as diurnal cycles of air temperature and relative humidity will be clearly defined. The relationship between the environmental data and daily museum activities (e.g., air-conditioner operation, museum operating hours) can be highlighted in a time series plot (fig. 8.3). Comparison of temperature, dew point temperature, and relative humidity recorded at the same interior location can also be helpful in discerning whether changes in relative humidity are driven by temperature or moisture (indicated by dew point temperature).

FIGURE 8.3. Interior air temperature and relative humidity during a one-week period with shading indicating operation of the air conditioning system (data courtesy of Franciza Toledo).



Time series plots can also be used to present several types of processed data on one graph. An example of this is shown in figure 8.4, which plots relative humidity data collected every fifteen minutes (blue), and processed data in the form of a seven-day moving average (red) and a daily range (green, difference between maximum and minimum values). Graphing the raw fifteen-minute relative humidity data shows the short-term fluctuations, while the seven-day moving average smooths out these diurnal changes and highlights longer-term changes. Plotting of the daily range draws attention to the magnitude of the short-term fluctuations, as well as detailing changes in the daily range over the course of a year. The addition of semitransparent gray boxes identifies a range of target conditions (e.g., upper and lower RH limits of 60% and 40%, daily RH range limit of 10%) and makes clear when these conditions are exceeded.

FIGURE 8.4. Time series showing 15-minute interior raw RH data, and the calculated 7-day moving RH average and 24-hour moving RH range. The semitransparent gray boxes indicate target conditions from 40–60% RH (raw and average) and 0–10% RH (range). Credit: Vincent Laudato Beltran



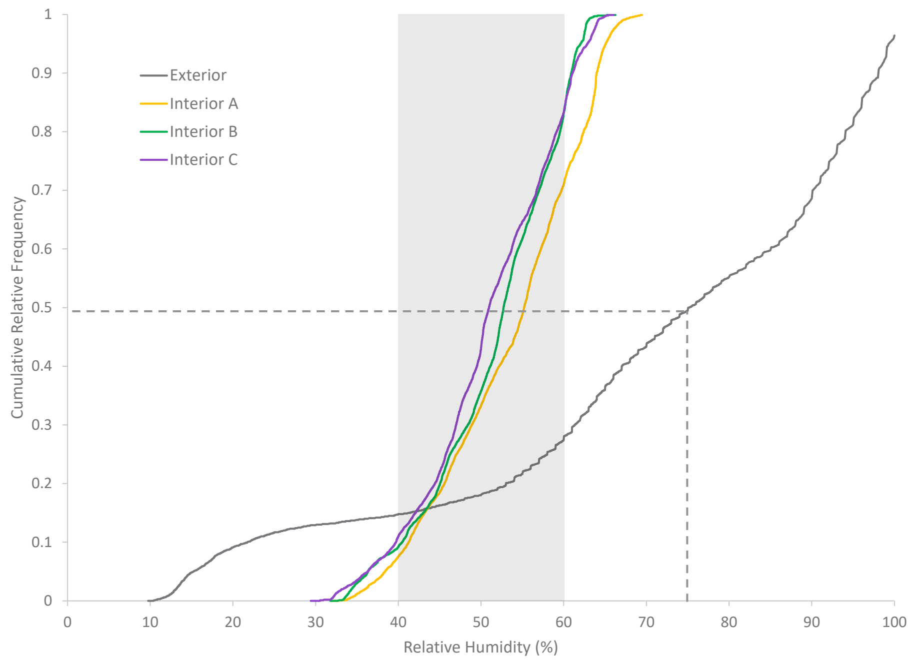
Probability Distribution Plots

An examination of the probability with which specific values occur in a dataset provides valuable information on the distribution of data and the occurrence of key threshold values. The concept of probability distribution was introduced during the discussion of interquartile range (IQR) and percentiles earlier in this technical note. Visualizations of probability distributions allow one to compare the spread of data for multiple datasets, which might represent data for various interior spaces and the exterior, seasonal shifts within these spaces, or the pre- and post-implementation of an environmental strategy. This section focuses on two types of probability distribution graphs: cumulative relative frequency plots and box plots.

Cumulative relative frequency plots display a variable of interest on the horizontal axis (e.g., temperature, relative humidity) and its cumulative relative frequency on the vertical axis. From this plot, one can determine the proportion of observations that are less than or equal to a specific value, or the value associated with a specific proportion. Figure 8.5 shows the cumulative relative frequency of relative humidity for an exterior location and three interior locations. If one wanted to determine the proportion of values less than or equal to an exterior relative humidity of 75% (which represents the high RH threshold for ASHRAE Class C control), one would first extend a vertical line from 75% RH on the horizontal axis to its intersection with the exterior curve (black). A horizontal line would then be extended from the curve to the vertical axis at left, whose intersection would define the proportion (~0.5) corresponding to 75% RH. In contrast, a similar vertical line at 75% RH would not intersect with the curves for the three interior spaces as relative humidity at these locations remained less than 75% RH throughout the study period. Proportions can be converted into percentiles (or percentages) by multiplying the proportion by 100. Thus, the IQR can be determined for each location by finding the corresponding values for the following proportions: 0.75 (75th percentile or third quartile), 0.5 (50th percentile or median), and 0.25 (25th percentile or first quartile).

Box plots or box and whisker plots provide an alternative way to visualize spread in a dataset. In contrast to cumulative relative frequency plots, in which proportions are shown on the vertical axis, box plots indicate probability distribution through the use of line markers, three of which are connected as a box. The top

FIGURE 8.5. Cumulative relative frequency of exterior and interior relative humidity. The dashed lines indicate how the cumulative relative frequency can be determined for a specific relative humidity, and vice versa. The gray boxes indicate a hypothetical range of target conditions. Credit: Vincent Laudato Beltran



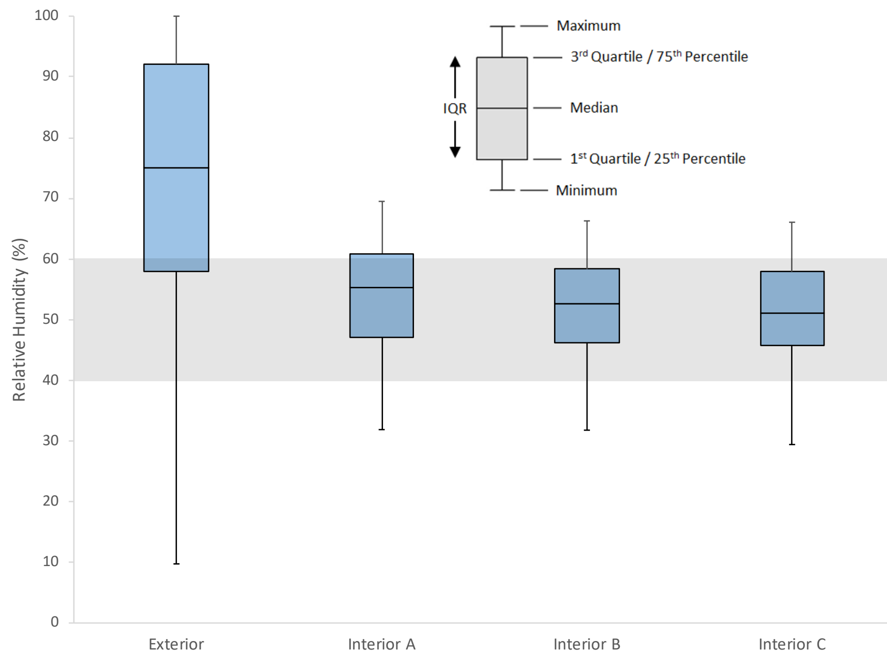
and bottom borders of the box indicate the third and first quartiles, respectively, and delineate the IQR, while the line within the box specifies the median value of the dataset (fig. 8.6). Extending from the top and bottom of the box are vertical lines (or whiskers), whose ends may denote several possibilities, including the maximum and minimum values in the dataset, 1.5 x IQR above and below the third and first quartiles, respectively, or various percentile pairs (e.g., 95th and 5th percentiles); thus, it is important to define the meaning of the whiskers for each box plot. Data that lie beyond the whiskers may be plotted as dots and considered outliers if they are beyond 1.5 x IQR above or below the third and first quartiles, respectively (for a normally distributed dataset, this approximates $\pm 3\sigma$ or 99% of the values). The relative positioning of the markers also informs one as to the skew (or measure of asymmetry around the mean) of the dataset—for example, placement of the median line closer to the third quartile or of the box itself closer to the upper whisker may suggest a negative skew.

In addition to the arrangement of the box and whiskers themselves, box plots show the variable of interest on the vertical axis and different data groupings on the horizontal axis. Shown previously in figure 8.5 as cumulative relative frequencies, figure 8.6 replots the relative humidity data as multiple box plots, each representing a different location. Examination of the two probability distribution plots shows the ease with which the box plot enables comparison of the IQR boxes. It is evident that the IQRs for the three interior locations are narrower and show minimal overlap with the much wider and elevated IQR of the exterior. Further, relative humidity in the interior spaces rarely exceeds 65% RH, despite the exterior relative humidity having a median value of 75% RH. These results suggest that the environmental management strategies implemented at these locations effectively mitigated the potential impact of infiltration of exterior air.

Psychrometric Charts

The data visualizations described thus far have shown time-series or probability distributions of one or two environmental variables. However, environmental parameters such as air temperature, relative humidity, humidity ratio, dew point temperature, and wet bulb temperature represent interdependent thermodynamic properties of moist air. The psychrometric chart provides a means of showing these relationships

FIGURE 8.6. Box plots showing exterior and interior relative humidity. The gray box indicates a hypothetical range of target conditions. Credit: Vincent Laudato Beltran



graphically. The concept of psychrometrics is applied to the properties of any gas-vapor system, but is commonly focused on mixtures of water vapor and air due to its relevance for heating, ventilation, and air conditioning (HVAC). While the format and application of the psychrometric chart are described in greater detail in a separate technical note, a brief review of its use in data presentation is discussed here.

Since the properties shown on the psychrometric chart are interdependent, knowledge of only two variables for a fixed barometric pressure or elevation offers access to the full suite of thermodynamic properties associated with a specific parcel of air. (Note that the psychrometric chart is dependent on elevation, and sea-level charts are typically used for elevations of less than 600m above sea level.) For example, if the air temperature and relative humidity are are 20˚C (68˚F) and 50% RH, respectively, for a parcel of air at sea level, a psychrometric chart or calculator allows one to deduce the associated humidity ratio (7.2 g/kg), dew point temperature (9.3˚C or 49˚F), wet bulb temperature (13˚C or 55˚F), enthalpy (38.5 kJ/kg), and specific volume (0.84 m^3/kg) for that air mass.

Environmental data can be plotted directly on the psychrometric chart, with each point thermodynamically describing a parcel of air at a specific time. Areas with higher point densities indicate more common conditions, and the spread of data can be further delineated with the use of contour lines. Different datasets or subsets of data may be plotted to visualize data collected at various locations, during different seasons, or before and after implementation of environmental management strategies (fig. 8.7a). The psychrometric chart also allows one to overlay zones of target conditions for collection preservation and/or occupant comfort (fig. 8.7b). A comparison of the relative positioning of prevailing environmental conditions with these target zones can help to inform the psychrometric strategies needed to shift the environment closer to or within the desired target range, or to establish whether a different target range might be more appropriate. Though specific process paths may not follow a straight line between the initial and final state points (e.g., dehumidification may involve cooling and subsequent heating), the net direction of change on the psychrometric chart identifies the overall psychrometric process.

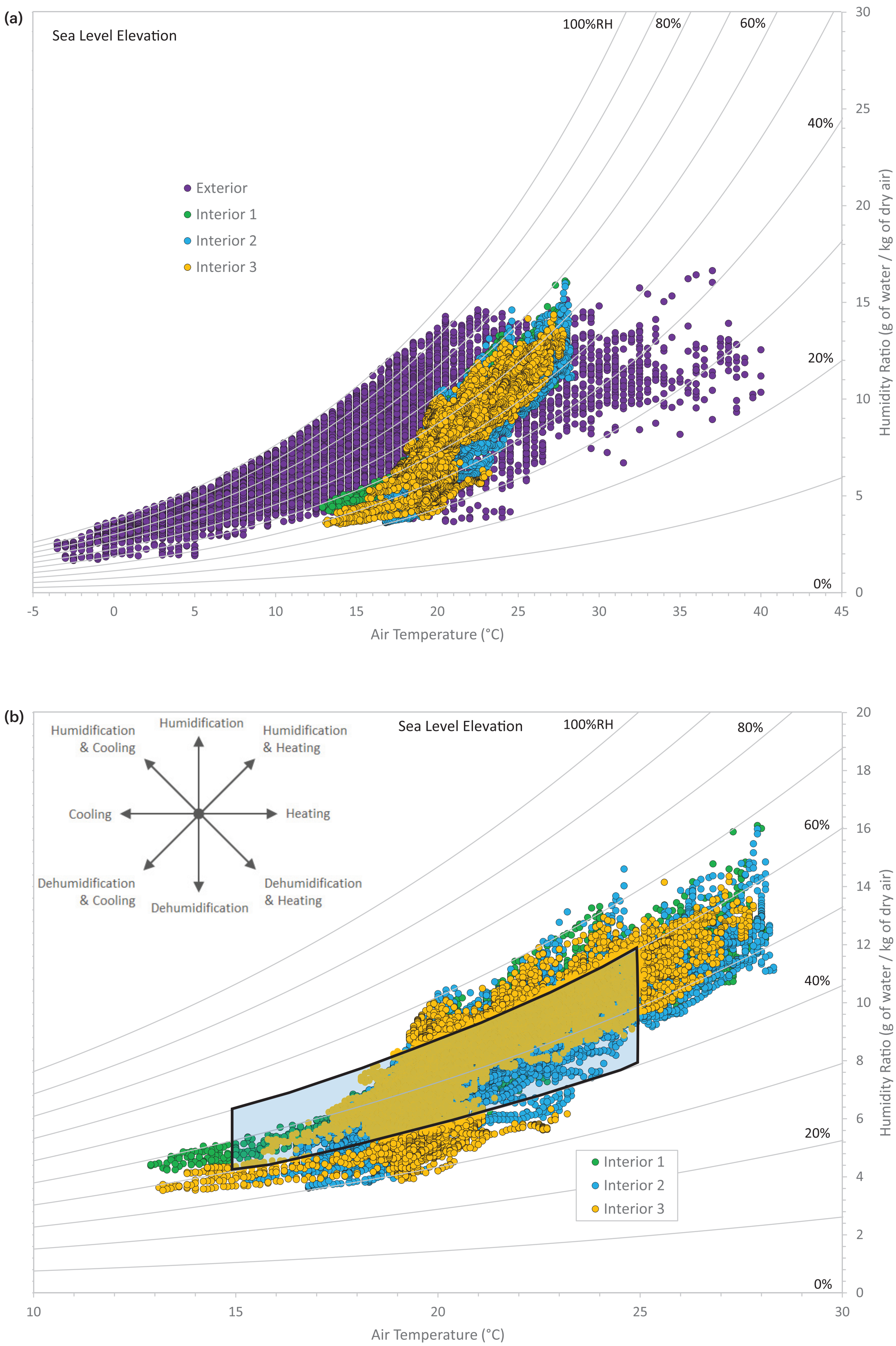


FIGURE 8.7. Psychrometric charts showing (a) data collected for the exterior and at several interior locations, and (b) overlaying a hypothetical range of target conditions upon the interior environmental data. Credit: Vincent Laudato Beltran

Summary of Visualization Types

Table 8.4 briefly summarizes the various visualization types presented here and describes the major benefits and drawbacks of each. While a single visualization type may emphasize one aspect of the environmental dataset, the use of multiple visualization types with complementary analytical objectives—short-term and long-term trends, dispersion, and psychrometrics—can provide a more holistic view of the existing environment.

TABLE 8.4.

Advantages and disadvantages of various visualization types. Credit: Vincent Laudato Beltran

Visualization Type	Advantages	Disadvantages
Time Series	• Common graphic that is broadly understood • View short- (e.g., day, week) and long-term (e.g., years) data • Plot multiple variables and locations, statistically processed data • Rapid identification of missing periods and out-of-spec data	• Long-term trends may be obscured by short-term fluctuations • No information on probability distribution • Does not depict relationship between thermodynamic variables
Cumulative Relative Frequency	• Provides information on probability distribution • Determine proportion/percentile for any value or vice-versa • For continuous data, determine percentage within target zone	• Difficult to compare interquartile ranges • Does not show data in time domain • Does not depict relationship between thermodynamic variables • Format may require additional explanation
Box Plot	• Provides information on probability distribution • Easily compare interquartile range, median, max/min for multiple data classes (e.g., location, season, pre-/post-implementation)	• Cannot determine proportion/percentile for any value or vice-versa • Does not show data in time domain • Does not depict relationship between thermodynamic variables • Format may require additional explantion
Psychrometric Chart	• Depicts relationship between thermodynamic variables • Relates psychrometric strategies to position of data and targets • Facilitates discussion about data and environmental management	• Graphic previously not easily accessible • No information on probability distribution (though percentile contour lines may be added) • Format may require additional explanation

Conclusion

The analysis of environmental data is an important aspect in understanding the environment in which a collection resides. The use of effective visualizations of the data aids in clearly conveying the results of a monitoring program to an interdisciplinary management team. Comparisons of the analytical results to guidelines in the field of cultural heritage allow one to assess the preservation state of the existing environment. The preceding sections create a framework for organizing, interpreting, and presenting environmental data in an effort to improve awareness of existing environmental conditions and facilitate discussion of environmental management strategies most appropriate in the context of the exterior climate, building performance, and collection.

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PART 3: APPROACHES TO ENVIRONMENTAL MANAGEMENT

Introduction

As discussed in parts 1 and 2, the complexities involved in object materials, the interaction between materials with temperature and RH, and the specific needs for the collection, the building, the public, and the institution result in systems that may not be easily understood. Although great advancements have been made in the past years, the fact is that no knowledge is ever going to be complete and gap-free. Nonetheless, decisions must be made. This requires a diverse range of information relevant to collection environments to be assembled, and for frameworks to determine how to move forward.

One approach is to avoid the uncertainty and adopt a precautionary principle, often leading to the pursuit of an "ideal" stable climate. Alternatively, one could assess the risks involved, establish priorities, and make informed and sustainable decisions. In the technical note "Risk Assessment and Management," Joel Taylor describes approaches based on risk analysis, assessment, and management that allow for the systematic presentation of conservation issues. By analyzing risk and putting uncertainties in perspective, this methodology certainly brings transparency to the process. The application of this numerical approach also introduces an important shift in preventive conservation practice, whereby collection care professionals are forced to confront the fact that we cannot preserve material forever and, therefore, need to decide upon an acceptable degree of change (or loss of value) within a given time frame.

Taylor's technical note "Considerations for the Process of Managing Collection Environments" reflects on how and when information can be used to make decisions and develop options, drawing together the issues in previous technical notes that can be addressed by defined actions and steps of a process. Rather than relying on prescriptive recommendations, the goal of this technical note is to describe a decision-making process—and the evolving responsibilities of the stakeholders—that can accommodate a range of project types (e.g., HVAC systems for purpose-built buildings, more energy-efficient strategies in historic structures). The first phase of this process gathers information about the institution and its needs to understand context. This is followed by a predesign phase, which assesses risk, defines priorities, sets realistic and objective parameters, and develops strategies that can be sustainably achieved. The final phase considers the design, implementation, and maintenance of the chosen strategies with feedback loops to continually monitor performance.

The next two technical notes in part 3 offer practical advice on nonmechanical and mechanical (HVAC) strategies and microcontrol solutions, all of which should be considered when developing, reviewing, and selecting potential environmental management strategies. Although discussed in separate technical notes for clarity, nonmechanical and mechanical strategies are not mutually exclusive. On the contrary, an underlying principle of the process-based approach advocated in this book is that no one solution fits all, and it is ultimately more sustainable to consider a range of strategies that are appropriate for each context, including hybrid strategies that comprise a blend of mechanical and non-mechanical methods.

Michael C. Henry presents an overview of "Nonmechanical Environmental Management Strategies," which includes the flows of energy and mass between exterior and interior environments that are dependent on the climatic context and the performance of the building envelope. The author provides guidance on the implementation and maintenance of control strategies for moisture, thermal flows, air leakage, stack effect, and moisture vapor flow for historic and nonhistoric buildings housing collections.

In the subsequent technical note, "HVAC Options, New Constructions, and Microcontrol," Jeremy Linden asserts that mechanical options should not always be assumed to be the best or only strategy for environmental management. The decision to implement mechanical strategies should consider the objectives and parameters for the collection and the building envelope, as well as the resources necessary for its implementation, operation, and long-term maintenance. In many cases, however, mechanical systems represent an inherited solution, with current stakeholders confronted with an HVAC system whose capacity and functionality may have diminished over time. Whether designing a mechanical system for a new building or renovating an existing HVAC system, the author reviews common HVAC configurations, various means of improving system performance, and the use of zoning and microenvironments that may prove more energy efficient and sustainable over time.

TECHNICAL NOTE 9: RISK ASSESSMENT AND RISK MANAGEMENT

Joel Taylor

Introduction

Many actors within collecting institutions routinely make decisions that influence the preservation of collections, consciously or by default. Actors who can influence preservation include collection managers, conservators, registrars, facilities managers, security managers, curators, and executives, among others.

The complexity of the museum environment means that decision-making is carried out in situations of uncertainty. Even simple decisions can involve a wide range of factors—often a mix of scientific data, subjective judgment, informal (and perhaps not validated) models, and incomplete information. A lack of meaningful feedback on the long-term effectiveness of countless possible preservation-enhancing initiatives adds greatly to the challenge.

Using risk-focused judgment allows for a more rigorous approach to the complexities of a given situation. Risk-based approaches can provide a rational framework to the common sense of decision-making. This helps to determine where uncertainties and knowledge gaps lie, and what information would have the greatest impact in reducing undesirable change to collections. Risk assessment and risk management can help establish a common understanding of the goals of preservation and contribute to the effective communication needed to achieve them.

Uncertainty and Complexity in the Museum Environment

Even with collections of similar material, considerable variations and uncertainty about how objects will respond to their environment can occur. In a furniture collection, variations in the assembly, grain direction of wood, and the tightness and quality of construction may be observed between items. Objects can also vary considerably in manufacturing processes, such as those for lined paper or tanned leather, or in burial environments for paleontological and archaeological materials. Further factors that can vary in assemblies of historic materials are age of material, existing damage (which could exacerbate or mitigate responses to climatic change), and thickness of materials and coatings.

The behavior of objects within given environments is not always the same as it is in theory (Ashley-Smith 2000). Conservation literature has demonstrated numerous occasions when the current theory of preservation has diverged from the reality, such as objects and collections that remained stable in conditions outside "acceptable" levels (Taylor 2005).

There is also much uncertainty in what is known about collection preservation. Research in conservation is often carried out on separate pieces of new material to maximize reproducibility. Interaction of assemblies over time is also hard to simulate. The extent to which one can generalize from and apply these data is not fully known.

Tests are often specific to certain materials and forms that can be analyzed. Scientific testing "has the disadvantage that it can only be applied to properties that are subject to quantitative measurement. That is, the attributes are chosen for their relative ease of measurement rather than by their relevance to the way the object is used or valued" (Ashley-Smith 1999, 113). In the absence of clear scientific proof either way, stances that focus on what can be stated with certainty can lead to precautionary and specific approaches to climate management. The consequence of avoiding uncertainty is that climate management is often positioned within accepted norms of moderate, stable climate, a theoretical "ideal." However, a range of uncertainties are present in all environments, and these require decision-making with incomplete or imperfect data. Dealing with uncertainty is a difficult but important aspect of managing collection environments. How this compares with other factors related to collection preservation, such as earthquakes, or how it relates to the institution's mission, is not always easy to gauge or communicate.

If sustainability can be considered the extent to which an activity, service, or entity can be kept going, sustaining heritage presents a range of opportunities and challenges for the future. How these challenges are met can often be understood in terms of risk and risk assessment. Some change is inevitable over time, but choosing a timeframe and the identifying types of change that affect value or use will allow information to be discussed meaningfully and risks to be compared.

Risk

Within collection preservation, decision-making frequently takes place at a managerial level (Baer and Snickars 2001), often drawing from fields outside of heritage conservation. Predictive approaches to heritage preservation, largely based on principles of risk management, provide the decision maker with ways to handle uncertainty, loss, and data that are varied or missing. Risk management presents a numerical language that can be utilized for a range of decision-making contexts that helps identify systemic biases and points at which uncertainty is greatest.

Although the idea of using information to make better decisions about the future has been in existence for thousands of years, the systematic evaluation of information to assess the probability of an undesirable event stems from mortality and health and, later, ecological risks. Its application to collection preservation has involved various innovations but is based on the same broad principles used in other fields.

The classical definition of risk, which is widely applied in many fields, is: probability of a successful "attack" from a hazard multiplied by severity of its impact (P x I)—in other words, how likely it is that something will happen and how much the relevant person(s) care.

This numerical approach has helped introduce a subtle shift within preventive conservation, from avoiding or minimizing loss (the ICOM-CC definition of preventive conservation) to considering the lifetimes of objects and collections, and what can be done to ensure the most benefit is gained from limited resources. This supports a shift from keeping historic material in perpetuity to acknowledging that all material undergoes change.

Risk-Based Approaches to Managing Collection Environments

Decision-making using risk-based approaches often focuses on whether or not to embark upon an action. The notion of maximizing value may involve the introduction of risk to collections, which may appear to contradict a duty to preserve them. In the case of loaning objects, this is precisely what is happening. To an extent, this question returns to the environmental standards debate wherein discussion about environmental parameters includes concerns that climates outside of a very stable (± 5%), moderate RH would present unnecessary risks to loaned collections. There are many facets to this debate, but analyzing how risk can be expressed illustrates some principles and indicates how decision makers can balance different kinds of information and, crucially, determine what information is most important to the decision.

A highly uncertain decision that employed a risk-based approach was the move of the Oseberg Viking ship—a national treasure in Norway—from one side of the city of Oslo to the other (Johnsen, Cassar, and Saunders 2017). The museum building that houses the ship and collections was open to external air, but many of the objects were vulnerable to moving because of flaking, due to a previous treatment of alum rosin. The expectation was that a move to new premises would present the short-term risk of physical damage but provide the benefit of a more stable future with reduced environmental risk. An international advisory committee considered a range of options. What became apparent was that "none of the Scenarios that are proposed to improve conditions can be completed without what the Committee considers to be critical short-term risks or critical long-term risks" (International Expert Committee 2012). Figure 9.1 shows the collective short- and long-term risk for each option. By comparing the options—leave items where they were (do nothing); relocate them to a new museum in East Oslo (Bjørvika); refurbish the existing museum

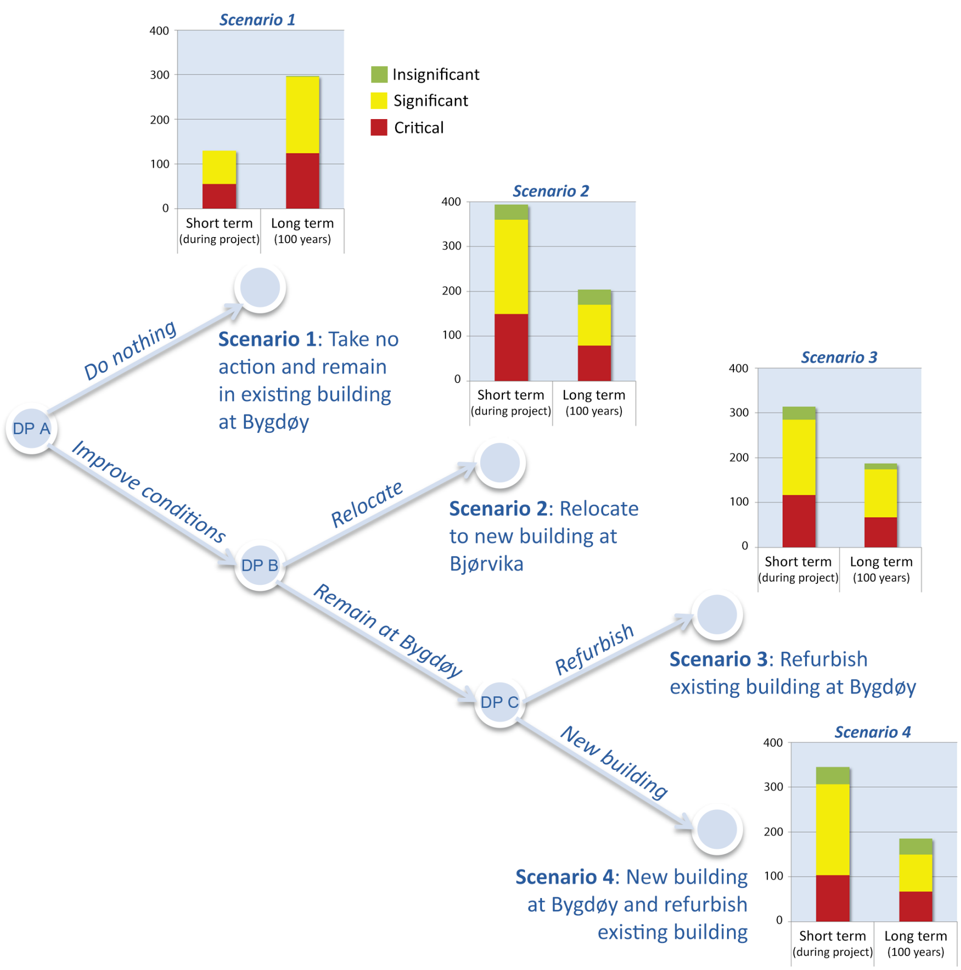

FIGURE 9.1. The different choices and decision points related to the proposed move of the Oseberg ship, with short- and long-term risks associated with each action (including no action). Red, yellow, and green indicate critical, significant, and insignificant risk, respectively, as defined by the expert committee (International Expert Committee 2012).

in West Oslo (Bygdøy); and construct a new building (museum) next to the existing option—"do nothing" held considerable short-term and long-term risks. Options followed a logical decision process.

The determination of risk was enabled by deciding what kinds of changes would be acceptable or unacceptable in the process. Identifying the characteristics that best defined the ship's significance allowed the various kinds of possible damage from the different short- and long-term options to be compared and potential consequences to be established and compared.

Risk-Based Decision-Making in Policy

An example of risk-based decision-making is developing institutional policies that account for expected collection lifetimes. The development of a lighting policy at the Victoria & Albert Museum involved consideration of risk-based conservation to gain maximum value from a collection (Derbyshire and Ashley-Smith 1999; Ashley-Smith, Derbyshire, and Pretzel 2002). The policy is well known but demonstrates an evolution from simply avoiding loss to maximizing benefit to current and future visitors. By committing to a timeframe, identifying the different values that were relevant to different audiences, identifying the basic vulnerabilities of the collection, and deciding what degree of change might be acceptable within the timeframe, a suite of conservation approaches that contributed to the same goal could be consistently applied. The policy presented ways of breaking down the important factors involved in decision-making for that context.

Total light exposure was defined through consideration of object lifetime, using the concept of a Just Noticeable Fade (JNF) to define damage. In order to elicit the most value possible from the collection, various groups were identified: current visitors (the next fifty years), current visitors with visual difficulties, future visitors (after the fifty years), and scholars.

Display options were categorized in terms of vulnerability of objects as follows, with a caveat for higher levels if objects were large or dark:
- vulnerable (light-sensitive objects in near-pristine condition, photogenic drawings)
- sensitive (color photos, plastics, poor-quality paper)
- durable (oil paintings, durable paper)
- permanent (most inorganic objects)

By defining an acceptable rate of change, object vulnerabilities, and intended uses, consistent decisions could be made in practice. Over the next fifty years, visitors would see sensitive objects without perceptible color change at 50 lux for 20% of the display period (with large or dark paintings in this category at 100 lux), durable objects without color change at 250 lux for 100% of the display time, permanent objects at 300 lux for 100% of the display time, while vulnerable objects were kept in storage. Older and visually impaired viewers would be able to see sensitive objects displayed at 200 lux one day per year (but would have a sub-optimal experience outside of those times). After the fifty years, a change of one JNF would be universally evident (some objects may see it sooner), but some sensitive objects might be seen in near-pristine condition by being kept from display. Scholars have access to these vulnerable objects in storage for limited periods. Applying the items' significance to the policy adds some nuance (Ford and Smith 2011).

Accepting some change within fifty years is required in any situation, but given the constraints, the policy can deal with different needs fairly by comparing the expected value that would result from different conservation approaches and decisions.

Risk Assessment

Risk management involves the identification of hazards and their consequences, and the generation, selection, and implementation of options to accept, change, or mitigate undesirable change. Part of this is risk assessment, which involves the systematic identification and evaluation of hazards with the potential to cause undesirable change. This has become a popular and influential aspect of risk management in collection preservation, where various techniques have been developed and applied (Waller 2008). Risk assessment is a comparative activity that examines which resource allocation or course of action is most beneficial.

Returning to the classical definition of risk as P × I, a risk is the potential for a hazard to impact upon something of value (e.g., a collection). A hazard is a phenomenon or entity that can lead to loss or deterioration. It is not necessarily undesirable in its own right, such as relative humidity, but its presence in a certain form or quantity might lead to an undesirable impact. An agent is a kind of hazard or group of related hazards that may arise from a similar cause or have a similar impact upon a collection. For example, fires may be electrical, intentional, or related to building works, but these different causes operate through the same phenomenon.

Risk assessment requires outlining the materials and values of the collection, aspects of its environment, and the relationships between them. As with any representation, assumptions and simplifications need to be made. The creation of a common language for different problems is very powerful, but how the map charts the territory should be well understood. Developing a profile of risk, like any modeling, involves many small choices about how concepts are defined. Risk assessment models are composed by considering the most rational choices within these frameworks. These choices may be determined pragmatically and based on the availability of data for risk assessment, the options for risk management, or other factors.

Some of these decisions are based on fundamental questions that emerge from the methodologies used and will have a significant influence on outcomes. The timeframe has a strong impact on the probability of an event. A common timeframe for collection risk assessment is one hundred years, which is long enough for a catastrophic hazard to be expressed. All deterministic hazards are considered certainties in a one-hundred-year timeframe for some methodologies (Waller 1999, 2003). Like many assessments, however, it is a snapshot of the situation at the time of analysis, with necessarily limited consideration of evolving context.

Often a risk assessment will be used to compare different collection units. The collection unit influences all of the factors of P x I to be considered, as well as how risks are addressed. Collections may be presented in varied ways and be dispersed among different storage locations and exhibitions. Location, material, and curatorial context are all valid ways of dividing up a collection unit. Again, this is a subjective choice, but it is important to consider what can help clarify risks. The kinds of collection units chosen will also influence how risks are dealt with after the analysis.

Agents of Deterioration

Risk assessment for heritage conservation is usually agent based. Various category sets have been used for characterizing agents. The most commonly used set for cultural institutions is CCI's ten agents of deterioration (Michalski 1990), and a later addition by Waller (1994). However, different category sets have been developed for cultural heritage, such as Baer's (1991) agents, which were divided into a matrix of natural/anthropogenic against slow acting/rapid, which includes development, war, and weathering as agents, and Camuffo's (1997) anthropogenic and natural risks, including mass tourism, restoration, and inappropriate use. Lists of agents go back as far as Plenderleith (1956).

Several of these approaches have subsets that distinguish between fast-acting and gradual risks. The most comprehensive is Waller's (1994), which accounts for sudden and gradual risks (and their impact) for all kinds of agents (table 9.1). An earthquake, for example, may result in rare, catastrophic building collapse, but other physical forces may simply be object "creep" from low-level vibration.

TABLE 9.1.

Agents of deterioration and typologies of risk suggested by different people working on collection preservation.
Credit: Joel Taylor

Plenderleith 1956	
Humidity	• Excessive Wetness • Rapid Changes • Excessive Dryness
Contaminated Air	• Sulphur Dioxide • Hydrogen Sulfide • Soot • Dust
Neglect	• Pests • Careless Handling & Packing • Exposure to Excessive Light & Heat • Accident

Michalski 1990 & Waller 1994
• Physical Forces • Fire • Thieves, Displacers, Vandals • Water (other than RH) • Pests • Contaminants (including Pollution) • Radiation: UV & Visible (Light) • Incorrect Temperature • Incorrect Relative Humidity • Dissociation Each agent can be: • Type 1 (Rare, Catostrophic) • Type 2 (Sporadic, Severe) • Type 3 (Constant, Gradual/Mild)

Baer 1991		
Natural	Rapid	• Earthquakes • Floods • Hurricanes • Tornadoes • Volcanoes • Wildfires
Natural	Slow Acting	• Biological • Erosion • Insolation • Oxidation • RH & Temp • Weathering
Anthropogenic	Rapid	• Accidents • Development • Fire • Vandalism • War
Anthropogenic	Slow Acting	• Acid Deposition • Acid Hydrolysis • Dams • Light Exposure • Loan Shows • Ozone

Camuffo 1997	
Natural	• Biological Factors (e.g., Lichen) • Meteorological Factors: Lightning, Wind, Solar Radiation, Climate • Geochemical Hazards: Salts, Groundwater • Natural Hazards: Earthquake, Fire, Flood, Soil Subsidence
Anthropogenic	• Pollution: NO_2, Acid Rain • Mass Tourism • Management: Heating, Cleaning • Inappropriate Use: Sudden Changes, Vibration • Bad Care: Handling, Neglect • Restoration: Poor Materials, Poor Treatment • Human Hazards: Theft, War, Economy

All of this engenders a way of rationalizing the real world, of parsing out information so it can be categorized and compared in order to make decisions.

The agents themselves are subdivided into separate entities, but they do interact and impact one another. For example, the impact of temperature on relative humidity is well understood. A rise in temperature might be caused by infiltrating daylight, which may impact pollution deposition or insect pest behavior (fig. 9.2). Furthermore, most forms of damage are the consequence of more than one hazard, and hazards defined by the same agent may lead to quite different effects. Dividing hazards into agents and types of risk can overlook their dynamic interaction and the secondary roles that can contribute to deterioration. Dissociation is separate because it affects all agents in a variety of ways. While among the list of agents within contaminants, inherent deterioration is not affected by blocking external factors.

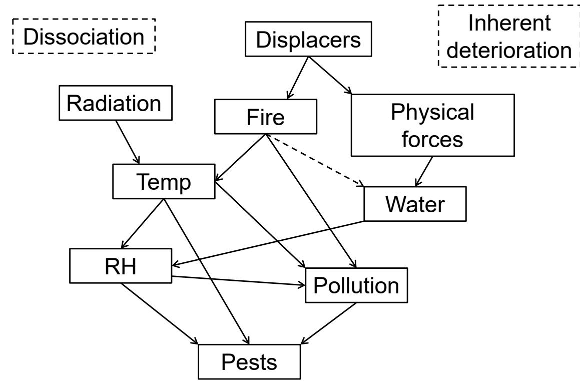

FIGURE 9.2. Different agent of deterioration categories and their potential impacts upon other agents (Taylor 2012).

Calculating Risk

Returning to the definition of risk assessment, P x I, much of the work in transferring this approach is related to the nuances of collections in cultural institutions. There is no single way in which this is carried out. However, concepts have been applied to make risk assessment more applicable to collection preservation (e.g., Waller 2003, Michalski and Pedersoli 2016), which tease out some of the issues.

The application of a concept or approach to a new context always requires some sensitivity to the nuances of the subject, and the preservation of cultural heritage is no different. Although probability is quite a universal factor, its treatment (mathematical prediction or general assessment of frequency) can vary depending on the aims of the assessment and available resources. One factor affecting the scope of this is the nature of the population. Where humans may have a broadly similar response to a hazard, such as a toxin (even if to different extents), collection material will often respond differently to the same hazard. A collection comprising oil paintings and unpainted ceramics would respond to light quite differently over time. The proportion of the collection affected (susceptible fraction) helps refine the population. Light exposure can also illustrate some of the different ways in which a hazard can impact a collection or object. Impact has been addressed in terms of value—often the total value of the collection (or sub-collection/unit) being examined, or the proportion of value lost if a specific hazard were to interact with the collection. "Loss of value" is a proportional term that considers the extent to which the successful attack of a hazard changes the value of the collection relative to its current value without assuming that any collection or unit is more/less valuable than any other, but only how much of that undefined value is lost. Value denotes the significance of that unit as a means to compare the loss of one collection/unit against the loss of another. Theoretically, expressions of "value" and "loss of value" could be used in tandem.

Connecting such variables together provides the opportunity to calculate the magnitude of different risks on different collection units. This may involve simple multiplication and addition or more complicated methods of combination. This further provides the opportunity to see how separately defined risks can be mitigated at the same time, or if control methods may exacerbate a different risk. When risk factors are represented with decimal places and multiplied, outcomes can be infinitesimally small, but not impossible, or highly likely but not certain (fig. 9.3).

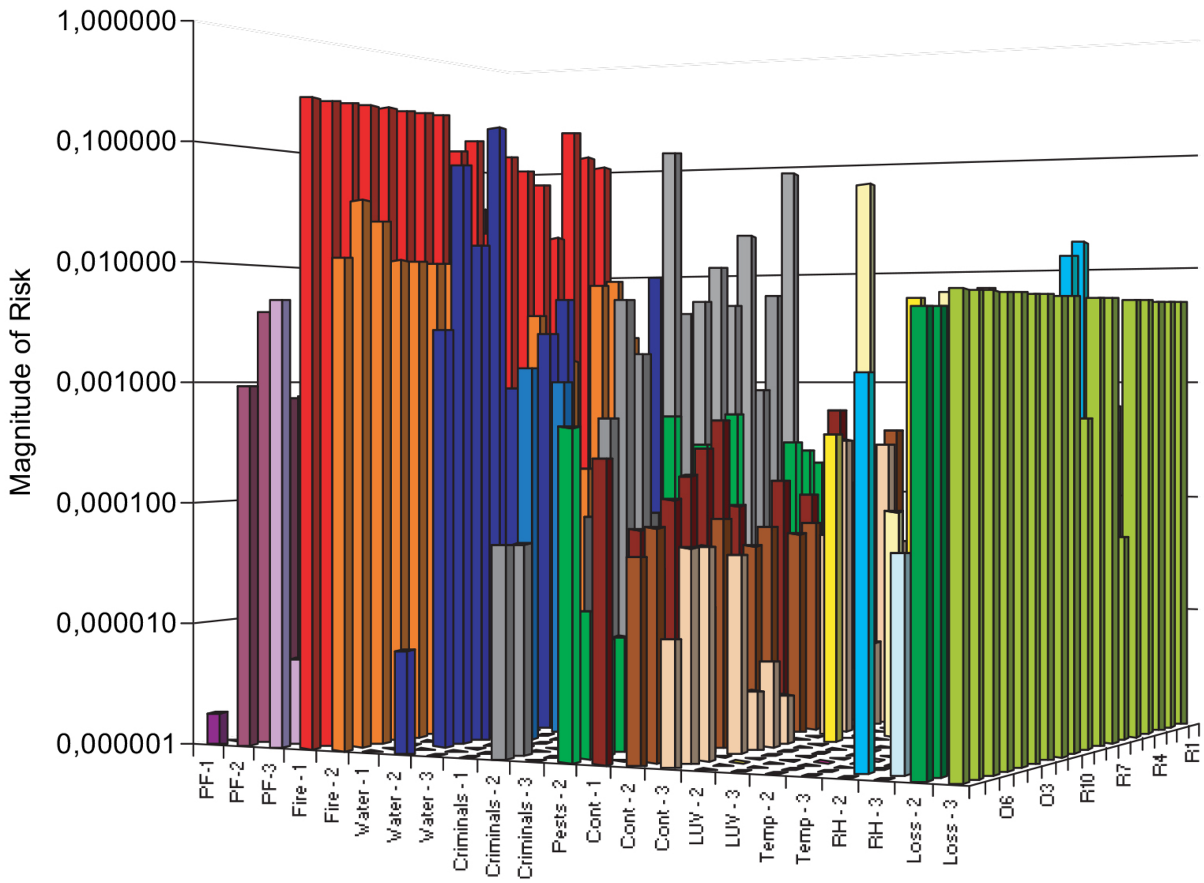

FIGURE 9.3. A graph of all the scores from an equation (magnitude of risk, y-axis) plotted against all the agents of deterioration (x-axis) and collection units (z-axis) identified at the Museum Amstelkring (Brokerhof et al. 2005).

Determining Risk

An advantage of quantification for decision-making is that it can standardize complex situations enough that different, fluid concepts can be expressed in a similar way. Using this probabilistic way of expressing terms allows very different concepts and data to be connected (such as P x I) to create a meaningful, comparable result. It also acknowledges the inherent uncertainties of the museum environment (and the world at large). Numerical scales are also used, which provide more intuitive analysis for the practitioner.

In calculation, it is necessary to specify the nature, intensity, and duration of a hazard's exposure to a heritage collection. Returning to the classical definition of risk (P x I), this information can be gathered in a number of ways, including through qualitative and quantitative, and general and context-specific data of all kinds, with varied assumptions and uncertainties.

Probability: The Chance of Something Happening within a Given Time Period

Assessing the likelihood of damage can involve a range of different data, which can be quantitative or qualitative, depending on the timeframe and kind of hazard. Occasionally, data may exist from other sources, such as environmental agencies or staff not directly connected to collection preservation (e.g., cleaner). These data may derive from the following sources:

- Environment (collected T/RH, external sources)

- Statistics on the frequency of an event (e.g., earthquakes)
- Anecdotal information, institutional memory
- Susceptibility and existing condition
- Records of movement, location, and disasters or near misses
- Expertise of the assessor
- Knowledge of damage mechanisms and damage functions
- Models of material properties

Impact: The Extent to Which an Event Affects a Valued System or Entity

How impact is defined may be based on a combination of factors, which can be assessed with support from curatorial colleagues and existing statements of significance about the collection. These include the following:

- Decrease in value(s)/significance
- Change in potential uses that elicit values
- Loss of authenticity
- Loss of aesthetic quality
- Loss of information
- Change in collection accessibility over time

As well as the uncertainties outlined in the introduction, which contribute to the challenges of ascribing a probability score, various factors affect how impact is understood. Understanding changes to materials only partially answers the questions that preservation specialists and managers may ask. The location of paint loss could impact its value, for instance if it occurs in facial features in portraits, as opposed to the background (Ashley-Smith 1999). Even highly quantified approaches are subjective when applied in practice.

Value and Risk

"The ultimate aim of conservation is not to preserve material for its own sake, but rather to maintain (and shape) the values embodied by the heritage" (Avrami, Mason, and de la Torre 2000, 7). Although risk assessment explicitly addresses value, connecting the loss of historic material to changes in values involves subjective judgment. Heritage values do not really fall under a single scale, like price, but embody a spectrum of values that shift as different kinds of relevance and uses, hence value, increase or decrease. Making this a semi-quantitative judgement requires simplifications because values are neither singular nor objective. This is how value is connected to the risk assessment process.

Values embodied by an object or collection are often fluid, interconnected, and changeable, so stating that 20% of an object's value is attributed to a particular physical property, like color, is a simplification required for comparisons. Ashley-Smith (1999) also points out that although some kinds of value (exchange/monetary, use, potential, complexity, documentary, scientific, aesthetic) are very likely to be altered by changes in an object's condition, others are highly unlikely to be altered (social/political; symbolic/spiritual, existence, rarity, material, age, context, history).

A common way of managing this multifaceted approach is by considering value or loss of value in collaboration with different members of the institution; the values prioritized by each member are averaged or aggregated as a sum of those values discussed. Another approach, often connected with risk-based activities like cost-benefit analysis, is to relate value to the institution's mission statement. Both are simplifications of complex relationships, but consistent with a broad-brush approach of analyzing a collection or institution.

Varying Perspectives for Well-Rounded Risk Management

The most obvious source of uncertainty for risk assessment is that it is entirely based on future prediction or projection. No matter how many facts are gathered and checked, answers cannot be definitive. The risk chain (fig. 9.4) outlines the different points before the successful "attack" of a hazard can be recognized.

An examination of any given stage will present uncertainties, since more than one cause may relate to visible consequences, or several mitigating or promoting factors that influence the attack (such as synergistic action from other hazards). Although many uncertainties are involved in the creation and projection of expectation based on limited knowledge of how historic materials might change in the future, biases and uncertainties are inherent in all methods applied in preventive conservation.

Examining risk with one lens can lead to some potential biases in interpretation, and risk assessment is no exception. Comprehensive risk assessments may include a range of different data, but this is not necessarily something that can be carried out with time constraints.

Potential causes can be identified, and their impact predicted, but they may not result in the expected effect. If no external hazards are identified, inherently unstable objects can deteriorate without an unsuitable environment. If predictive information was the only kind of information considered, all risks would be treated the same, regardless of their actual impact. For deterministic risks, like pollution and relative humidity, this need not be the case, as condition of an object (the result of that interaction) can be an indicator (Taylor 2005).

Past performance, however, can be a poor indicator of the future. Examining condition on its own can obscure existing problems with past damage and multiple processes of deterioration. Furthermore, the absence of symptoms does not mean that no risk is present.

Considering different assessments that correspond to different stages of the risk chain, or different kinds of data, can be a way to enhance or supplement the data that comes from just one approach. The drawbacks of one approach may be the strengths of another. Also, discrepancies between different assessment methods do not necessarily mean that one is correct and the other wrong; rather, these can draw out some meaningful information that comes from understanding the differences in perspectives. Conflicting information may appear inconsistent or problematic but can actually be a strategic or diagnostic advantage (Taylor 2018).

This can be illustrated by considering the qualities of different assessment approaches used in preventive conservation. Discrepancies between these data can actually prompt a deeper analysis of a situation as they present a more complex picture that leads to questioning the issues in different ways. For example, condition and risk assessments focus on different parts of the risk chain (fig. 9.4). They might disagree for temporal reasons—for example, the risk is rare so not evident on collections, or the effect is being realized more quickly or deeply than anticipated. Latent damage might not yet be observable, or existing damage

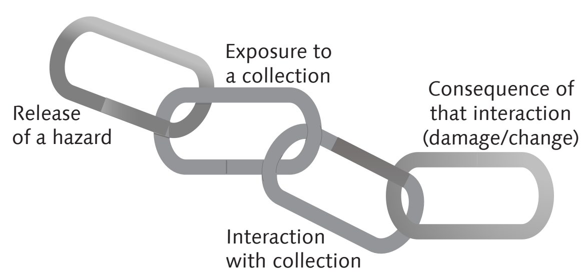

FIGURE 9.4. A risk chain applied to conservation, involving (1) the presence of a hazard, (2) its proximity to a collection, (3) its interaction with a collection, and (4) the resulting damage (Taylor, Blades, and Cassar 2007).

may be mitigating some impacts from risks such as climatic variation. The identification of synergistic responses, or of the impact of unmeasured hazards, is enabled by looking at the same system from different perspectives.

Making Decisions

Once a risk analysis has been carried out, decisions can be acted upon. A formal risk assessment provides opportunities to see which mitigating actions can contribute to the control of more than one risk or collection unit. A risk-based appraisal of options or decisions provides the opportunity to consider intangible aspects of decision-making. It also creates a way for decision-making to be transparent and communicable to people in different disciplinary groups, with various levels of expertise and responsibility within collection preservation. This can help promote understanding, secure resources, and provide a broad perspective for all parties.

Conclusion

Risk assessment offers a means for collection preservation issues to be represented in a systematic way that allows matters to be documented, communicated, and prioritized. The systematic framework requires the quantification of subjective and dynamic concepts, which can lead to imperfect representation, but provides consistency for collection preservation goals. This can support closer collaboration between allied professionals whose skills, knowledge, and information can contribute to the assessment of risks and implementation of any solutions. By connecting to the wider functions of a collecting institution, collection preservation approaches have an increased chance of being effectively implemented, of contributing to the wider mission of the institution, and of aligning with broader sustainability goals.

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TECHNICAL NOTE 10: CONSIDERATIONS FOR THE PROCESS OF MANAGING COLLECTION ENVIRONMENTS

Joel Taylor

Introduction

Deciding upon the appropriate climate for a collection, and a strategy for achieving it, requires many considerations. Environmental management is the result of a number of smaller decisions, often based on different kinds of information and made with varying degrees of certainty.

Debates surrounding climatic ranges have often been framed as a choice between "tight" or "narrow," "broad" or "relaxed." Those arguing for both sides have cited the complexity of the situation as a reason for their stance[1]—collections are too varied to be represented by a single number or the science is not clear enough to offer a broad range of RH without introducing risk. Both kinds of complexity are present in the management of collection environments. Decisions can feel overwhelming, and environmental ranges present an oversimplified "pass/fail" situation. Beneath this "pass/fail" situation, however, is a wealth of contextual information.

The practitioner should not be discouraged, though. This technical note reviews some of the types of information that can contribute to environmental strategies by considering a process that goes beyond the boundaries of a specific discipline or role. It discusses some of the varied factors that can contribute to deciding on an appropriate climate strategy.

The Differences

Situations in cultural heritage institutions can vary in a number of ways, which appear to make them incomparable in terms of managing their collection environments.

The aims of the institution, the reason for collecting, the kinds of collections, and the vulnerability of the building can all vary. Resources can differ in terms of budget, institution size, staff and training, and services. Strategies may be required for buildings that are in a development process, for collections undergoing rapid development, for spaces being repurposed, or for spaces that have seen few changes over many years. Institutions in different climatic zones (for instance, Manila, which is extremely hot and humid, or Anchorage, which is very cold) will face different challenges and meet them with different solutions.

1 "It is time for the museum professions to recognize that different objects have different requirements, that need to be understood individually not collectively… and for more effort to be put into understanding the real environmental performance of existing spaces" Mark Jones, *Museums and Climate Change* (London: National Museum Directors› Council, 2008); "All that can be said in general terms at the moment is that a stable room climate prevents deformations and thus guarantees a stable state of preservation." Andreas Burmester and Melanie Eibl, *Stable Is Safe. The Munich Position on Climate and Cultural Heritage* (Munich: Doerner Institute, 2014).

Even the reasons for considering an environmental management strategy may vary, including planning at the design phase of a new building project, creating a strategy in an existing museum, engaging an engineer or conservator to improve an undesirable situation, or aligning preservation with institutional goals and activities. Decision-making starting points for environmental management will vary, as will their integration into the institutional programming or building.

The relative importance of these matters will also change from situation to situation, and perhaps over time. Considerations of building preservation, for example, are relevant to all situations, but often more so for historic fabric. While a new, purpose-built art gallery and a historic house museum may both require systematic consideration of environmental management, the manifestation is quite different.

Decision Points and Contextual Factors

Differing outcomes or opinions that result from different information applied to the same process does not mean disagreement. Some differences may be so embedded in practice they can seem fundamental but they result from considerations at similar decision points. While a "How To" guide can be counterproductive, focusing on the decision points and the considerations that arise from such guides can be beneficial. By focusing on processes that connect with the wider aims of a cultural institution, one can step back and consider climatic ranges and strategies that are appropriate to a specific institutional context.

Garry Thomson's well-known climate recommendations include an often-quoted range, but that is based on a combination of factors elucidated in his book (1986). These factors include the climate's proximity to critical ranges for materials, the historical climate for the collection, the building's expected response to the exterior climate, and the capabilities of the system managing indoor climate. With wood representing the collection, and the main consideration being damage from fluctuation, baselines and priorities can be established. Importantly, Thomson's range didn't start with numbers, but with a process; and more recently, the emphasis on process has become more explicit in conservation guidance, such as the publicly available specification PAS 198 (BSI 2012).

The assumptions that exist in guidelines or standards are, by definition, not specific to the context of a collecting institution. The decision to adopt a standard or guideline may be valid but it is not a neutral act, as each one is created with background assumptions.

However a range or set point was derived, and however informally, the numbers stand before a network of interrelated (and sometimes changing) factors internal or external to an institution, and can be new or inherited from previous staff or situations. Some factors, however, are so embedded in one's daily practice that they are not visibly contemplated, such as the response of a building to the prevailing outdoor climate, the values embodied by the collection, or the in-house capacity to deliver the desired climate. The internal climate serves a purpose, or set of purposes, defined by the institution.

By reviewing environmental parameters systematically, in ways that connect with all functions of an institution, collection preservation can be more closely connected to different forms of sustainability. Rather than choosing between preservation and access, all functions of an institution can be embraced as forms of access, navigated over time and encompassing the needs of different groups and generations. Decision points are similar for different situations, even if institutions' aims vary, such as reducing energy consumption or minimizing risks. Amounts of time and resources for individual actions will vary from context to context and with different projects.

Decision Process Diagram

The diagram below (fig. 10.1) describes a strategy for managing climate that helps determine what information is necessary, how and when to use that information, and who might be involved.

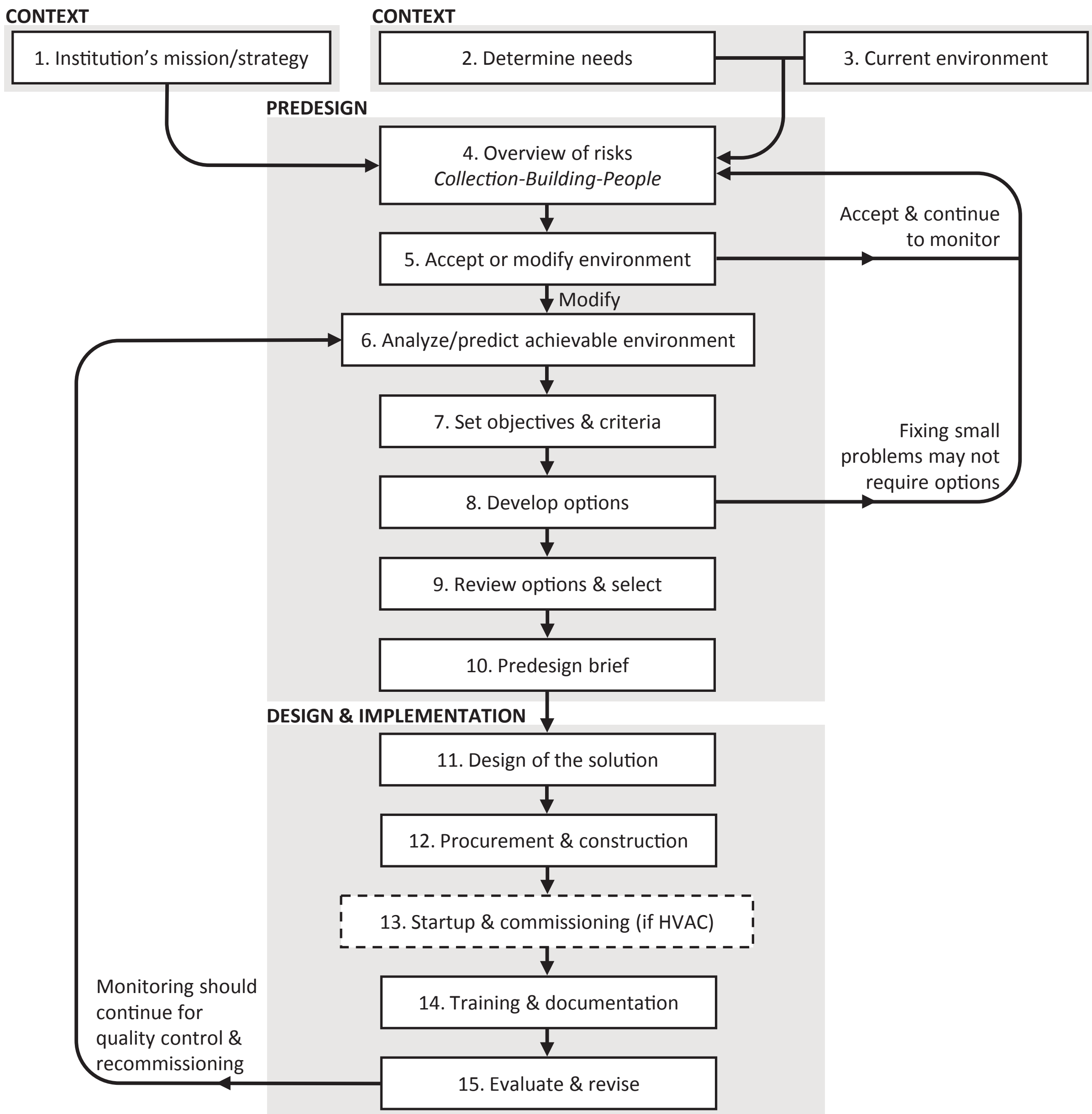

FIGURE 10.1. A process diagram outlining the decision points for an environmental management strategy. Credit: Joel Taylor; rendering by Annelies Cosaert

The diagram is intended to be broad enough to avoid some assumptions (e.g., disciplinary perspective, purpose of process, starting point in process) and robust enough to absorb different kinds of information (e.g., space capacity, climate, buildings, collections, condition, use). It expands the scope from climate alone in order to accommodate the broader institutional priorities.

The breadth of the approach is intended to allow integration into wider strategic initiatives. In a similar vein, as well as being intended to work for mechanical, nonmechanical, and integrated systems, it can accommodate passive building design as part of an environmental management system.

Scope of the Diagram

The diagram directly reflects the ASHRAE chapter "A24—Museums, Galleries, Archives, and Libraries" (ASHRAE 2019), which was based on this process. There are existing process diagrams related to environmental management and museum design that vary in aim, scope, and approach. These include various works that have provided systematic overviews and contributed to relevant situations within the scope of this process, such as Cassar (1995), which discusses environmental management, and Lord, Dexter-Lord, and Martin (2012), which addresses wider institutional functions. The final phase, the design and implementation section, draws from Maekawa, Beltran, and Henry (2015). It is intended to be consistent with concepts laid out in standards, guidance, and texts including EN 15757 (CEN 2010), PAS 198 (BSI 2012), IIC/ICOM-CC (2014), BS EN 16893 (BSI 2018), Ankersmit and Stappers (2017), and Elkin and Norris (2019). The "context" stages are intended to be broadly consistent with the ABC Method (Michalski and Pedersoli 2016), and the Probability x Impact dynamic of risk assessment applied to collection preservation as explained by Waller (2003) and Ashley-Smith (1999). The process builds on these approaches, but also includes some characteristics that differ from them.

Notably, the process described does not assume that relative humidity presents a problem to collections; this assumption is often a starting point for collection preservation processes. Conservation-oriented approaches are often developed to deal with a perceived problem, when an external conservator or conservation scientist would be engaged to identify and diagnose the problem. Defining the problem is part of the process. The process acknowledges that there is no single discipline or role that necessarily has all the answers. Because the process doesn't assume a conservation problem upon review, its initiation can be related to other operational matters that affect collection preservation, such as energy efficiency.

Explicitly looking at the context first reveals what is considered a "problem" and for whom. So, after the information gathering and monitoring necessary to make a decision, the diagram includes a stage at which one can opt to "do nothing" or quickly resolve. This encourages continual monitoring going forward so future action is based on evidence.

Although collection preservation is a vital part of the process, it is not intended to be solely a conservation process. Some institutions do not have a conservator on staff. There are many reasons to review or develop a preservation strategy. An equally significant matter may be the energy consumption required to sustain a climate that meets a desired specification, or that the prevailing climate specifications are not appropriate or necessary. Addressing these issues can reduce the load on mechanical systems that may be strained by increased energy insecurity or a discrepancy between indoor and outdoor climates. Such considerations can help integrate mechanical and nonmechanical methods of environmental management, as well as benefit exhibition programming or security.

Each decision point is accompanied by multidisciplinary stakeholders (table 10.1) whose level of involvement can vary as a project progresses. As different institutions will have different roles and responsibilities for professionals, the diagram tends to refer to broad areas of responsibility instead of titles.

Characteristics of the Decision Diagram

Divergence between situations becomes more pronounced as the process continues, so no one diagram can encompass all situations in detail. Figure 10.1 shows a decision diagram for the design of environmental

TABLE 10.1.
A list of different stakeholders, defined by their areas of responsibility in terms of their involvement in the stages outlined in figure 10.1. (Note that a "/" indicates "either/or.") This has been adjusted after input from the committee for the 2019 ASHRAE chapter "A24—Museums, Galleries, Archives, and Libraries." Credit: Joel Taylor

Stage	Step	Lead	Consult	Inform
Context	1	Directorial / Curatorial	Collections, Internal Facilities	Architect, Engineer, External Consultant
	2	Collections, Internal Facilities	Curatorial	Engineer
	3	Collections / External Consultant, Internal Facilities	Curatorial, External Consultant, Security	Architect, Engineer
Predesign	4	Collections / External Consultant, Internal Facilities	Architect, Curatorial, Engineer, External Consultant, Security	Directorial
	5	Directorial / Curatorial / Collections	Architect, Engineer, Internal Facilities	Directorial
	6	Architect, Engineer, Internal Facilities	Architect, Collections, Curatorial, Engineer	Directorial
	7	Collections, Engineer, Internal Facilities	Architect, Curatorial, External Consultant	External Consultant
	8	Architect / Engineer / External Consultant	Collections, Curatorial, Internal Facilities, Security	All Staff
	9	All Staff	All Staff, External Consultant	All Staff
	10	Curatorial / Directorial, Collections, Internal Facilities	Chief Financial Officer, External Consultant, Security	Architect, Commissioning Agent, Engineer
Design and Implementation	11	Architect / Engineer	Collections, External Consultant, Internal Facilities, Security	Commissioning Agent, Curatorial / Directorial
	12	Architect / Engineer, Chief Financial Officer, Internal Facilities	Collections, Commissioning Agent, Security	Curatorial / Directorial
	13	Commissioning Agent, Engineer	Chief Financial Officer, External Consultant	Collections
	14	Engineer, Internal Facilities	Collections, Commissioning Agent, Security	All Staff
	15	Engineer / External Consultant, Internal Facilities	Collections, Security	Curatorial / Directorial

- This list is not exhaustive, and the specific nature of the decision will vary with the context of the situation. It is intended to be broad enough for many situtations.
- The titles refer to general roles, rather than specific jobs, because of the variation between institutions and countries. Their position may also vary from this general guide.
- In general, informing and involving people early is best; deeper collaboration is also more challenging and time-consuming in the short-term.

management strategies, but not whole buildings or collection preservation strategies. Although principally focused on indoor climate, some matters may be relevant to others, such as indoor air quality.

The decision points are designed to accommodate existing situations, such as historic houses, new buildings, and, to an extent, those in the planning stage. Contextual information may exist, but potentially be dispersed or insufficient to make decisions. Although practitioners or external consultants may not be involved in developing mission statements, they should be aware of this contextual information. Including stages in the diagram that may occur before a conservator or engineer is engaged underlines the necessity of contextual information in all their decisions, and the potential for other non-technical information to be of value to the process. This information should be collected before environmental management systems are developed.

Although a process with defined steps, figure 10.1 can be used informally and stages (such as steps 1–3, or 4 and 5) may overlap in time and action. A more complex process may break down stages such as planning, holding, and reporting on meetings (Step 9). Different parts of the process will be more relevant for some situations than others; the steps just represent guidance on how information can be connected. Regardless of how much information is collected, different kinds of uncertainty are likely to be embedded in many aspects.

Decision Makers and Stakeholders

For a complex project, the involvement of participants from particular disciplines or with a certain form of expertise may vary over its course. Ideally, individuals of different disciplines will be present at all stages, but will not necessarily carry out the main activity at each step.

While it may encompass a small number of identifiable outcomes, the process of managing the environment involves a number of smaller decisions and requires input from a variety of sources.

Table 10.1 presents a range of professionals who could or should be involved to varying degrees at a given stage in figure 10.1, based on the kind of decisions (represented by different stages in the diagram). While an individual or group may be working through the process, the steps designate key decision points that are most relevant to specific actors. These will, of course, vary with specific contexts but they indicate the communications that can be involved.

The levels of involvement are expressed as three broad categories of action: taking a leading role ("lead"), having a potential contribution to decision-making ("consult"), and being affected by the outcome of a decision ("inform"). The stakeholders mentioned serve as a broad guide to areas of responsibility and/or competence (such as "collections" or "building," which are often the domain of conservators or facilities managers, respectively). People carrying out these duties do not always have a permanent position at the institution, nor does staff always specialize in the discipline; this is especially the case in smaller institutions. External advice is suggested at certain stages but can be incorporated at any time—including while guiding an institution through such a process. External experts noted in table 10.1 may have a range of competence, such as soil science, audience engagement, or even specialisms within the identified roles, such as preventive conservation.

The following looks at the different sections and subsections of the diagram in figure 10.1 and the considerations related to those decision points and broad stages of the process. Subtitles related to progress refer to several decision points.

Context (Step 1–3)

In terms of decision-making, several broad, connected categories reveal the context of a climate management strategy, whether evaluating the appropriateness of an existing range or determining a new range:

- *The values*: The reason a collection is important can vary among collections and sub-collections. These values may not all be signified by material preservation alone.
- *The collection*: As well as material properties, which will respond differently to RH levels and fluctuations, condition and vulnerability of objects can be an important factor and indicator in choosing a range. Loaned objects, with agreements about climate, are a further factor.
- *The people and uses of the space*: Behavior in and around the collection space, including mode of use (e.g., gallery, storage, office) and activities (e.g., exhibition, visitor routes, and cleaning). Spaces may serve different communities and engage with them in different ways.
- *The building*: Its materials, condition, envelope, morphology, and qualities influence the internal environmental conditions. If historic, the building is likely to embody values (including views) that are considered important.
- *The indoor environment*: The current conditions to which the collection is exposed, which are likely to vary over time and space.
- *The external environment*: Immediately outside the building but also historic and general trends in the region, and predictions of future climate, should be noted.
- *The capacity of the institution*: Many existing decisions will be influenced by what is or has been manageable for the institution, including its budgets, as well as staff and staff training.
- *Other risks and activities*: Other factors may be related to collection preservation and access that are more pressing or are connected.

Institutions may already have relevant information, such as collection surveys or significance assessments. Much of this information may exist in varying formats, degrees of completeness, and pertinence to environmental management. Some institutions may have a statement of significance about a collection, others an institutional mission statement. In some cases climate will be routinely monitored at object level. In other cases all that is available are data from a building management system (BMS) in a return duct, and sometimes monitoring will need to be established.

Decisions with profound consequences on the collection, such as the building's location, orientation, and its envelope design, might have even been taken long ago—or be in planning stages without the consultation of a collection specialist.

Even if they carry less weight in a specific context or cannot be changed, these aspects have to be considered. Archives that are not open to the public may not need staff presence or a means for items to be accessed. Often historic buildings, even the view, can be more significant than the collections therein, whereas new buildings might play a purely functional role. Contextual information helps to establish the appropriate balance for each situation.

Decision-Making Factors

The three parallel information-gathering steps of determining an institution's mission and values are interconnected. These are (1) needs of the collection; (2) building and institution; and (3) current environment. For example, information about needs will involve looking at the current situation and, after reviewing the context, putting the information in perspective. Predesign decisions are developed in relation to other institutional risks and priorities. Documenting this information is important, regardless of the final outcome.

Mission/Strategy (Step 1)

The role of collections in the functioning of an institution, as well as the institution's priorities, are factors that implicitly or explicitly shape environmental management decisions. Considerations include: what values are embodied by the collection, what changes might most impact those values, the perceived importance of different collections within the institution. Some of these factors are among the most profound and are connected to the very core aims of the institution, including the institution's values and the importance of environmental management in relation to the other activities.

How collections are valued determines how they should be preserved and what is understood as a risk. The biggest risk for an institution may be lack of access to collections rather than material change. The values of a collection will directly inform the impact of any potential change to a collection. Where an archive may prioritize informational values and access, a fine arts museum may prioritize aesthetic elements, and a contemporary art museum may prioritize functionality.

Almost all institutions will have a mission statement, and many operating institutions will have statements of significance and even specific values coded to conservation purposes, such as a risk assessment. Questioning and active listening with different staff, and community engagement at all levels, can also lead to a greater understanding of priorities and practice (and of the environmental management strategy). External experts may be helpful in understanding the nature of the collections or specific objects.

Determine Needs (Step 2)

The needs of the collections, in terms of their physical embodiment of their attributed values, must be balanced with the comfort needs of occupants and the building itself, along with capital and operating costs. The following lists are not exhaustive. The respective importance of these needs will vary among institutions and even spaces, and their requirements can conflict. For any actively collecting institution, a collection is seldom completed, but this is especially the case for a new or planned museum. All of this information is helpful in determining what is necessary from the perspective of environmental management.

Collection needs are impacted by:

- The nature of the objects in the collection(s). Materials and their behavior, their construction/assembly, and their condition and vulnerability (see step 1).
- Specific climate history to which the objects have been exposed and to which they have adapted (therefore, also changes in location over time), if available.
- Current and intended uses of the collection (see step 3).
- Frequency and kinds of access (see step 3), and location.

Collections databases, collection surveys, and condition surveys can all provide useful information. So, too, can communicating with staff involved in conservation, exhibitions, facilities, and curatorial roles. Material qualities can be found in a range of written sources, (e.g., Adelstein 2009; ASHRAE 2019; CCI 2020; Elkin and Norris 2019, appendix). From collected climate-monitoring data, the conditions to which the collections have already been exposed can be determined. Information about different materials can require specialist knowledge from conservation or science experts, who may be external to the institution.

Building needs are:
- materials, construction, and significance;
- condition, vulnerability, and location;
- current and intended uses of the building; and
- changes to the building over time.

A key source of information is an inspection, and there may well be regular reports on building condition and good documentation on repairs and other works. Historical information about changes to the buildings over time can be highly valuable to understand the building's current condition and behavior. Taking a multidisciplinary team around the building's interior and exterior can be very instructive in both defining needs and understanding the context, and in fostering communication.

Institutional and human needs encompass:
- the number of staff members and their current and/or intended activities (including staff residents, if any);
- the communities that the collections serve—numbers of visitors, demographics, and visitors' current and/or intended activities (such as community events, scholarly activities, education)—as well as qualitative engagement;
- current and intended use of spaces;
- legal requirements (such as working conditions); and
- expected visitor clothing (which can affect comfort and expectations).

This information can be obtained in a number of ways, including through writing, discussion, and observation. Discussion with staff is vital. Some policies are written down, and observation can help clarify how they are implemented. Visitor surveys can be carried out by facilities and visitor services staff for different purposes, and may provide helpful information regarding numbers, uses, and visitor feedback.

Breaking down an institution's needs in spatial terms can facilitate decisions that creatively accommodate different needs that may seem to conflict at the outset. Floor plans help identify clusters of activity and/or behaviors in adjacent spaces. High occupancy spaces require temperature control for comfort and ventilation for safety (both can be impacted by legal requirements), and collections areas require some degree of RH management. In some areas, it may be possible to prioritize temperature over RH control (e.g., cafes, entrances) or RH over temperature control (e.g., some storage locations). Some may require both (exhibitions, especially without display cases) or be dictated by other factors (computer server spaces), or not require any specific conditions. Like interpreting climate data, these requirements are not static and needs can change, including programming, collections growth, and space use. Requirements are not always the institution's decision alone, as loan agreements may impact climate needs in particular spaces.

Current Environment (Step 3)

The current environment refers to several things: the indoor climate(s) and the external climate and surrounding area, but also professional culture, procedures, and resources connected to collection preservation.

Information about the past and current conditions within and surrounding the buildings, and the interactions among climates, buildings, people, and collections, is essential in developing appropriate environmental management, even if no intervention is carried out. Historic features that have influenced indoor climate, such as passive ventilation, may have been changed, blocked, or removed to accommodate new uses. Information relevant to understanding the influence of the environment on the building, collection, and people includes:

- climate zone and predicted climate change;
- the site in which the building is situated (considering trees, neighboring buildings, elevation);
- the morphology of the site;
- the building and its orientation (see step 2);
- the existing methods of environmental control; and
- indoor and outdoor climate.

Some of this information can be found externally (e.g., climate zone), and some require monitoring (for at least one year). Visualizing data can be a powerful way to understand and communicate issues.

Other factors that must be considered to understand the context are staff and their roles and training (an organizational chart can be very useful), institutional policies, budget, and operating costs. They may not be affected by the environmental strategy, but all influence the current situation and future possibilities.

Understanding the institution's current operations on different levels is very important. Examples include:

- energy consumption, which can be aided by itemizing units;
- an institution's opening times;
- current methods of storage and display;
- organizational charts;
- strategic plans and vision documents; and
- specific strategic goals, such as United Nations Sustainable Development Goals.

Understanding the context of the site in general is also important, as in:

- demographics of the location and changes over time (and maps of the area);
- historic images of the building and interior; and
- archival information on changes to the site or building.

Knowing the intended and desired climate is also useful, as they can differ from measured data. The current set point, range, and desired output can all merit review during this process, especially in light of the other data collected.

Predesign Phase (Steps 4–10)

The opportunity to synthesize the diverse forms of qualitative and quantitative information can help identify connections. This information includes simple matters, as in the impact of basic routines, such as cleaning of climate data, but also more complex relationships among the different systems involved. This also allows climate to be considered in terms of other risks, sectors, and strategic priorities. It places collection sustainability in the context of other kinds of sustainability, from the institutional to the global level.

Overview of Risks (Step 4)

Having gathered the information, one may already have an overview of the situation: what problems may exist and how serious they might be. It is necessary to synthesize and analyze the information provided, and to connect that to the wider issues of the institution.

An important step in this understanding is to identify relationships and influences. The three aspects mentioned before—collections, buildings, and people—influence one another in numerous ways. Addressing one factor can influence others. The importance of these factors and the relationships between them depend on the kind of institution, but general trends can be observed (fig. 10.2).

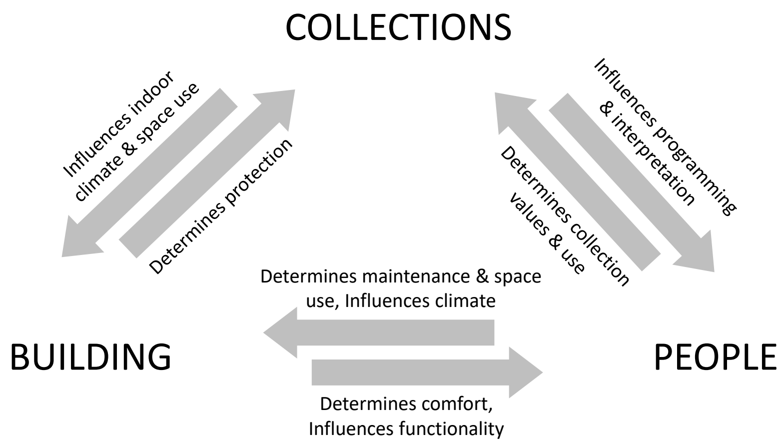

FIGURE 10.2. Potential influences between buildings, collections, and people (general influences are not exhaustive). Credit: Joel Taylor

A degree of balance is often required, and prioritizing one factor over another can lead to negative consequences (table 10.2) that will vary in relevance between contexts. Breaking down information in terms of space (rooms, floors, zones), time (operating hours, seasons), and need (functions, vulnerabilities) can help indicate the most pressing matters and identify creative solutions rather than just trade-offs.

TABLE 10.2.
Imbalances caused by one aspect (building, collection, people) being favored over another. Credit: Joel Taylor

Priority	Negative Consequence
Building over Collection	Inconsistent internal climate in certain seasons (affecting display/ storage locations)
Building over People	Building needs (and any problems) can affect programming
Collection over Building	Potential for internal condensation, HVAC installation damaging building fabric
Collection over People	Preservation needs affect programming
People over Building	Uses (and related climate needs) impact building fabric
People over Collection	Misuse or lack of care for collection

How the current environment compares to the range of risks to the collection (such as security or documentation) and needs of the institution (such as visitor services or exhibitions) will rest on factors outside of collection preservation and may involve administrative strategies.

Accept or Modify (Step 5)

With the necessary information, an institution can elect to modify the current environmental strategy or accept it, making minor changes for which they have sufficient information. In abstract terms, a collection environment can always be "improved," but the real benefit may not be significant. The internal climate may not be ideal (this is a subjective matter to an extent), but other risks and activities beyond collection preservation may be prioritized above climate management. The process of assessing risks is a comparative act that involves accepting risk, or at least prioritizing other risks. No situation is free of risk, and an intervention is always possible, even if one is not necessary or less important than other matters. How to proceed at a given time should be weighed against other factors that also contribute to the sustainability of the institution.

An understanding of the building and nature of the collections allows for measures that can be low cost. It may be decided that broad goals are met and intervention is not needed, or that more information is necessary. The diagram (fig. 10.1) shows a return loop to step 4 for this reason. Either way, further monitoring of the climate is required to make effective decisions.

Knowing the current and recent environments can provide insight into the specific history of the climate surrounding the collection, which, aligned with information about its condition, provides insight into the climatic conditions to which the collection is accustomed. If a collection has acclimatized, or previous damage reduced the impact of climate-induced strain ("proofing," in Michalski 2016), there may be no need to minimize fluctuation.

If change is required, the information collected should present a path for developing clear goals and targets, which may include gathering further diagnostic information. Monitoring should continue whether or not an intervention is required, to either evaluate modifications or identify future changes.

Specifying Climate Ranges

Analyze/Predict Achievable Environments and Impediments (Step 6)

There are two questions that guide this matter: "What is possible?" (in terms of both the contextual limitations and the potential outcomes) and "What is necessary?"

An element of pragmatism is involved in determining what might be possible, which can set limits on environmental management expectations in the building. Understanding this early on can help set realistic objectives for managing climate. A historic house will not be able to meet the tightest specifications of mechanical control without serious alterations to the fabric—which is often highly undesirable—regardless of the equipment's capabilities. Equally pragmatic is considering what is necessary to achieve the preservation goals set out for the collection. Given that spaces may need to serve different functions, and that external climates may present greater challenges in the future, an institution's energy consumption and activities should be considered to avoid stretching its capacity in terms of energy use or personnel.

The current situation may offer an impression of what is possible (step 3)—especially if the current indoor climate measurements differ from the intended climate. The situation may require closer analysis, which can include diagnostic monitoring and/or modeling of the building, to understand the dynamics of problems. Information can be expressed and ideas communicated in a number of different ways—for example, walk-throughs of equipment (such as the HVAC plant) with both collections and facilities staff, discussing plans for capital projects, connecting findings to a building model to simulate hygrothermal behavior, or evaluating information with up-to-date resources on material responses to climate.

Set Parameters and Objectives (Step 7)

Existing guidance for collections can be a good starting point for setting parameters and objectives, provided that guidance can be applied to the specific institution. Much advice provides a degree of flexibility on the set point, from slight variations within a median range (e.g., Thomson 1986) to using the historical annual average of the climate surrounding the collection (e.g., ASHRAE 2019). Seasonal variation and setbacks, especially in terms of temperature, are common (e.g. Thomson 1986, ASHRAE 2019, PAS 198 (BSI 2012), BS EN 16893 (BSI 2018)). Following guidance and aligning with one's current situation need not always involve tension. Based on knowledge of the situation and the needs, adjustments can be made that take into account comfort and legal requirements.

There are very few specific RH thresholds for general collections, and beyond avoiding extremes, the range is a judgment comprising many of the factors discussed. To an extent, the process may be iterative as realities of what is possible and necessary.

Knowledge of a specific collection may involve more bespoke climatic ranges, such as archaeological metals, historic plastics, and mineral specimens. Yet, these special accommodations may not require a separate system, but only a degree of accommodation, such as "box-in-box" enclosures with local control for storage and cases for display. Stating objectives, rather than suggesting solutions early on, allows those involved to be creative and return to the problem with new ideas later.

It is worth considering where and when these objectives are met or need most attention. Loaned objects may require longer-term storage, for example, but not every storage space has to meet those loan requirements. Challenges in meeting specified ranges during the summer may vary from those in the winter. Combined with some expertise in conservation science and material, a range may provide insight into the expected lifetime of a collection, which can contribute to decision-making about its use. Such matters can influence the options that are developed and chosen.

Options for Climate Management

As the process continues, decisions involve more and more people and have a greater impact on the institution. Once information is reviewed—and specific action is deemed necessary—approaches to managing the environment must be developed, considered, and selected. This might not always be a formal process, but openness and transparency are still important. For all options to be relevant to the context and a broader notion of sustainability, and fair for all parties, their impacts beyond traditional collection preservation matters should be acknowledged by the institution early on.

Options may be deeply influenced by budget, and low-cost options may be the only viable ones for some institutions, but consideration of different approaches (including doing nothing, as a baseline reference point at this stage) can help work through the best approach.

Develop Options (Step 8)

A broad consideration that involves sustainable collection preservation is the choice between mechanical and nonmechanical control. Many environmental management strategies will involve a combination of aspects related to the building, mechanical control, nonmechanical equipment (such as a display case), and management of spaces. These different aspects can work together to avoid reliance on one approach and consequent overexertion of equipment. This may mean integrating new options with existing features, such as the design qualities of a historic house (including features that address the local climate) and staff roles (e.g., operating traditional blinds in historic houses). For a new building, the solution may be part of a larger, integrated approach. Although HVAC design options may be a common consideration, particularly in new buildings, the building is a powerful means of managing climate that plays a major role in any suggested solution.

Contextual work (steps 1–3) should provide the basis for understanding what resources are and could be available, so options can be developed and evaluated. In addition to their expected effectiveness in terms of collection preservation, their initial investment and operating costs will be important factors for decision-making, as well as whether they are considered to be part of the building (e.g., passive design), services (e.g., HVAC), equipment (e.g., cases), or management (e.g., staff time). Who works on developing options and who is consulted will vary with the complexity of the problem, the range of possible options, and the size of the institution. Options do not necessarily have to be detailed, as the chosen ones can be developed at the predesign stage (step 10).

Review and Select Options (Step 9)

Appraising and deciding upon options for managing climate, and reaching consensus decisions, involve all the staff affected by potential changes. All of these voices should be represented. This can be difficult and time consuming. Many staff members are already in place and ideas and procedures set out.

Types of options can vary, from installing a new HVAC system to ensuring that staff members keep doors closed at certain times and manage shutters effectively. Often a combination will be implemented. The implications of options will affect different issues to varied extents and will impact the priorities and activities of different people in different ways. Engaging staff affected by the strategy, after providing them with relevant, clear information, offers an opportunity to consider the options, examine different perspectives, and resolve apparent conflict through discussion. Discussion and scrutiny of different options may even present the opportunity to adjust the chosen one.

Not everyone will have a firm understanding of the issues at the outset—i.e., theoretical aspects of collection preservation or the details of the specific context—and ensuring that consensus decisions are built on informed discussion can take much preparation. Distilling this information, including that in the Context stage, can be very helpful for attendees' preparations and for effective communication.

Consensus can be built in different ways, such as classic cost/benefit techniques, depending on context. Such processes, however managed, can be difficult and time consuming. They often require trust that the options are clear and sound, that the information is sufficient, and that the method of evaluation is fair and can acknowledge nuance. Quantitative approaches can be more objective, but also require a degree of goodwill and cooperation from participants. Transparency regarding the chosen method in its application and recording can contribute to building trust. Facilitated, recorded meetings where criteria are addressed systematically and transparently will always be necessary, but are especially useful for larger initiatives.

Important considerations in selecting conservation options are preservation benefits, impact of use on historic fabric of the building, collection uses, and institutional mission. Financial and logistical costs should also be taken into account. A new storage facility could require a complex move—a project in its own right. Connecting to existing institutional priorities to weigh and assess options can be a way to help frame discussions.

The Predesign Brief (Step 10)

Once a management strategy has been selected from the possible options, work is still to be done before implementation. Implementing a strategy may lead to specific works, such as new buildings or control systems. This will often involve a new set of actors, possibly from beyond the organization, such as contractors, specialists, and/or architects. Developing a predesign program brief is an opportunity to distill the priorities, requirements, and criteria of design solutions for a wider audience who will act on the information collected earlier in the process. A predesign program brief will be essential for a project, but even in simple cases where a formal brief is not required, certain questions should be considered going forward, regardless of the direction taken.

A clear, articulated vision helps the cultural institution work through any development. Communicating design needs will aid in setting criteria. As the scope and collaboration of the project widens, this allows the project goals to be aligned with the wider mission of the museum and any other institutional goals, such as sustainability agendas. In addition to a written document, project goals are often advocated and communicated through a project. These goals can identify aspects beyond the scope of the design solution or specialists, and help evaluate potential solutions if problems arise. This can require a specific "project champion" who represents the collection and the values it embodies. Representation at a senior level is also highly desirable. Complex projects can involve different backgrounds and assumptions. An architect, for example, may be more familiar with offices, whereas a collections manager may not easily read blueprints. A written program brief that expresses the collection needs can help gain support internally.

Designing, Implementing, and Sustaining (Steps 11–15)

Realizing the Strategy

Because the kinds of management can differ so much, depending on the choices made, decisions from this stage will be deeply contextual. Consequently, decision making from this stage will vary considerably if the existing processes and equipment are being adjusted, replaced, or newly commissioned. Fundamentally, however, the approach, scope, design team, and timeline should be determined. Instead of key decision points, one can consider key questions whose answers can impact the communication and capability of the project team:

- Is a dedicated collections professional necessary to oversee collections preservation issues during works (e.g., construction)?
- Will the chosen climate strategy involve moving collections during works?
- If the strategy involves works, should a commissioning agent for mechanical solutions, who understands the underlying design goals and can be present through the process, be identified?
- Will a risk assessment be required for the designed solution?
- How will information recorded or gathered at the context phase be accessible to new parties (e.g., the values of the collection and building)?
- How can existing information help communicate in-house skills and expertise to the design team?
- Of any materials or equipment introduced, how does the initial cost relate to the life-cycle cost?
- Are any historic values of the building impacted?
- Is the collection expected to grow over time, and with similar or different materials?
- Who will be responsible for the day-to-day operations of climate management?
- What kind of communication will be required if the strategy integrates different approaches, such as mechanical, passive, and nonmechanical?
- Is training of internal staff required (and have resources and time been set aside for this)?
- Is the strategy robust (e.g., can it effectively cope with staff changes over time; do data and management methods have sufficient backup)?
- Does the environmental monitoring carried out during the predesign stage contribute to evaluating the quality of the solution? If not, what monitoring would?
- Can the criteria set out objectives and options to evaluate the strategy (see return loop arrow in step 15)?

Cultural collecting institutions may approach the climate(s) for their collection(s) in many ways, with very diverse outcomes, but the key decisions share common principles. Understanding how and when to use existing knowledge, to seek expertise, and to gather information can contribute clarity, cohesion, and transparency to a process that involves complexities, requires balance, and benefits from considering nuance and difference. Sustainability at both the global and institutional level requires preparation and consistency that are bolstered by analysis, synthesis, communication, and clarity.

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TECHNICAL NOTE 11: NONMECHANICAL ENVIRONMENTAL MANAGEMENT STRATEGIES

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Introduction

Strategies for environmental management in buildings fall under two broad categories: nonmechanical and mechanical. Nonmechanical strategies use fixed and operable elements of the building envelope to moderate or amplify the effects of external thermal, moisture, and convection loads on the interior environment. Many nonmechanical strategies require periodic adjustments, such as the manual operation of window shades by building occupants. In contrast to nonmech nical strategies, mechanical strategies change the psychrometric state of the interior air by mechanical systems for heating or cooling and humidifying or dehumidifying.

The two approaches of nonmechanical and mechanical strategies are not mutually exclusive. In practice, the complete environmental strategy for a particular building should be a combination of nonmechanical and mechanical strategies. This technical note considers how nonmechanical strategies can be effectively employed for the environmental management of cultural heritage collections, thereby reducing the energy necessary to operate mechanical systems. As an added benefit, nonmechanical strategies can enhance the management of the building's interior environment if the mechanical systems are not operating.

This technical note provides environmental management guidance for cultural heritage collections that are housed in historic and nonhistoric buildings. Because of the wide range of climatic contexts, building construction, and environmental sensitivities of collections, this technical note does not provide detailed design guidance. The design of modifications to building envelopes or the soils around a building should be prepared by a professional engineer or a registered architect.

This technical note is intended to be used in conjunction with technical note 4, "Museums and Their Exterior and Interior Environments."

It provides an overview of:

- basic principles of flows of thermal energy and mass in buildings;
- flows of thermal energy, air and moisture through the building envelope;
- ASHRAE guidance for building envelope performance for buildings housing collections such as museums, galleries, archives and libraries;
- strategies for environmentally managed spaces that are separated from exterior walls and roofs;
- strategies for source moisture control;
- strategies for moderated thermal flows;
- strategies for moderated air leakage and stack effect;

- strategies for moderated moisture vapor flow;
- implementation of nonmechanical strategies; and
- maintaining performance of nonmechanical strategies.

Basic Principles of Flows of Thermal Energy and Mass in Buildings

When considering nonmechanical environmental management, it is important to have a conceptual and systemic understanding of the flows of energy and mass that pass from a source (higher concentration) through a material body to a sink (lower concentration). In the case of environmental management and buildings, we are specifically interested in the flows that pass through the building envelope. These flows take place between the exterior and interior environments and include thermal energy, water, vapor, and air.

Thermal Energy Flows

Thermal energy always flows from a solid/liquid/gas at higher temperature (the source) to a solid/liquid/gas at lower temperature (the sink). In the case of a building envelope, the flows can be bi-directional, depending on whether the thermal energy source is inside or outside of the building. For example, in ASHRAE climate zone 4B, mixed-dry, the thermal energy flow at night will be from the interior and surfaces of a heated building toward the clear sky and to the cooler air. During a summer day, the thermal energy flow will be from the hot exterior air and solar radiation toward the cooler, air-conditioned interior.

The law of conservation of energy dictates that the thermal energy flows must be balanced, that is, the amount of energy flowing from the source equals the amount of energy stored in a material or medium plus the amount of energy flowing to the sink, as shown in figure 11.1.

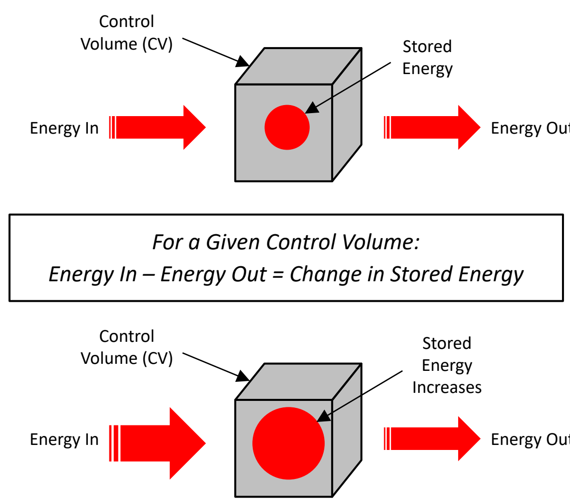


FIGURE 11.1. Conservation of thermal energy. Credit: Michael C. Henry

Thermal energy flows by three processes of heat transfer—conduction, convection, and radiation—as shown in figure 11.2.

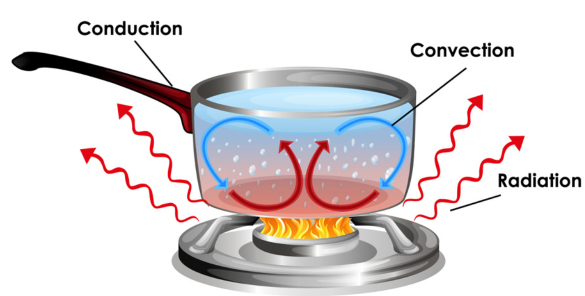


FIGURE 11.2. Types of thermal energy transport. © Blueringmedia | Dreamstime.com

Conduction heat transfer takes place through or between solid materials in physical contact; for example, in a building, conduction occurs through walls, roofs, and soils where materials are in direct contact. Convection takes place between a moving liquid or gas and a solid or liquid. Natural convection results from temperature differences. For instance, in a building, natural convection occurs at a radiator, or when warm air rises from the first floor to the second floor, or when the wind moves air across a surface. Forced convection results when a fan or pump creates a pressure difference; this is often the case with mechanical systems. Radiation heat transfer occurs through electromagnetic waves in the infrared spectrum; the sun heats a building by radiation heat transfer and the majority of the heating effect of a fire in a fireplace is by radiation heat transfer from the fire to nearby surfaces, such as the exposed skin of occupants.

Mass Flows of Water and Air

Mass flows of water and air in buildings are more complex than thermal energy flows. Mass flows may occur as liquid water, dry air, water vapor, or a mixture of water vapor and dry air. The law of conservation of mass dictates that the mass flows must be balanced. In balanced flows, the amount of mass flowing from the source equals the amount of mass stored in the medium plus the amount of mass flowing to the sink (fig. 11.3).

When applying the law of conservation of mass, all masses of liquid water, water vapor, and dry air should be included. Although the air mass and water vapor mass may be small compared to the liquid water mass, they are significant with respect to each other, and the water component may have changed phase, from liquid water to water vapor or reverse, during the transport. Changes in the mass of water vapor will affect relative humidity.

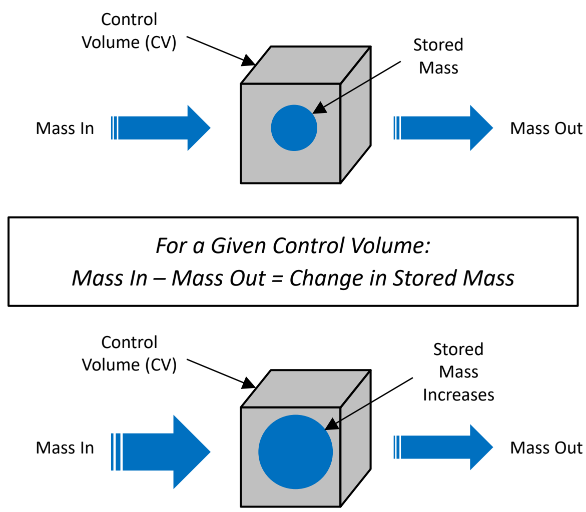


FIGURE 11.3. Conservation of mass. Credit: Michael C. Henry

Mass flows of liquid water result from differences in height (gravity flows), pressure or density (convective flows), or surface tension between the liquid and small pores in a material (capillary flows). Mass flows of water vapor, dry air, or mixtures of dry air and water vapor result from differences in pressure or density (convective flows) or concentration or partial gas pressure (diffusion), both of which are affected by temperature. Figure 11.4 illustrates typical moisture flows in/out of "storage" in building materials, with the associated transport processes, wetting/drying processes, and moisture sources/sinks.

Figure 11.4 yields the insight that while there are many sources and paths for moisture to enter a building material, the opportunities for water to leave a building material are limited to drainage as a liquid and to evaporation/desorption to the interior or exterior air as vapor. This conclusion places primacy on source moisture control as the most effective strategic approach for nonmechanical environmental management of moisture; examples of this will be discussed later in this technical note.

Figures 11.1 through 11.4 illustrate thermal energy and moisture flows as occurring separately. In building and natural environments, the flows usually occur as combined heat and moisture flows. For example, during

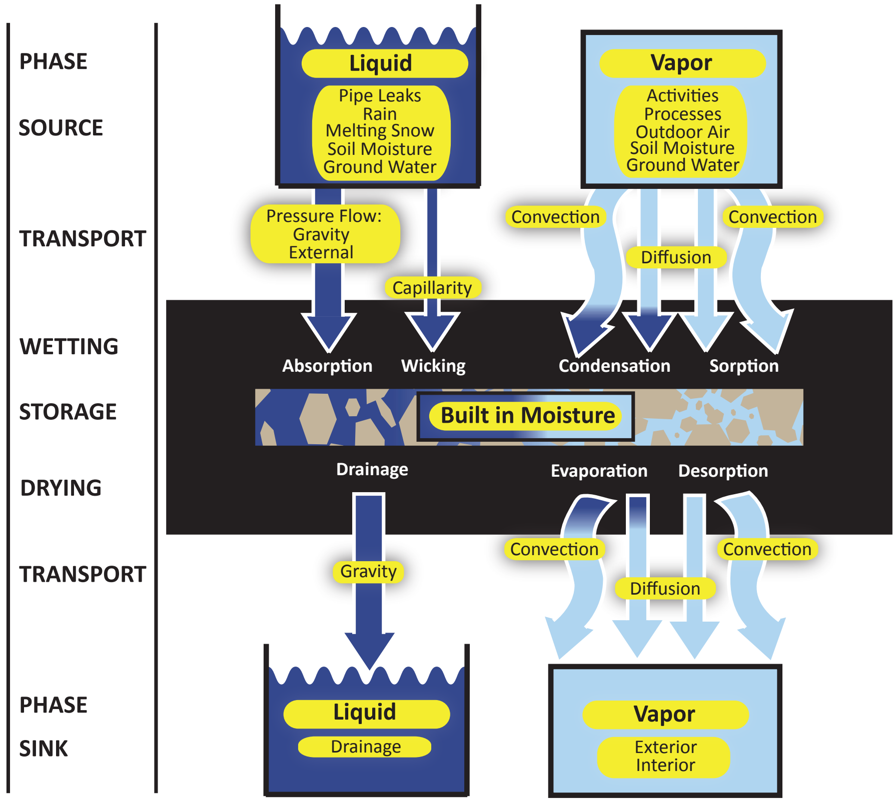


FIGURE 11.4. Moisture flows in building materials (after Straube 2002). Credit: Christine Beckman

a cold, dry winter, warm, humidified interior air may pass through an exterior wall cavity to the outside. Depending on building materials, temperatures, and moisture levels, moisture vapor may condense within porous materials in the wall during this process. These combined flows of moisture and thermal energy are studied as simultaneous hygrothermal flows.

For a specific temperature and pressure, any mass of liquid water, water vapor, or air contains a calculable amount of thermal energy. Therefore, the flow of mass from one location to another also involves the transport of thermal energy. Differences in temperature between source and sink can influence mass flows by influencing vapor pressure (vapor diffusion flows) or surface tension (liquid capillary flows). Changes between the water and vapor phases, such as condensation or evaporation, can occur because of changes in thermal energy.

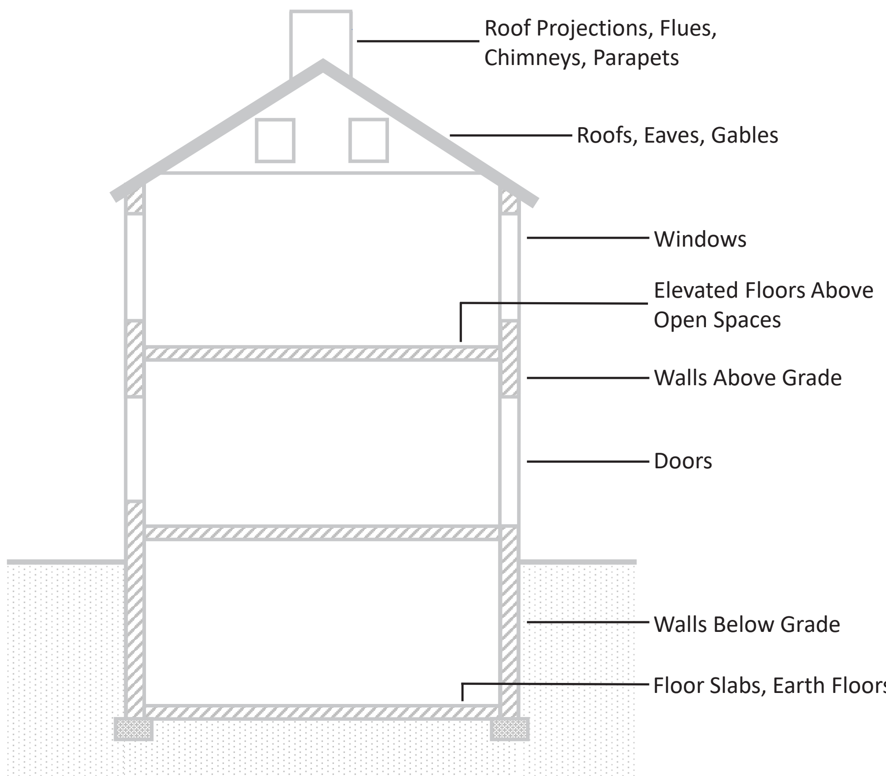
In the past, static equilibrium analysis was used to assess combined flows of thermal energy and moisture across building envelopes (ASHRAE 2021). Today, computer modeling such as WUFI® (Wärme Und Feuchte Instationär) enables analysis of these flows as combined processes in dynamic equilibrium.[1]

Thermal Energy and Moisture Flows through the Building Envelope

The building envelope is defined by materials, thickness, complexity, perforation, and transparency/opacity. These characteristics and properties vary according to climate, culture, building use, and period of construction. Building envelopes incorporate a number of fixed and operable elements that mediate the thermal energy and moisture flows between the interior environment and exterior environment (fig. 11.5).

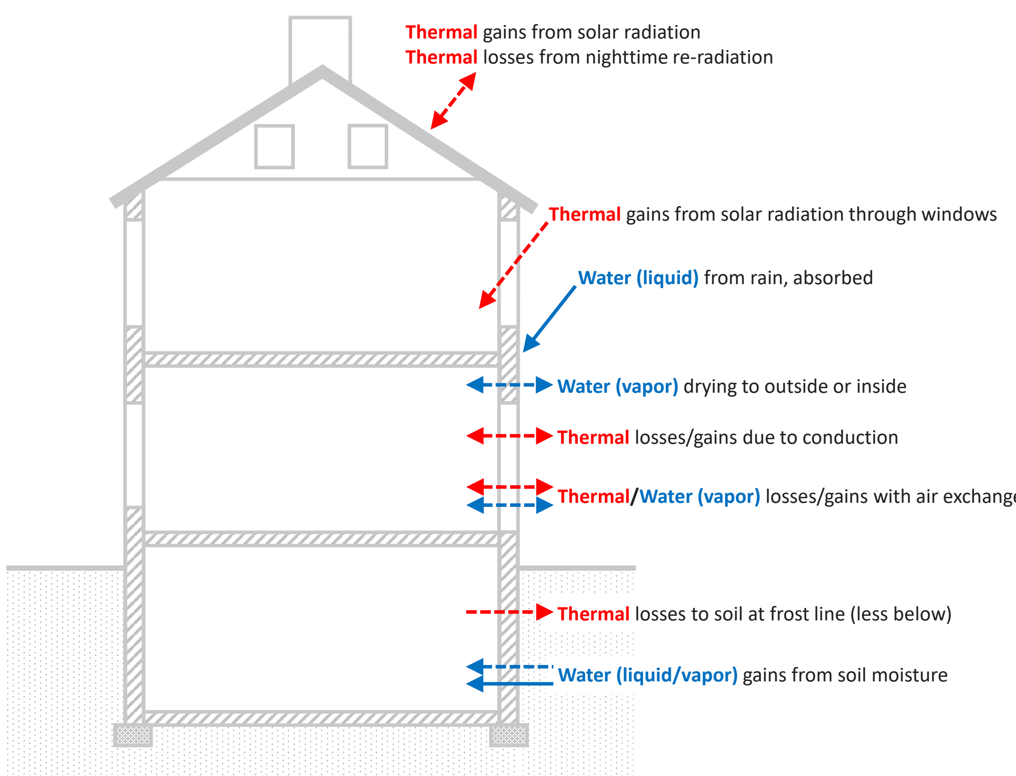
1 "Home Page," WUFI, https://wufi.de/en/.

FIGURE 11.5. Elements of the building envelope. Credit: Michael C. Henry and Vincent Laudato Beltran



Thermal flows and air/moisture flows through discrete elements of the building envelope will vary in intensity and dominant direction, but they can be generalized (fig. 11.6).

FIGURE 11.6. Thermal and air/moisture flows through the building envelope. Credit: Michael C. Henry and Vincent Laudato Beltran



Within the building, convective transport can occur vertically due to thermal stack effect or vapor pressure stack effect. In the absence of wind-induced static pressures, thermal stack effect can greatly influence infiltration and exfiltration of air and moisture vapor. In winter, for example, thermal stack effect will dominate, with exfiltration of heated interior air at upper levels and infiltration of cold outside air at lower levels. Convective transport can also occur between conditioned spaces because of imbalances in pressure or between conditioned and unconditioned spaces due to air leakage in supply and return ducts.

Because vapor may be transported by either convection (with air movement) or differences in vapor pressure (movement of moisture molecules alone), buildings with low air infiltration rates are still susceptible to vapor stack effect, which can drive vapor flows in the absence of air flows.

Understanding the thermal, air, and moisture flows through a building envelope helps us identify opportunities to intervene with nonmechanical environmental management strategies by influencing the transport of moisture (as vapor or liquid), air, thermal energy, and light between the interior and exterior.

ASHRAE Guidance for Building Envelope Performance for Museums, Galleries, Archives, and Libraries

In buildings containing cultural heritage collections, it may be necessary to maintain interior conditions of relative humidity and temperature that differ greatly from exterior conditions in order to prevent damage to the collections. The temperature and moisture gradients that result from these interior/exterior differences can result in accelerated deterioration or damage to the individual envelope materials or the entire envelope assembly. The resultant temperature differences and moisture differences and flows across the building envelope may lead to high moisture content or saturation of porous wall materials. Other potential consequences include condensation on low permeability surfaces or migration and subsequent crystallization of soluble salts within the envelope material(s).

ASHRAE (2019a) addresses these risks by considering the various categories of interior environmental control for preservation of collections, the climate zone in which the building is located, and the building envelope performance necessary to maintain the differences between the interior and exterior conditions without sustaining envelope damage (table 11.1).

ASHRAE (2019a) also provides examples of building envelope features that correspond to the minimum performance levels (Controlled, Moderated, or Optional) for thermal flows, air leakage, stack effect, and water vapor, as well as minimum performance for source moisture control of liquid water, as shown in table 11.2.

For certain combinations of climate zone, interior environmental performance, and envelope performance, table 11.1 also indicates that designs for building envelope performance, including performance improvements, need hygrothermal analysis. This requirement applies to situations where the desired interior conditions and the exterior conditions of the climate zone result in steep thermal and moisture gradients across the envelope. This is due to the complexity of combined thermal and moisture flows through building envelopes. Because these simultaneous flows are dynamic and complex, computer simulations are often used in order to assess the risk of creating potentially damaging conditions within the envelope.

As can be seen in table 11.2, there are many opportunities to improve building envelope performance with optional measures, and these strategies will be discussed in the remainder of this technical note.

TABLE 11.1.
Type of control, climate zone, and typical envelope performance necessary (after ASHRAE 2019a, table 11). © ASHRAE, www.ashrae.org

Type of Control	Liquid Water Loads		Hygrothermal Loads	Necessary Envelope Performance			Hygrothermal Analysis	Design Considerations
	Rain Exposure	Source Moisture	Intl Climate Zone(s)	Thermal Flows	Air Leakage & Stack Effect	Moisture Vapor		
AA Precision Control	All	●	All	●	●	●	■	Building envelope should be separated from interior enclosure of collections space
A1, A2 Precision control with seasonal changes	All	●	5A, 5B, 5C, & colder	●	●	●	■	Building envelope should be separated from interior enclosure of collections space
	All	●	4A, 4B, 4C	◯	◯	◯	♦	
	All	●	3A, 3B, 3C, & warmer	●	●	●	■	Building envelope should be separated from interior enclosure of collections space
	All	●	6A, 6B, & colder	●	●	●	■	
B Limited control with seasonal changes	All	●	5A, 5B, 4A, 4B, 3A, 3B	◯	◯	◯	□	
	All	●	5C, 4C, 3C	◯	○	○	□	
	All	●	2A, 2B, & warmer	◯	●	◯	♦	
	All	●	All B	◯	◯	○	□	Where diurnal T differences are large, insulation may be needed to prevent high RH at night caused by cooling
C Prevent RH extremes	All	●	5C, 4C, 3C	◯	○	○	□	
	All	●	All other zones	◯	◯	◯	□	Moderated or controlled envelopes can eliminate or substantially reduce size of HVAC equipment
D Prevent very high RH	All	●	All B	◯	○	○	□	Where diurnal T differences are large, insulation may be needed to prevent high RH at night caused by cooling
	All	●	5C, 4C, 3C	○	○	○	□	
	All	●	All other zones	◯	◯	◯	□	Moderated or controlled envelopes can eliminate or substantially reduce size of HVAC equipment
Cool Store	All	●	All	●	●	●	♦	• Specialized collections enclosures separate from the exterior building envelope are typically used • Where cooling loads are low (e.g., Climate Zone 6 or colder) and in some subgrade locations, specially designed exterior envelopes can achieve this performance without a separate interior enclosure
Cold or 'Frozen' Store	All	●	All	●	●	●	♦	Specialized collections enclosures separate from the exterior building envelope are typically used
RH Controlled Below Critical Value	All	●	All	●	●	●	♦	Vapor control is a priority in moisture zones A and C, and thermal control is typically needed to maintain RH stability below critical values

Legend
Moisture and hygrothermal loads: ● Controlled, ◯ Moderated, ○ Optional   Hygrothermal analysis: ■ Necessary, ♦ Recommended, □ Optional

TABLE 11.2.

Examples of typical envelope assemblies or features (after ASHRAE 2019a, table 12).

Loads	Minimum Performance	Examples
Liquid Water Loads	●	**Source moisture control** is typically achieved by intercepting and diverting rain and surface and subgrade water away from above- and below-grade parts of the building envelope *Examples:* roof drainage systems; surface water drainage systems, including swales and piped systems; drainage planes in above-grade walls; subgrade drainage systems consisting of waterproofing, drainage planes on subgrade walls and under slabs, and subgrade piping
Thermal Flows	●	**Controlled thermal flows** are typically achieved by building envelopes that meet current ASHRAE Standard 90.1 requirements for building envelopes
	⭘	**Moderated thermal flows** are typically satisfied by: Climate Zones 4 and higher: Building envelopes with robust wall construction and thermal mass, retrofitted insulation, storm windows, or insulated glazing and insulated ceiling planes in the uppermost story attics *Climate Zones 3 and lower:* Radiant barriers in attics or a double roof with a ventilated cavity *Climate Zones 5 and lower:* Summer solar gain through glazing may be moderated by low window-to-wall ratios, or by fixed or operable features sich as brise soleil, roller shades, shutters, or blinds
	○	Controlled or moderated thermal flow measures provide benefits but may not be necessary
Air Leakage & Stack Effect	●	**Controlled air leakage** is typically achieved by building envelopes that meet current ASHRAE Standard 90.1 requirements for building envelopes **Controlled stack effect** is typically achieved by minimizing the number of open communicating stories or by mechanical destratification among floors **Moderated air leakage** is typically satisfied by limiting overall air intrusion. Examples include air barriers in walls and in the ceiling plane of uppermost stories, weather-stripping of door and window openings, vestibules or buffer spaces at heavily used entry points
	⭘	**Moderated stack effect** is typically limited by not more than two open communicating stories plus air leakage improvements If building pressurization is used, interior pressure should be slightly negative during heating and humidification and slightly positive during cooling and dehumidification
	○	Controlled or moderated measures provide benefits but may not be necessary
Moisture Vapor	●	**Controlled moisture vapor flows** are typically achieved by building envelopes that meet current ASHRAE Standard 90.1 requirements for building envelopes
	⭘	**Moderated moisture vapor flows** are typically satisfied by building envelopes with robust envelope construction and limited vapor permeability, such as thick masonry walls. For less robust envelope construction, such as stud-framed walls or wood-framed ceilings in the uppermost stories and wood-framed floors over crawlspaces and basements, a vapor retarder may be needed
	○	Any controlled or moderated measures provide benefits but may not be necessary

Legend

Moisture and hygrothermal loads: ● Controlled, ⭘ Moderated, ○ Optional

Strategies for Environmentally Managed Spaces Separated from Exterior Walls and Roofs

As the name suggests, environmentally managed spaces that are separated from exterior walls and roofs utilize buffer spaces to separate the conditioned rooms from the building envelope. This is accomplished by constructing interior wall, floor, and ceiling planes for the conditioned spaces that were not in contact with exterior envelope assemblies (fig. 11.7). Often this is done by constructing perimeter corridors around the collection space, nesting the conditioned space within the building. Typically, the conditioned space is enclosed by walls, ceiling, and floor that have been constructed for moderated thermal flows and moderated moisture vapor flows as identified in ASHRAE (2019a).

Separating environmentally managed spaces from exterior walls and roofs is a highly effective and energy-efficient method to reduce gradients in thermal energy and moisture across the building envelope. This strategy effectively places a buffer zone between the exterior envelope and the conditioned space, improving the stability of the conditioned space. This method is effective in climate zones 5A–C and lower, and where hygrothermal analysis is optional.

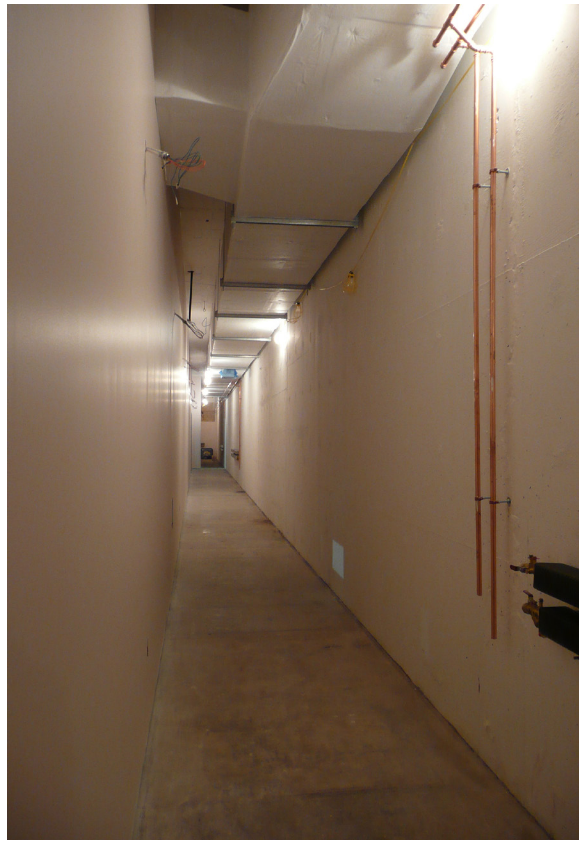


FIGURE 11.7. Typical buffer space between conditioned space and exterior wall (right of image).
Photo: Michael C. Henry

Strategies for Source Moisture Control

As shown in figure 11.4, there are more opportunities for liquid water and water vapor to enter a building envelope than there are opportunities to remove the same moisture. As a result, source moisture control is considered to be the first step in nonmechanical environmental management in all ASHRAE climate zones. As precipitation events increase in frequency and intensity as a result of climate change, source moisture control strategies will become even more important for interior environmental management.

Source moisture control is typically achieved by intercepting and diverting rain, surface water, and subgrade water away from the above- and below-grade portions of the building envelope. Source moisture control is necessary in all climate zones.

Examples of source moisture control measures include roof drainage systems, surface water drainage systems, drainage planes within above-grade walls, subgrade drainage systems incorporating foundation waterproofing and drainage planes, and venting/drainage systems under slabs to remove moisture vapor and liquid water.

Poorly drained surface water and groundwater can saturate the soils around and under a building and make the soils a potentially significant source of moisture in liquid and vapor phases. Voids in granular soils such as coarse sands and gravels hold liquid water against foundation walls, creating sufficient hydrostatic pressure that can force water past embrittled waterproofing membranes and into cracks or pores in foundation walls. Clay soils may not pass water quickly but have the capacity to retain water so that it is available for slow release by capillary flow or by vapor diffusion to more porous materials such as mortar and/or sedimentary foundation stones. The exterior surfaces of foundation walls, especially those in historic buildings, may offer little resistance to vapor migration or water seepage. Where it is practical, the foundation surfaces of a building should be investigated and examined to determine their effectiveness for source moisture control.

Figure 11.8a shows a test pit at the foundation of an early nineteenth-century house and figure 11.8b shows the interior of the same wall in the crawl space.

In figure 11.8a, the foundation stones are unusually small in size, resulting in a large ratio of joint volume to stone volume, and the joints were found to be filled with disaggregated mortar and soil particles. A modern waterproofing membrane extended only partway down the wall. Overtopping of roof gutters saturated the silty sand soil at the foundation. This soil moisture was drawn into the wall masonry, which then evaporated at the interior wall face into a dehumidified crawl space, disaggregating the interior wythe of brick in the drying zone, as shown in figure 11.8b.

(a) (b)

FIGURE 11.8.
Example of (a) exterior foundation condition likely to allow excessive water and vapor flow from exterior to the interior, and (b) the resulting interior moisture damage that can occur during drying of the wall. Photos: Michael C. Henry

Source moisture control measures should proceed from two distinct starting points based on the location of the moisture source. If the source of moisture is rain or surface water, the capacity and performance of the roof drainage system and surface drainage around the building should be evaluated and improved if needed. If the source of moisture is below grade, such as groundwater, capillary rise of groundwater, or the lateral movement of soil moisture, then subgrade drainage systems incorporating foundation waterproofing and drainage planes on subgrade walls should be considered. In some cases, soil moisture occurs under the building and venting/drainage systems under slabs to remove moisture vapor and liquid water are necessary.

Buildings constructed before the mid-twentieth century relied on thick walls of masonry or earth to handle absorbed water from rain. These walls, also known as mass walls, are sufficiently thick that penetrating rain can be absorbed and then subsequently dried to the exterior, and moisture does not pass to the interior surface of the wall. During the twentieth century building materials became lighter, thinner, and functionally specific, enabling much thinner wall systems to be developed. These modern wall systems manage rainwater penetration, wind pressure, and drying by placement of a vented drainage plane and water barrier within the wall assembly. These types of walls include cavity walls, rain-screen walls, or pressure-moderated walls (Straube 2010, 2011). The effectiveness of these walls depends on the quality of construction and materials; failures or performance problems are difficult to correct without removal of the exterior layer to access the water-barrier layer.

Interior moisture in a building may result from construction/restoration or from mechanical and plumbing systems. Construction/restoration moisture can be significant, especially with traditional building materials such as wood, masonry, plaster, concrete, and water based-coatings. As these materials dry and release their initial moisture, the moisture load on the interior environment decreases. The effects of construction moisture on the interior environment should be anticipated when planning for completion and occupancy of the building so that drying takes place before collections are installed.

Mechanical and plumbing systems may be a significant source of moisture, especially if not properly maintained. Examples of unintended sources of interior moisture from systems include open floor drains and sumps (drainage pits), plumbing and mechanical system leaks, clogged or undrained dehumidifier trays and cooling coil drains, and failed humidification systems.

Strategies for Moderated Thermal Flows

Strategies to moderate thermal flows reduce conduction, convection, and radiation heat transfer between the interior and exterior. These strategies are appropriate in climate zones 3C, 4C, and 5C in situations where the maintaining the interior relative humidity below 75% RH is acceptable for collections; this is equivalent to ASHRAE Type of Control D (ASHRAE 2019a).

Examples of moderated thermal flow measures vary by climate zones. In climate zone 3 and lower, moderated thermal flow strategies include small window-to-wall ratios, radiant barriers in attics, and, in some cases, a double roof with a ventilated cavity. In climate zone 4 and higher, moderated thermal flow strategies include building envelopes with robust wall construction and thermal mass, retrofitted insulation, storm windows or insulated glazing, and insulated ceiling planes in the uppermost story. Thermal flows from sunlight are important, especially in climate zone 5 and lower. Solar radiation can be moderated by fixed or operable features such as brise soleil, roller shades, shutters, or blinds.

Several of the above strategies require selection of appropriate insulating materials and determination of the appropriate location for the insulation within the wall or ceiling/roof assembly in order to avoid moisture problems. The advice of an architect or engineer is recommended.

Strategies for Moderated Air Leakage and Stack Effect

Strategies that moderate air leakage and stack effect will reduce air and moisture vapor infiltration/exfiltration in a building. These are appropriate in climate zones 3C, 4C, and 5C, with hygrothermal analysis being optional.

Examples of measures for moderated air leakage and stack effect include air barriers in walls and in the ceiling plane of uppermost stories, weather-stripping of door and window openings, and vestibules or buffer spaces at heavily used entry points. Stack effect may be moderated by limiting the height of open vertical spaces that connect two or more stories. These strategies are often straightforward to implement with respect to the necessary costs and skills.

Strategies for Moderated Moisture Vapor Flow

Moderated moisture vapor flow measures can be employed to reduce vapor flows through envelopes in climate zones 3C, 4C, and 5C, and hygrothermal analysis for most buildings in these zones is optional.

Moderated moisture flow improvements include installation of a vapor retarder in walls and uppermost story ceilings in wood-framed buildings combined with vapor retarders in floors above crawl spaces and basements. The vapor retarder must be correctly sequenced with the other materials in the envelope assembly. For building envelopes with robust envelope construction and limited vapor permeability, such as thick masonry walls, addition of a vapor retarder may not be necessary.

These strategies require selection of appropriate vapor control materials and determination of the appropriate location within the wall or ceiling/roof assembly so that moisture problems are avoided; therefore advice of an architect or engineer is recommended.

Implementing Nonmechanical Strategies for Environmental Management

"Buildings often do not perform as expected, in spite of the best efforts put forth by the parties involved in the process. In order for a building to meet its true performance potential, all facets of the planning, design, construction, maintenance and operation must work holistically focused on common goals for the building's performance" (ASHRAE 2019b).

Although the nonmechanical strategies for environmental management outlined in this technical note may seem to be simple to implement, these strategies are not exceptions to the above comment. For example, enlargement of gutters in a roof drainage system in order to increase capacity may fail to meet objectives because the gutters were not installed with adequate slope to the downspouts or drains. Similarly, waterproofing a foundation may not give good results if the waterproofing membrane was not properly sealed at the edges or seams, and once the error is discovered, the cost of excavation to find and remediate the problem area may be prohibitive.

The causes of building performance problems can be traced to a variety of factors. The fragmented allocation of responsibility among the many specialists involved in design and construction of a project is one example. The building design professions and construction contractors have responded to this problem by establishing a process known as "building commissioning," defined as "a quality-focused process for enhancing the delivery of a new and existing building project .... [for] verifying and documenting that all of the commissioned systems and assemblies are planned, designed, installed, tested, operated and maintained" to meet the owner's requirements as stated at the project inception (ASHRAE 2019b).

ASHRAE (2018) provides an overview and strategic guidance for the commissioning process as well as resources for deeper understanding of the procedural requirements and how they might be adapted for smaller projects. ANSI/ASHRAE/IES (2018) provides additional detail for new systems and buildings and ASHRAE (2015) addresses existing systems and assemblies.

Maintaining Performance of Nonmechanical Strategies

After initial implementation, the performance of nonmechanical environmental management strategies must be sustained through maintenance programs, feedback to stakeholders, and implementation of necessary adjustments and improvements. This is best accomplished via an environmental management team consisting of conservation, curatorial, registration, and facilities staff from the institution, as well as service contractors for the system and on occasion the design engineer and the institution's finance officer.

The environmental management team should periodically review environmental monitoring data to assess the effectiveness of nonmechanical strategies relative to the objectives and operational costs. These periodic reviews are also an opportunity to confirm that maintenance work is being undertaken and to follow through on resolving issues of poor performance.

The environmental management team should also plan the funding for major repairs and upgrades to, or replacement of, the nonmechanical elements and mechanical systems as these elements and systems approach the end of their functional service lives or become technologically obsolete.

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TECHNICAL NOTE 12: HVAC OPTIONS, NEW CONSTRUCTIONS, AND MICROCONTROL

Jeremy Linden

Introduction

Heating, ventilation, and air-conditioning (HVAC) technologies comprise a broad spectrum of equipment and design strategies focused on managing the interior environment of a structure to a desired temperature and/or moisture condition that is different from prevailing outdoor weather conditions. Implementing mechanical strategies for collections environments is a common practice in United States cultural heritage institutions, whether to provide for human thermal comfort in a local historical society or specially designed preservation environments in a purpose-built collection storage facility. Globally, the use of mechanical strategies in collections environments may be less common, and depends on the availability of utility infrastructure and contractors, the geographic or climatological region, and the age and nature of the building/structure, among other factors.

Mechanical strategies can provide a range of interior conditions within a particular structure, from a consistent target condition throughout the majority of a building to multiroom, room-sized, and smaller zones and microenvironments with environmental conditions for specific applications or material types. Careful consideration is required during planning and design phases to find the proper combination of necessity, practicality, and long-term sustainability and maintenance of mechanical control in buildings. "Commissioning" is the verification process meant to ensure that, once designed and installed, mechanical systems are capable of operating according to the original stated intent. Recently, the practice of recommissioning—going back to a system some time after its original installation and ensuring that it is still capable of providing the intended operation—has become popular as a component of long-term maintenance.

Mechanical strategies for environments require, by definition, an application of energy to perform the work in question. Recent research and practices have shown that it is possible to achieve appropriate and desired preservation environments in many buildings and locations with reduced energy consumption through optimized operation and control. Some interior environments may be maintained using non-mechanical strategies without energy-driven mechanical intervention, for part or the entirety of a year, depending on outdoor weather conditions, building construction, and desired interior environments. Collections staff should always consider whether mechanical intervention is necessary in a given situation, and should not simply presume that an appropriate preservation environment requires a significant input of energy.

When Are Mechanical Strategies Necessary and Appropriate?

Change in the psychrometric state of an interior environment through the use of mechanical systems powered by various sources of energy (fossil fuels, renewable, etc.) can be accomplished by five basic operations that directly impact preservation:

- Raising temperature (heating)
- Lowering temperature (cooling)
- Adding moisture (humidification)
- Removing moisture (dehumidification)
- Removing particulates or gaseous pollutants (filtration)

The temperature and relative humidity conditions of a particular environment, and thus its overall preservation quality, are primarily determined by the moisture content present. Although nonmechanical strategies and effective building envelopes can temper exterior thermal and moisture loads on a building, management of moisture content and temperature in many buildings will require mechanical intervention to offset the remaining interior and exterior thermal and moisture loads. In many cases, interior environments in nonmechanized structures will over time tend to reflect the behavior of the outdoor environment where they are situated. Due to air exchange and diffusion through the envelope, moisture content—represented most easily by dew point—will be similar in the interior and exterior (fig. 12.1). In some cases, localized sources of interior moisture may actually lead to higher dew point indoors than outdoors.

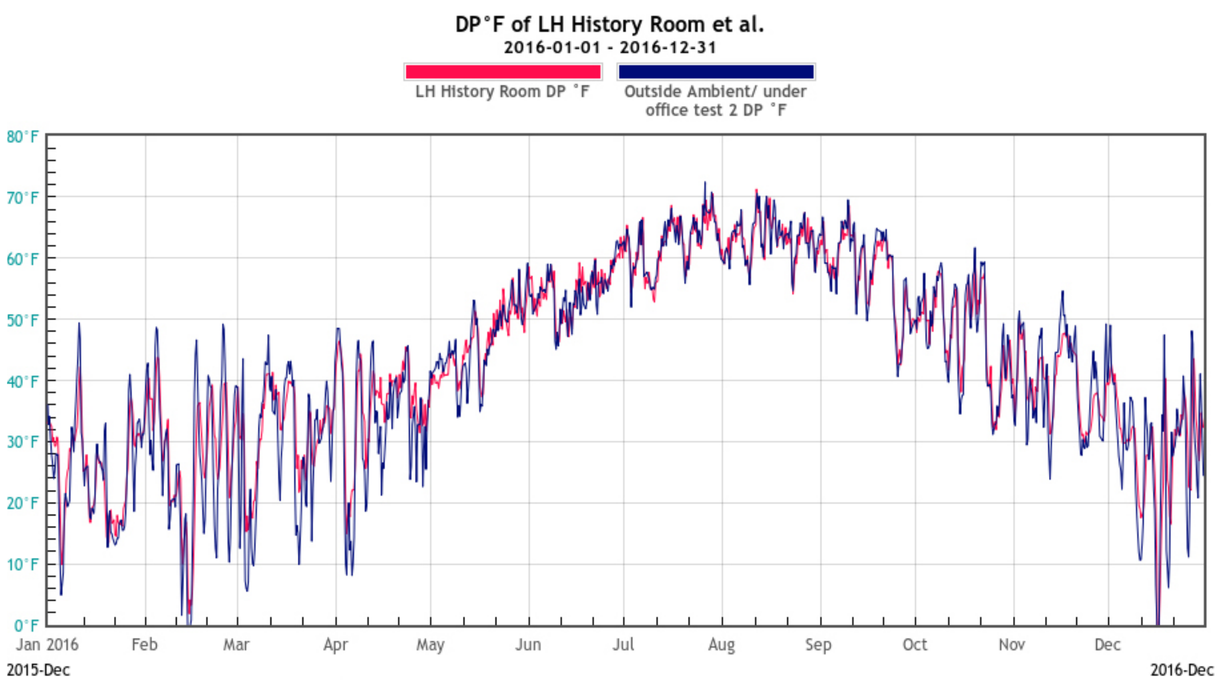


FIGURE 12.1. Interior dew point conditions reflect moisture patterns of the outdoor environment in a nonmechanized building. Dataset from coastal Maine, United States. Credit: Jeremy Linden

Temperatures, though affected by assorted factors ranging from insulation in the envelope to focused solar gain to interior stratification as heat rises through the building, will also tend to vary with outdoor conditions (fig. 12.2).

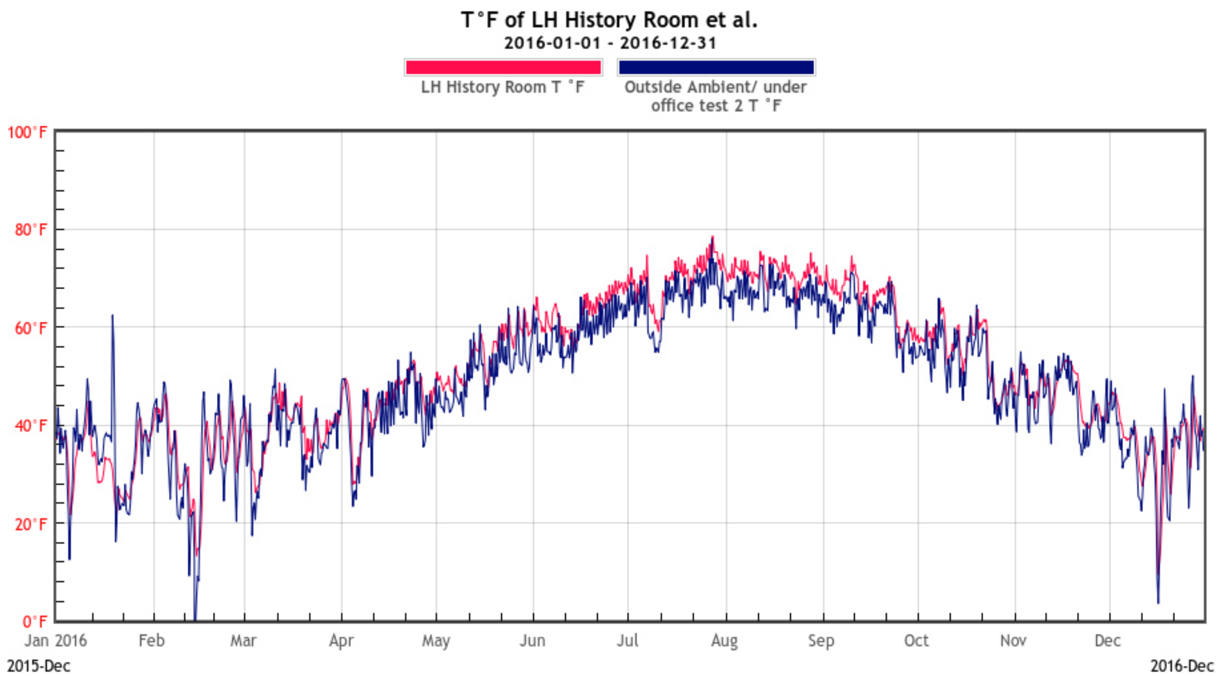


FIGURE 12.2. Temperatures in a nonmechanized building vary with outdoor conditions. Warmer interior summer temperatures are due to unblocked solar gain through windows. Dataset from coastal Maine, United States. Credit: Jeremy Linden

In cases wherein the outdoor climate is not conducive to long-term collections preservation, institutions must carefully consider whether mechanical intervention may be the solution and, if so, what the goal of the mechanical solution might be.

Factors to Consider Prior to Mechanical Strategies

As stated above, mechanical intervention should not always be assumed to be the best option. The following are among the factors that institutions should consider before choosing to include a mechanical solution for environmental control:

- *The defined goal for the preservation environment*: is it attainable without the application of systems? Is a nonmechanical, partial nonmechanical, or envelope solution a possibility?
- *The building in question*: do any factors make it an unsuitable candidate for mechanical systems? Historic integrity/aesthetics? Highly porous or leaky envelope? Poor electrical infrastructure? Potential for structural damage due to moisture movement/diffusion?
- *Energy considerations*: these may go hand in hand with envelope quality, but will the maintenance of the interior environment require an undue or unsustainable amount of energy?
- *Availability of maintenance and/or repair professionals*: this will vary among institutions and locations, but be wary of installing or selecting mechanical solutions that the institution does not have the staff expertise or local contractors to keep operational.

In cases wherein one or more of these issues exist, the application of mechanical systems may actually be detrimental to the overall health of the collection or organization.

Existing Systems

Many cultural institutions exploring the best use of mechanical strategies for a cultural heritage environment will already have some form of mechanical or HVAC system in place. These may vary from air handlers intended to control temperature for human comfort (such as a typical residential HVAC system) to historic hot water or steam systems to an older environmental system meant to create preservation conditions according to past standards and research. In some cases, an existing mechanical system may be wholly unsuited to the preservation or operational goals of the team or institution, thus requiring a significant equipment renovation or upgrade. In other cases, such as those in which a recently installed system is in place, but was designed for different environmental conditions, some environmental or energy improvements may be possible without major capital improvements. The capability of an existing mechanical system may be indicative of the capability of the building envelope, so envelope performance should always be considered before looking at significantly different operation of a mechanical system.

In addition to the primary HVAC or air-handling unit in question, numerous other aspects of the overall mechanical system—such as zoning, ductwork, air flow/distribution, and chillers and boilers—directly influence the system's ability to manage the environment in a particular space. Failure or improper operation in any of these can cause deviation from expected environmental conditions. It is common for mechanical systems to lose capacity or functionality as equipment ages, and systems may require additional maintenance or component replacements. Typical expected operational lifespans for HVAC equipment can vary from fifteen to twenty-five years; operating practices, the operating environment (for example, arid environments versus coastal salt air), appropriate preventive maintenance, and technological obsolescence can all impact this figure positively or negatively. Additionally, budgetary cycles and institutional prioritization for collections environments may cause equipment to remain in service long past its expected service life—it is not uncommon to find mechanical systems that have been in service for forty to fifty years or longer in various cultural heritage settings.

The first step in evaluating any mechanical system and its capability is to monitor current operation and preservation conditions with a basic documentation process. Environmental monitoring of the spaces in question, gathering data related to the design or installation of the unit, and tracing ductwork or piping runs will help determine three critical factors: the capability of the installed equipment, the spaces (zones) that the equipment serves, and the actual space conditions created by typical operation. Once these factors are determined, the team can weigh the current operation and capabilities of the system against the desired environmental conditions, and move forward with either an operational or capital solution as necessary.

Common HVAC Design Configurations

Mechanical systems and design vary greatly among two primary families: convection and radiant conditioning systems. Forced-air convection systems condition air at a central location (heating/cooling/

dehumidifying/humidifying) and use fans to circulate the air to and from the spaces to be conditioned. Forced-air convection systems have the benefit of not only conditioning the air, but being able to filter and introduce a supply of outside air if necessary. Other convection systems (e.g., radiators, baseboard, and chilled beam systems) and radiant systems (e.g., under- or in-floor or in-wall systems) use electricity, circulated hot or cold water, or steam to condition spaces by transferring heat energy to or from the surrounding air (convection) or transferring heat energy to or from surrounding objects, such as the floor or a wall (radiant). While common in comfort applications, in preservation applications non-forced-air systems have the disadvantage of being unable to control moisture content in an environment. Any moisture control, air circulation, filtration, and often cooling would typically have to be handled by an additional forced-air system. This section focuses on forced-air systems as the more common when looking to accomplish the five operations listed above.

Basic HVAC systems circulate air to and from the spaces to be conditioned in what is commonly referred to as “the loop” (fig. 12.3). Along the loop, various components can modify the air in different ways in order to achieve the necessary condition in the space. Air can be:

- heated or cooled;
- humidified or dehumidified;
- filtered for particulate or gaseous pollutants; or
- exhausted or supplemented with outside air.

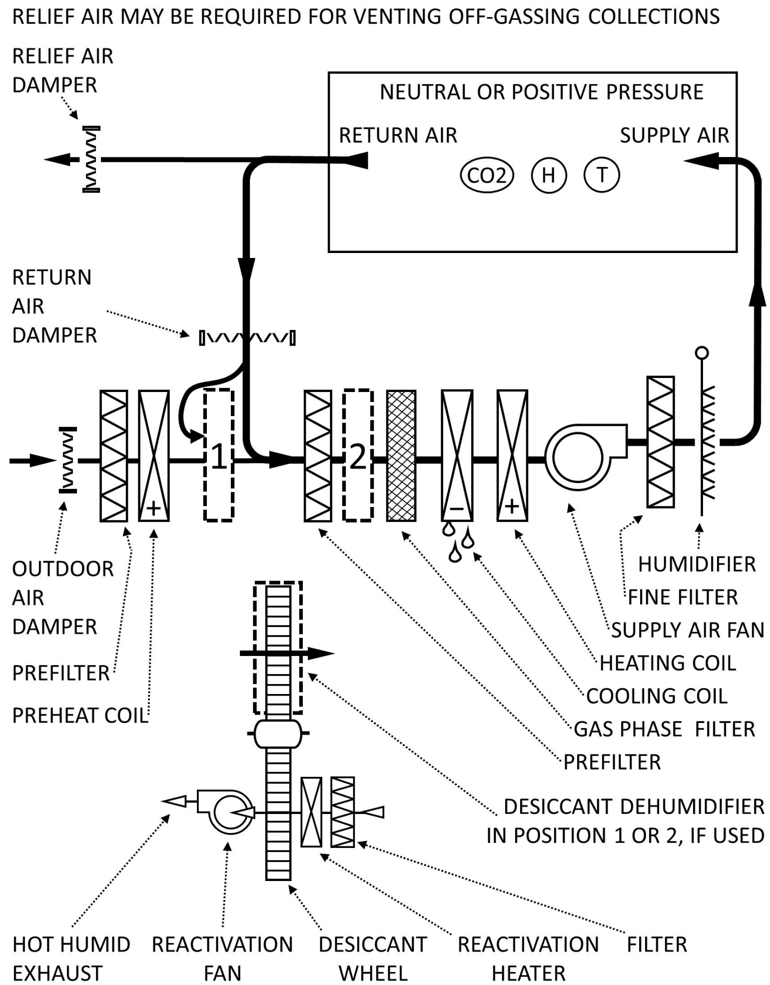
Heating, cooling, humidification, and dehumidification all focus on changing the amount of thermal energy present in the air. Sensible heat—measured by a thermometer and having no impact on volume or pressure in the system—can be increased or decreased via heating or cooling. Humidification and dehumidification, which change the moisture content of the air, impact the latent heat of the system; latent heat, or energy, is thermal energy that is released or absorbed when moisture undergoes a phase change, such as evaporation (in humidification) or condensation (in dehumidification via subcooling).

As shown at the top of figure 12.3, as return air comes back from the space, a portion may be exhausted via the relief air dampers. The remainder comes back to the air handling unit (AHU) where it may be mixed with a quantity of outside air in the mixed air chamber. This process allows fresh outside air to be brought into the building, most commonly for human health purposes, but also potentially as a way to purge and dilute off-gassed pollutants from some collections.

The mixed air is then typically passed over a series of filters. Common configurations include an initial “rough” particulate prefilter, followed by a fine particulate filter, which may be positioned immediately after the prefilter or further downstream. Gaseous filtration—typically activated carbon or treated sorbents—may be located after the pre- or fine filters, typically before the coils.

In systems designed to dehumidify via a subcool and reheat process, the cooling coil will be the next component in line. The coil, which contains circulating chilled water, glycol, or refrigerant, can serve two purposes. The first is to provide sensible cooling when all that is necessary in the space is a reduction in temperature. In this operation, the air temperature may be dropped only a few degrees before being sent downstream. The second is as the means of dehumidification, or latent cooling, in the system; in this operation, the coil will “subcool” the air temperature below its incoming dew point, condensing moisture out of the system and lowering the dew point of the air stream. The result will be cold air at near 100% relative humidity. Cooling coils typically receive chilled water from a chiller or central plant, or refrigerant from a nearby condensing unit.

FIGURE 12.3. A common mechanical configuration for forced-air systems (ASHRAE 2019, figure 16). © ASHRAE, www.ashrae.org



In a subcool-reheat design, the heating coil's purpose is to reheat the air to a suitable temperature and relative humidity to deliver to the space downstream. If air is delivered too cool, and the heat load in the space is not sufficient to bring the temperature up to the desired condition, the result may be a cool space temperature with high RH. In warm or seasonally hot climates where there is a significant heat load on the space, the delivered air may be significantly cooler in order to account for warming in the space. When sensible heating is required in cool climates or seasons, the heating coil can increase the supply air temperature to maintain appropriate conditions in the spaces. Heating coils are typically supplied with either hot water or steam from a boiler or central steam plant.

Humidification may occur at various locations in the AHU, but is commonly found downstream of the coils, either before or after the supply fan. The humidifier's role is to add moisture to the air in order to bring the conditioned spaces to the desired relative humidity level if the moisture content of the mixed air (return and outside air) is too low. Humidifiers come in a variety of designs and models, but broadly fall into two categories: adiabatic (evaporative humidification such as cool mist or ultrasonic systems) and isothermal (steam humidification from direct steam, a steam generator, or other sources). Proper placement of the humidifier and humidifier nozzles in the airstream is critical for absorption and mixing; moisture must be dispersed evenly throughout the airstream, with adequate open-duct length for full absorption/evaporation. While downstream humidifiers can be common in some applications, care should be taken that the equipment and the downstream absorption area are not located above collection spaces, in case of leaks from condensed water.

Air is circulated around the loop through the operation of fans, which push the air out to the space through supply duct work while simultaneously creating negative pressure that draws the air back to the unit through the return air path or ductwork. A supply air fan is typical, usually coming after the other components in the AHU. Return air fans may also be present, especially in large air volume systems and in scenarios where the system is programmed to economize, or use outside air to condition the interior of the building, regularly. Variable frequency drives (or, alternately, variable speed drives) are more commonly used to control the speed of fan motors, reducing energy consumption during periods when the maximum air flow is unnecessary. Fans are among the most critical components for total energy usage in any forced-air system. Not only do fan motors consume electrical energy, but, as the determining factor in the total volume of air being circulated, they also dictate how much air other components—such as the coils and humidifier—have to work on. Preventive maintenance factors, such as cleanliness of filters and coils, as well as proper duct design, can significantly influence energy consumption by increasing static pressure in the system, and potentially forcing a fan to work harder to deliver the appropriate volume of air.

Other equipment or components may be present depending on the outdoor climate or desired indoor climate. Desiccant dehumidification (also referred to as a desiccant or energy wheel) is common in cases where a cool/cold space temperature at moderate RHs is required because of the ability to dehumidify to dew points below water's freezing point. For dehumidification, a desiccant media (often silica gel) is embedded in a wheel, which spins slowly in the conditioned airstream, absorbing passing moisture and then, in a separate regeneration airstream, being heated to evaporate and exhaust the moisture out of the desiccant. Evaporative coolers, which pass hot, dry air over a water-saturated pad to cool the air through evaporation, are common in hot and arid climates and have the dual benefit of cooling as well as adding some humidity to the air.

Design Conditions and Capacity

A mechanical system is designed to do a certain amount of work: to be able to add or remove defined quantities of moisture, sensibly warm or cool the air temperature, and move a volume of air through the loop and various AHU components. This capacity is often represented in plain terms as the ability to meet certain design conditions.

Cities around the world have calculated "design day" conditions, based on historical outdoor conditions, which are used as the target against which an HVAC system may have to perform. If the HVAC system is designed to meet the 95% design-day condition, it has the capacity to meet its conditioning goals for 95% of the days in a given operating season (for example, heating or cooling). For the other 5%, say in a hot and humid summer condition, the unit may not have the capacity to cool enough to keep up with the heat and moisture loads. Latent cooling capacity is often the first operation to suffer—relative humidity in the HVAC zone would begin to rise, followed by temperatures.

Cultural heritage institutions have traditionally set design conditions as a certain temperature and RH, plus or minus a few degrees or percent RH—for example, 20°C ± 1° (68°F ± 2°) and 50% ± 5%. Engineers use several factors—including the outdoor climate design days, calculated heat and moisture loss and gain through the envelope, design outside air quantities, and internal loads from sources such as lights, equipment, and people—to estimate the load on the building, and design the system to circulate a particular volume of air (cubic feet per minute in the US, cubic meters per hour in Europe) at supply conditions that will achieve the desired space condition. The key point is that the design capacity creates limitations that will define what operational choices may be possible in the future. An institution with a preexisting system that was designed to provide a 20°C (68°F) and 50% RH environment in summer would not be capable of changing its set points to maintain a 10°C (50°F) and 30% RH summer condition for the purposes of preservation without significant capital changes to the equipment.

Generally, the limiting factor in cultural applications is the system's ability to control moisture, or dew point. If a storage environment is served by a system with a 20°C (68°F) and 50% RH design capacity, that system is likely capable of dehumidifying to a 10°C (50°F) dew point. If the new preservation goal was to achieve 10°C (50°F) and 30% RH in the same storage environment, the system would be unable to dehumidify to the required −7°C (19°F) dew point; it is missing the design capacity as well as the necessary equipment (for example, rather than chilled water, it would likely need to dehumidify with desiccant technology) to achieve the new condition. Similarly, an exhibition space whose HVAC system was primarily designed for sensible temperature control—rather than latent (moisture) control—may only be capable of dehumidifying to a 13°C (55°F) dew point, which would provide a 60% RH condition at a 21°C (70°F) room temperature; it would be incapable of dehumidifying sufficiently to maintain a 45% RH environment during peak hot and humid conditions.

New materials research and a better understanding of where risks occur for various materials are leading to alternative ways of defining design conditions—rather than using a year-round set point with a ± range, institutions are beginning to use seasonal limits that manage risk while also taking advantage of energy opportunities. In seasonal warm/cool climates, an example of a summer max condition for storage may be 18°C (64°F) and 55% RH (9°C or 48°F dew point), which avoids degradation risk for most collections while also reducing the energy requirements of a lower RH condition. As outdoor conditions cool during a winter season, the institution may strive for a passive temperature drop down to a low limit of 10°C (50°F) and 30-40% RH (−7°C or 19°F dew point) in order to improve preservation quality while reducing the energy spent on heating and humidification. While the appropriateness of this example is entirely dependent on the specific collection and the design and capabilities of the building and HVAC system in question, the underlying concept—maximizing preservation while optimizing energy usage—is increasingly common in environmental management for cultural institutions.

Zoning and Environmental Control

An air handling zone refers to the group of spaces that the AHU serves in the building. Zoning in buildings can be broken down into four simple groups:

- One AHU to one space
- One AHU to many spaces
- Many AHUs to one space
- Many AHUs to many spaces

One AHU to one space is a fairly simple proposition: the single air handler provides conditioned air to maintain the environment in one space. This space can be large or small, and may be physically adjacent to the mechanical room or halfway across the building.

Ideally, a single HVAC zone will serve several spaces that are used for the same purpose, have similar criteria for interior space conditions, and have similar interior and exterior thermal and moisture loads. For example, a single AHU could provide air to three separate exhibition areas that have the same environmental requirements, and will likely satisfy the needs of all three spaces. However, were a single AHU designed to provide air to a storage room in the basement, a research room, and the director's corner office with windows, the mixed uses, operational criteria, and loads would produce difficulties regarding the defined operation of the HVAC system. A key question would be which part of the zone takes precedence—the director's office or patron comfort may be viewed as a more critical customer than the needs of collection preservation—and would likely lead to suboptimal operation for both preservation and energy.

In the case of large spaces, such as high-density off-site storage facilities or large galleries and atria—multiple HVAC zones may serve a single large space with open air flow. In this case, the AHUs would ideally operate similarly, creating the same supply air condition that achieved the necessary environment throughout the large space. Unfortunately, it is common to find examples of "fighting"—where one AHU heats while the other cools, perhaps resulting in an acceptable space condition, but created through suboptimal operation on the part of both mechanical units.

Less common are cases of "many to many," where several AHUs each serve a portion of several spaces. One common example is large, multilevel facilities that do not share air between levels. External heat loads may be significantly different at various times of day and on various levels, and efficient airflow design may be better achieved by splitting a large physical space into smaller zones. As a result, one AHU may serve the west side on the A, B, and C floor, while another AHU serves the east side of the same three levels.

Zones can also be "subzoned" through the use of equipment such as variable air volume (VAV) boxes, downstream reheat coils, and downstream humidifiers that are placed in supply air ducts, often near the space served. These allow the AHU to provide one primary supply air condition, but the various parts of the zone downstream can maintain different set-point temperatures or RH conditions based on varying needs or heat load or loss. Note that in most cases dehumidification is performed by the primary unit, and all spaces downstream will receive the same dew point in that operation, regardless of their final temperatures. Among other configurations, VAVs are often present in large zones that serve a variety of purposes.

Most zoning problems occur when a building has "mixed-use" zones. In many cases, the need to satisfy the human thermal comfort criteria defines the HVAC system operation, and results in environmental conditions that are unsuitable for long-term preservation. An additional concern is the possibility of inefficient operation, where the system works hard at one stage to meet the needs of preservation and then sends the air to downstream reheats, which expend even more energy heating the cool temperature to a satisfactory condition for human comfort.

Generally, mechanical systems and buildings function best when AHUs and zones are logically divided according to purpose. One AHU may handle all cool storage environments with low dew point needs. Another may control labs or galleries—spaces that need human comfort temperatures—but lower dew points to manage RH levels. A third may control all spaces that are primarily human comfort: offices, classrooms, and similar areas.

In buildings with preexisting mechanical zones that are mixed use, keep in mind that, short of whole-building renovation, it is often quite difficult to rezone mechanical operation. If inappropriate zoning is an issue for the institution, programmatic changes—such as relocating an office out of a primarily collections storage zone—may be an option for correcting the issue, in addition to looking at building renovation or mechanical zone changes.

Microenvironments—Purposeful and Accidental

Microenvironments are any spaces where the prevailing environmental condition is different from the environmental condition of the larger space or zone surrounding them. These can be purposeful or accidental. Examples of purposeful microenvironments may include vitrines or cabinets treated with silica gel for RH buffering, or display cases that include a small unit for temperature and dew point control to create a distinctly different environmental condition. On a larger zone scale, purposeful subzones may be single rooms that have downstream equipment (such as a reheat coil or a booster humidifier) to maintain a condition separate from that of the majority of the air-handling zone.

Microenvironments have the distinct benefit of being able to create and maintain a specific environmental condition, either mechanically or nonmechanically, that is physically limited to the exact space or collection that requires it, allowing for more efficient control of collections environments. For example, if the majority of a collection is paper or organic media stored at a maximum 60% RH, an institution may decide to use a gasketed cabinet with silica gel to create a lower RH environment for storage of a small silver collection, which would be at risk of oxidation at RHs approaching 60%, without expending the energy necessary to reduce the entire zone's RH condition. While this nonmechanical solution would still require the periodic regeneration of the silica gel, the end result is the effective management of a separate environment within the larger HVAC zone.

In other cases, microenvironment design allows for the creation of specific environments in spaces where they might not otherwise be possible. This happens regularly in exhibit and loan situations—for instance, the host institution's gallery is maintained at 20°C (68°F) and 55% RH (11°C or 52°F dew point) in summer, but a lending institution requires no more than 45% RH (8°C or 56°F dew point at a 20°C or 68°F temperature) for its loaned object. The HVAC system that serves the zone was not designed for and does not have the capacity to meet the 8°C (56°F) dew point, so a vitrine with silica gel or small HVAC system is designed to reduce the RH inside the case for the object. If the object is too large for a vitrine, or if the entire room is used regularly for loaned materials, subzone control of the HVAC system, via downstream VAV boxes, heating coils, humidifiers, and even small in-duct dehumidifiers, may be an appropriate solution.

Accidental microenvironments—put simply, those that occur without the knowledge or measurement of the organizational staff—can be devastating to collections preservation. Examples can range from additional heat and light fading risk, introduced to an object through older gallery lighting or direct sunlight, to areas of poor air circulation that may result in locally cooler and damper conditions that allow for mold germination. Mold is a key issue: large-scale outbreaks caused by power outages, weather events, or improper AHU operation are commonly discussed, especially in terms of costs of remediation. However, most small outbreaks—those that may be commonly handled by institutional staff—are directly attributable to an accidental microenvironment. Water leaks, poor air circulation in a corner or between a range of books and a cold exterior wall, excessively cold supply air conditions, and other situations can lead to a mold outbreak in days or weeks. If the root cause is not discovered and mitigated, it may become chronic or seasonally repetitive.

Regular space walk-throughs are key opportunities to assess whether portions of the building may be susceptible to microenvironments. Corners that are far away from any supply or return air diffuser or intake, basements that may see water incursion, collections that are exposed to direct sunlight during certain parts of the day or seasons, shelving or cabinetry that block air circulation along an exterior wall—any place that might contain a physical cause for the air temperature or RH to be different from the rest of the space can be at risk. Whenever damage to an object is discovered—whether mold, corrosion, mechanical change, fading, or others—consider the local area where it has been displayed or stored, and inspect other items for similar issues. Use environmental monitoring data loggers to compare that location to a location where no damage was found and determine whether a temperature or RH microenvironment may be the cause.

Commissioning and Recommissioning

Commissioning is defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) as "a quality-focused process for enhancing the delivery of a project. The process focuses upon verifying and documenting that the facility and all of its systems and assemblies are planned, designed, installed, tested, operated, and maintained to meet the Owner's Project Requirements (ANSI/ASHRAE/IES 2018)." While the process is intended to (and ideally should) begin with the Owner's Project Requirements (OPR) and continue through the design, construction, and final verification phases, not all commissioning processes follow this workflow. Building staff, including facilities and collections staff, may only be exposed to a small subset or the final stages of the commissioning process, if any of it.

Broadly, commissioning is the general term used to describe a quality-control and verification process conducted during the design and after the installation of the new HVAC system, and is generally performed by a third-party commissioning agent who was not responsible for design or construction. This party's role is to test the operation of the system and confirm that it is capable of creating the conditions as defined in the design documentation: the proper volume of airflow, appropriate operation of components, and the desired environment in the spaces. Commissioning is often the final step in the design and construction process before the project is declared complete.

Recommissioning (commissioning a previously commissioned system) and retrocommissioning (commissioning a never-before-commissioned system) are practices that have gained popularity in the facilities maintenance field. Similar to the commissioning process, both occur after the system was originally installed, and have the goal of ensuring that the system is still capable of performing to its original design intent. If the AHU falls short in some aspect of the evaluation, the process typically results in a list of repairs or upgrades that are recommended to return the system to its design capability.

While commissioning, recommissioning, and retrocommissioning all have their uses, cultural professionals need to be aware of common misconceptions regarding the processes. Commissioning, while meant as quality control, may only test system performance at the moment that construction is complete—i.e., if construction is completed during a winter season, winter operation may be confirmed, but the commissioning is unlikely to adequately test and confirm summer operational capability. In addition, designs—and thus commissioning as quality control—are based on load and loss calculations and energy models that are best estimates, not actual operating characteristics of the new or existing building. Continued communication beyond commissioning is critical with any new building or renovation project in order to achieve the necessary environmental conditions in a sustainable manner.

Recommissioning or retrocommissioning are often touted as a solution to operational or control failures with older mechanical systems. However, if the operational limitation is that the twenty-year-old system cannot achieve new or adjusted set-point conditions for collections, the problem is more likely with the original design capacity, which recommissioning alone will not fix. As with the owner's project requirements in a new design or renovation, agreement on the goal of the process—whether the intent is to return the unit to its "day 1" operational capability or to define new operational goals—is the first stage in recommissioning or retrocommissioning.

Conclusions

HVAC and mechanical intervention can be equal parts opportunity and risk; appropriate and judicious application, with a clear understanding of the relationship between the collection needs, building needs and capability, and potential system design and operation, is necessary. An optimal preservation environment is one that achieves the best possible preservation and the least possible energy cost, and is sustainable over time. HVAC system and mechanical intervention can play a critical role in the creation of an optimal preservation environment, which provides the appropriate preservation conditions at the least possible energy cost. An understanding of typical HVAC design, operation, and limitations is critical in managing and sustaining the appropriate environment for collections.

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PART 4: BUILDING AND COMMUNICATING SUSTAINABLE CHANGE

Introduction

Up to this point, the readings have focused on the scientific and technical aspects of environmental management. However—as many readers may know from experience—the application of diagrams, execution of designed solutions, and implementation of strategies in the real world are less than straightforward tasks. Often, obstacles to change are due not to a lack of technical knowledge, but to the interpersonal challenges that are part of any project-based work, in terms of demonstrating long-term advantages of a project, communicating and negotiating effectively, and influencing decision makers. The technical notes in part 4 bring collection care professionals out of their comfort zone to expand and advance these necessary soft skills and support their ability to lead change.

While it is relatively common to see collection professionals actively involved in the selection of environmental management strategies, they are often less present during the implementation phase. In the technical note “Project Predesign and Stakeholder Analysis,” Walt Crimm describes how the collection care professional can satisfy preservation goals despite a diminished or absent decision-making role. The author emphasizes the importance of the predesign phase and the key decisions made during these early stages. The culmination of this initial phase is the Predesign Brief, which acts as an authoritative guide for the remainder of the process. The Predesign Brief should include both a work plan and a stakeholder analysis map; the latter allows for the identification of actors who have a direct and pervasive impact on the final outcome, and who the conservation professionals can act to influence.

Some preservation solutions for cultural heritage that only apply risk mitigation as a criterion often imply the use of high energy levels and materials that contribute to climate change. To develop truly sustainable solutions, the decision-making process should consider other factors, like environmental impact and financial cost. In the technical note “Long-Term Thinking for Sustainable Preservation Planning,” Sarah Nunberg and Matthew Eckelman present a practical overview of two quantitative tools that help to analyze, consider, and express the large-scale consequences of a given solution in concrete terms, leading to informed and thoughtful choices. Through a series of case studies, they demonstrate how life cycle analysis (LCA) can identify actions and materials that have environmental and human health impacts, and how life cycle costing (LCC) can be applied to compare short- and long-term costs and benefits. These techniques may also be useful in justifying necessary financial outlays to stakeholders, including directors, chief financial officers (CFO), and governance boards.

The final two technical notes explore the application of soft skills and leadership models to obtain a seat at the decision-making table and effectively negotiate and build consensus. In the technical note “Negotiation and Consensus Building,” Jane Henderson astutely recognizes that entrance into a negotiation means that parties have agreed to discuss, but it does not assume that each party has equal power. To overcome the challenges posed by this situation, the author presents the Harvard Law approach, which seeks a consensus decision by establishing a clear communication plan, sharing goals, doing prior research, being flexible, listening to others, demonstrating expertise and creative solutions, and building long-term relationships.

As well as the immediate concerns of interpersonal communication, collection preservation projects require long-term strategies to bring about sustainable change. Bob Norris similarly recognizes that collection care professionals often have to lead projects without the organizational power to make decisions. In the technical note "Leadership and Communication," the author demonstrates how to apply influencing skills, embrace leading communication practices and leadership techniques in everyday activity, and employ the "art of diplomacy" to lead when having limited authority. When not in a position of power, the collection care professional will need to reach out to other sources of power via relationships and a value-based personal approach. This allows people to "lead from the middle," to influence those not immediately engaged with sustainability and collection preservation, and to ensure that their point of view is fully understood and impacts the outcomes.

TECHNICAL NOTE 13: PROJECT PREDESIGN AND STAKEHOLDER ANALYSIS

Walt Crimm

Introduction

The preventive care of collections is an ongoing team effort, wherein all preservation team members contribute their specific skills focused on their shared goals of stewardship. Special projects, such as a major digitization effort or the development of new storage space, require the same teamwork, but a different process to create the most successful outcomes. "Special project" is used here to describe any work of any duration that is intended to improve collection care and is not part of the ongoing preservation activities. Special projects require additional resources (financial, staff, supplies, space, outside expertise) to implement. A special project may add new internal and external stakeholders into the process, whose interests and responsibilities may be related but quite different from those of the preservation team. These stakeholders will depend upon project type: rehousing, new database application, digitization, photography, or a major capital-building project. This note focuses on the stakeholder engagement process that occurs during the predesign phase, when 80% of the decisions are made that will determine the project outcome. Equally important, this note recommends when and how to engage the added stakeholders.

Regardless of project type or scope, the most successful outcomes occur by undertaking a process that spans four distinct phases with specific milestone results (work products) at the end of each phase:

- *Predesign Phase:* Detailed definition of the project requirements and scope, the required outcomes, and the resources needed for the project's implementation. Final work product of this phase is a report called a "predesign brief."
- *Design Phase:* The solution that best addresses the project requirements within the fiscal resources available. Final work product of this phase are the "design documents."
- *Implementation Phase:* Hiring the vendor or contractor to implement the design. Final work product of this phase are new preventive care tools or space.
- *Operations:* Move in and resuming preventive care of collections.

Certain project types are within the skill sets of collection professionals, but virtually all require added resources for the work effort that must be approved and budgeted. This brings in stakeholders such as the director, the chief financial officer, and potentially board members. Other project types, such as a once-in-a-generation upgrade of building systems, a renovation of collection storage space, or a major addition for collection care, might be outside of the collection professional's area of experience or comfort zone.

These projects generally involve many institutional staff, whose agendas might compete. The voice of the collection care team can be lost in the process of managing much larger budgets with many more stakeholders. For these types of capital projects, a frequent complaint by collection care professionals is the difficulty in obtaining a seat at the table where decisions are made. This challenge is widespread and suggests that long before any project is contemplated, the collection team must prepare by defining the project scope and each stakeholder's concerns and spheres of influence. This early preparation should take the form of a predesign brief that not only engages all stakeholders and acknowledges their concerns, but also proves to leadership that collection care professionals understand how to support a project process that is challenging to all involved as they develop project budgets and cultivate support on the board. The process of developing the predesign brief can prove the value of the collection team's participation and make a place for the team at the table.

Scope, Duration, and Work Products of Each Phase of a Project

In order to understand the creation of a predesign brief, it is important to recognize when it should be developed during a project's lifespan. Project-based work of any type or scope falls into four distinct phases, each with specific activities that require different levels of preparation and engagement.

To describe these phases, a project of selecting new collection management software is used as an example.

1. Predesign Phase—Defining the Problem to Be Solved
   - *Scope/Duration*: Like all project-based work, this begins with identifying the need for new software with specific capabilities. The team may start by communicating with peer institutions that have recently been through the process. The project team will need to define the data that will populate the new software, various interfaces required, and any customization that might be necessary to interface with the institution's website. The predesign brief should include time allowed for the work to take place and an order of magnitude budget for procuring the software as well as all internal costs (e.g., staff time for data migration and website interface) required to implement the work. At the end of the predesign phase, the problem and program requirements or criteria are clearly articulated and documented.
   - *Work Product*: Predesign brief, functional program or project brief, or feasibility study.
2. Design Phase—Documenting the Solution
   - *Scope/Duration*: Begins by working with the internal team or hiring a consultant (or, in a capital project, hiring a design team) who document all the features identified in the predesign brief, including how existing information will be migrated into the new system, the staff resources required to implement that work, and the space where the project work will take place.
   - *Work Product*: Procurement or design document that defines requirements, allowing multiple vendors or a select vendor to supply software that addresses all project requirements.
3. Implementation or Construction Phase
   - *Scope/Duration*: Begins with added staff or contractor preparing the product to the institutional criteria established in the design phase. For a new collection management database or software, this means customizing any modules to the museum's specific requirements and adding staff to migrate material from the old database to the new database.
   - *Work Product*: Complete and operation-ready project scope.
4. Move In or Operations
   - *Scope/Duration*: Training and operationalizing improvements. Troubleshooting any "bugs."
   - *Work Product*: Results of the meeting criteria established in predesign phase.

In the three subsequent phases after predesign, museum leadership will expect the project goals to be met within the resources allocated and timeframe identified. Project success will be defined by the clear metrics of the predesign brief.

Advantages of a Detailed Predesign Brief

To ensure that preservation goals are met, a detailed predesign brief will serve as the authoritative guide over the course of the next three phases. The predesign brief may be a few pages or hundreds, depending upon the project scope, but all have common elements that should be included to ensure that it accurately reflects the project requirements.

Some institutions skip the predesign phase and start with the design phase when a consultant team or vendor develops the solution. This jump ahead to finding a solution neglects that the problem to be solved is not fully understood, which may lead to compromises in preventive care later, when the project is fully operational. In the case of a building project, moving to a solution may lead to overly complicated solutions, for example an expensive hard to maintain mechanical system rather than creating microclimates or other buffering strategies that allow for a simpler mechanical system that may be more sustainable over the long term.

Some institutions have all the expertise needed for the predesign, design, and implementation phases. Any staff expertise that is missing should be supplemented by outside technical expertise from consultants (e.g., risk assessment, programmer/planner, move consultant) who share the preventive conservation approach. In the case of a capital project, the planning phase is the time to determine what solutions outside the scope of the design team (such as buffering collections in microclimates within cabinets or housings, or development of a new online catalog) will be included as part of the overall project effort and budget.

A good place to start is to benchmark peer institutions. Be mindful not to assume that the peer institution's baseline in starting the project (e.g., current state of collection housing) is the same as your institution's because relatively minor differences will impact the approach, stakeholders, and costs significantly. Understand the differences; ask what compromises were or were not made and which have proved consequential. If institutional leadership considers skipping the predesign brief, reinforce why this is not best practice and remind leadership of the distinct advantages to developing a very detailed predesign brief prior to hiring the design team, as it:

- provides a complete and compelling case statement for funders;
- provides more information that will build board and leadership confidence in collection team efforts;
- identifies and unites all stakeholders by presenting a clear vision and shared project definition, including any approvals or sign-offs required by staff or board;
- develops layered solutions in which cost-effective passive systems are used to meet as much of the preservation criteria as possible, with active systems addressing the balance;
- integrates institutional goals (e.g., sustainability) with collection preservation goals (e.g., buffering collections);
- allows for more accurate cost projections to be developed;
- reduces staff fatigue by identifying and documenting needs up front in a process likely to last years;
- clarifies the project schedule and staff utilization in project-related work for that time frame;

- aids in informing outside consultants on the scope of work and required expertise;
- potentially reduces cost-contingency budgets; and
- enables the design team to focus on a more comprehensive design solution by communicating all needs and project criteria up front.

Remember, by the design phase all stakeholders will need to agree upon and understand the information contained in the predesign brief. By waiting, changing expectations, timeframes, and budgets may put the project in jeopardy, as well as reduce the confidence of board members or donors supporting the project. A detailed predesign brief serves everyone's interests and results in a better design process and better preservation outcomes.

When the project moves from predesign into the design phase, the predesign brief serves two purposes:
- For the collection team, the predesign brief is the definitive guide during design and implementation phases. As the authoritative voice, it enables the collection team representative to hold the design phase team accountable to meet the criteria outlined.
- For the design team, the predesign brief provides clear guidance in their development of a solution and builds confidence in the collection team as a well-prepared client.

Some changes in criteria are inevitable in the design process. However, they should be accompanied by written documentation of the change, including any cost and schedule impact.

Leading the Effort—Collection Team Project Representative

The ability to manage project-based work through all four phases is critical for collection professionals, and requires time that is often in short supply. When a project is first identified, one collection professional should be tasked to "represent" the collections; that person should be relieved of some daily responsibilities in order to devote the time required as the collection representative.

For larger projects, the number of consultants and other engaged parties will increase, each playing a part as the project progresses. Depending upon project size, the project representative role may or may not grow into a full-time position. This person may or may not understand design and construction, but must understand collection preservation needs, must be very organized, and must be an excellent communicator and tireless advocate for the project.

Project representatives who are not conservators or collection managers should not be empowered to make decisions on behalf of the collection team where preservation goals are at stake. However, empowering your representative in all but the most critical decisions is more likely to increase the confidence of institutional leaders who see the effort as well organized and well prepared.

If the collection preservation areas are one part of a larger capital project, other departmental project representatives are likely to be at the table. Depending upon the project size or institutional governance (e.g., university or government agency), a project manager may be assigned as the representative to speak for the institution to the design and construction teams. This person might be a staff member at the institution or governing agency, or a consultant called an owner's representative. In any of these circumstances they should not be authorized to make changes or decisions impacting collection preservation goals.

Organizing the Work for the Predesign Phase

At the beginning of the predesign phase, two documents should be developed and integrated to guide the process.

Work Plan

A work plan is an organizational tool that should be tied to a schedule identifying every task and meeting, and the development of every work product so that the entire project scope is created and documented in an orderly manner to make the best use of everyone's time (fig. 13.1). The work plan often accords with the schedule of major board or collection committee meetings, allowing the board and leadership to be engaged and informed on progress. The plan should not be condensed to meet deadlines as inaccurate information or budgets are remembered and changes in budgets, schedules, and outcomes destroy board and funder confidence.

Workshop/Report	Activity	Duration
Workshop 1: Big Picture, Criteria, & Project Requirements	Project Familiarization & Preparation	2 Weeks
	Conduct Workshop	3 Days
Workshop 2: Review Analysis, Space Needs, & Space Adjacencies	Preparation	4 Weeks
	Conduct Workshop	2 Days
Workshop 3: Review Concepts & Sites as Identified	Preparation	4 Weeks
	Conduct Workshop	2 Days
Workshop 4: Review Concepts, Site Information, & Cost Estimates	Preparation	4 Weeks
	Conduct Workshop	1 Week
Final Report: Reconcile Needs, Concepts, & Budgets	Preparation & Delivery	6 Weeks
	Presentation	1 Day

FIGURE 13.1. Example of a shortened work-plan task list. Credit: Walt Crimm

The work plan should begin with a kickoff meeting; next, a series of meetings with various stakeholders should explicate all information that fully defines the project scope. The first tasks are goal setting, followed by studying the issues to establish project criteria that should be met. The final step is to identify resource requirements (e.g., money, staff, space, additional expertise) needed to achieve the criteria. Time should be allotted for discussion and documentation, which includes making time for scope revisions if the costs are too high. A work plan that anticipates how consensus will be built within an institution is most likely to be successful. A good way to understand what a work plan might include is to develop a table of contents (see example in "Predesign Brief Contents" section) for a final report and then draft the work plan by identifying how and when each section's criteria is populated. Talking with peers at other institutions, or putting the word out on listservs, are productive ways to obtain examples of work plans that may apply to the specific project type.

Stakeholder Map

While all stakeholders share institutional goals, their roles, responsibilities, internal reports, and the language they use to achieve those goals differ from those of collection professionals. A stakeholder map is a visualization that prompts consideration of the sphere of influences on the project. This will help determine the level of communication with stakeholders over the predesign phase. Some stakeholders will require frequent one-on-one meetings, whereas others need only be informed in briefings with other staff.

A conceptual framework for managing stakeholder roles prior to identifying whom to engage can help in developing a strategic overview. Mendelow's power/interest matrix is one such example (fig. 13.2, after Mendelow 1981). Presented in the form of a scatterplot with "level of interest" and "power to influence" on the x- and y-axes, respectively, this tool allows one to conceptualize the appropriate level of stakeholder engagement. High power/high influence stakeholders require close management, while those with low power/low influence can be monitored. Stakeholders with high interest/low power should remain informed, and those with high power/low interest need to be satisfied. The importance of various stakeholders' level of engagement may change during a phase or phase by phase. For instance, the chief financial officer's role during functional programming may be very prominent when the project's first budgets are developed. This role may change significantly during design phases, and even be delegated day to day to a comptroller or budget manager who tracks disbursements as funds are spent.

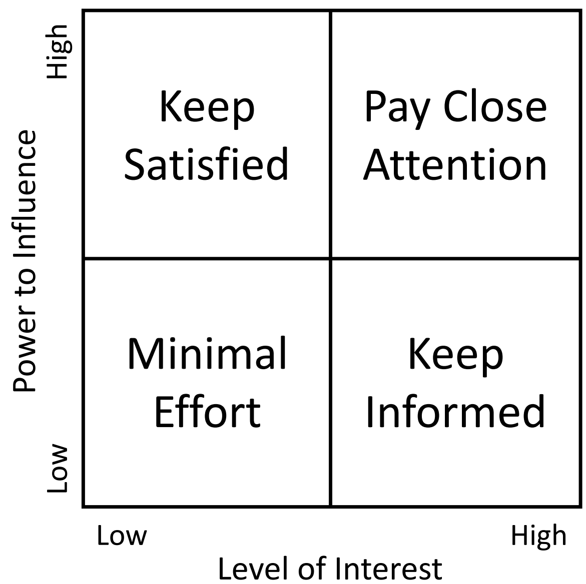


FIGURE 13.2. A power/influence matrix (after Mendelow 1981).

Identifying Internal Influencers and Stakeholders

Advocating for collection preservation and for the project's advancement are not necessarily the same, nor do they require the same skills. The skills of a project manager can be instrumental in responding to the project's influencers, the staff who are not directly responsible for the preservation outcomes.

For internal stakeholders, a good starting point is the organizational chart. Each department head is an influencer. While developing the work plan, meet with influencers to identify their concerns, what they need to know, and when they need to know it. This provides key insights into a project's delivery, which includes important details like understanding the format of the necessary information or if specific forms or formats are required (for instance, with the chief financial officer or CFO). Identify staff structure and who reports to whom; for instance, the budget manager indicates who needs to be involved, and whether they will speak for departmental interests at certain time frames during the project. Key stakeholders/influencers may include any of the parties below and their concerns are likely to include the following:

- *Governing Board*: How does this project fit within the strategic plan and align with preservation practice at peer institutions? Are the collections, facilities, and development chairs on the board?

- *Director*: Is this an institutional priority and what is the case statement? What does the board expect from this project? Can we deliver the project within the budget and timeframe promised? Does this help draw in donors and their collections?
- *Development*: How can this effort be positioned to make it attractive to donors? Can we improve access or position this as an engaging project while meeting preservation goals?
- *Curator*: How will this attract new collections? Will it allow sufficient space for new collections, including the major acquisitions expected over the next few decades? Will it provide better access and research space?
- *Collection manager*: Will it provide proper working spaces and safe access to collections? Will I have additional staff that can rehouse existing collections prior to the move? Can the budget support new imaging for an online catalog?
- *Registrar*: Will we have bar coding to allow better tracking during temporary relocations or the move? Will the database software be upgraded?
- *Conservator*: What are the risks to the collections from an environmental, light management, pest management, and security perspective? As these risks are significantly higher during a building project, particularly from a security and fire-protection risk perspective, what are the best approaches to mitigating those risks, and what building systems will provide optimal performance?
- *CFO*: What will this project cost to design, build, and operate? Are the budgets accurate? What cash flow will be required to pay for design fees and construction costs? Will construction impact earned revenue projections and visitor attendance?
- *Facilities*: Will added staff and annual budget to take care of this building be included? Will the building systems require staff training? Will parts be difficult to procure? How will construction impact our operations? What will this do to the energy budget?
- *Security*: How does this facility provide better safeguards and levels of security than the older facility?
- *Housekeeping*: What cleaning materials and equipment are required that meet preservation concerns yet do the job well? Will cleaning staff even be allowed into the space?
- *Institutional Colleagues*: How will the resources allocated for this project impact my upcoming project?
- *Education and Public Programs*: How can we generate excitement and expand the visitor experience in this new facility? Will collection staff allow tours or windows for visitors to see them work?

Document their input and use that document to ask them to reconfirm a mutually agreed upon approach. For those influencers within the institution who manage external stakeholder relationships, such as a government funding agency, reach out and understand their concerns and how to help them as they support the project.

Predesign Brief

With the project-organizing tools (work plan and stakeholder map) complete, it's time to define the project scope. At its core, a predesign brief is a statement of requirements that defines what must be accomplished, with guidelines setting those standards. Its function is to describe the qualitative and quantitative requirements of staff-led solutions (e.g., a rehousing project) or built solutions (e.g., new building systems) to achieve a specific outcome. If project planning is defined too subjectively, what constitutes a completed plan is often determined more by skillsets of staff (or consultants), internal politics, available time, or budget than by fact-driven planning.

Whether planning new cabinets or a new space, complete predesign planning defines the project scope and resources that must be allocated prior to starting the design process. A successful predesign brief fully defines the following:

- *The Problem*: Mission alignment, collection risks, working conditions, volume of storage space, etc.
- *The Approach*: A preventive preservation solution with an emphasis on simpler solutions (e.g., buffering) with proven outcomes.
- *Collection Professional Scope*: Rehousing the collection or bar coding to better use the space, for example.
- *Criteria*: Quality, quantity, and performance with clear metrics and references.
- *Prototype Development*: Where appropriate, what are the models and/or solutions that other institutions have employed that will be explored during design and implementation? Can any mockups be prepared to test potential solutions for their quality, efficacy, cost, and time impact?
- *Design Scope*: Design tasks required to solve the problem as defined (both in-house work and work that is outsourced to consultants or contractors).
- *Outcomes*: Improvements achieved.
- *Schedule*: Timeline through design and implementation, including phasing and move in.
- *Stakeholder map*: An update of what every stakeholder needs to know.
- *Resources*: Budgets for all project-related costs escalated to reflect the year in which the work will occur. Make sure to add a contingency for the entire escalated cost, which may range between 10% and 25% depending upon the complexity and project unknowns.
- *Risks and Unknowns*: Feedback and think through what unknowns still need to be addressed in design (e.g., phasing of work to minimize risk to collection during construction). This is often overlooked.

While making these decisions seems linear, significant and critical influencers determine the final program document. Every institution will do things slightly differently, and those differences are critical to achieving the best outcome for collection preservation.

Predesign Brief Contents

This section uses a potential predesign brief table of contents based on a hypothetical project scope to explain what should be included. A new building may require all of this information, while a rehousing project may require significantly less. The type of institution, including funders and governance, will also impact the format and content significantly.

Executive Summary

This is primarily for the board, donors, and outside stakeholders, who will rely on museum leadership to review and endorse the detail. Include compelling and well-designed graphic information to engage those who will scan the document.

Project Case Statement of Need

Develop a statement of need following a simple list, incorporating minimal superfluous narrative. Include:

- Statement about collection and collection preservation strategy in the institution's mission and vision statements
- Project alignment with the current strategic plan
- Alignment challenges: collection preservation risks

- Identification of any precipitating event, accrediting agency assessment, accident, climate change impact (e.g., storm severity or change in definition of 100-year floodplain)
- Identification of current conditions and collection risks (summarizing risk assessment)—refer to technical note 9, “Risk Assessment and Risk Management”
- Outcomes expected
- Project time horizon: e.g., how many years the space will accommodate collection growth, or how long the new systems will perform reliably

Process and Participants to Date

This should include:

- An outline of the steps taken and how they informed the predesign brief
- Identification of key gaps in knowledge and unknowns, including how and when these will be addressed
- Identification of expertise of those participants working on the predesign brief

Best Practices and Standards

These include:

- References to best preservation practices, including any benchmarks or standards applied
- An approach to risk mitigation based on a prior risk assessment that achieves the performance criteria established for the project
    - Initial identification of passive means of mitigating risk (methods that do not require ongoing maintenance are largely failure proof, such as environmental buffering using new housing)
    - Subsequent use of active means to mitigate the remaining risk (methods requiring maintenance can fail, such as mechanical heating and cooling systems) that achieve the established criteria for environmental conditions over a given time duration (e.g., 24-hour, seasonal)
- Identification of knowns and unknowns of an existing building that will impact the project (e.g., historic preservation, envelope, or structural loading analysis)
- Institutional sustainability goals and alignment with preservation goals

Collection Plan Overview

- Growth anticipated for each collection and object type
- Collection care work to be performed by staff that requires staff time or resources, including new databases, digitization, photography, rehousing, and rights for online catalog
- Identification of hazardous materials and remediation plan, if any

Project Requirements

- Spaces Impacted or Required
    - Narrative of spaces.
    - Workflow diagram showing the activities of all collection care staff from loading dock to storage shelf (if scope appropriate). As shown in figure 13.3, this very detailed diagram shows major processes and equipment.
    - Blocking diagram depicting the relative size of all spaces where collections are present, their adjacencies, and pathways between these spaces to track collection movement from receiving area to storage area. This makes the case for best practices, preservation, and safety for collections. As shown in figure 13.4, the plan indicates the preferred relationships, but it is not a building design solution.

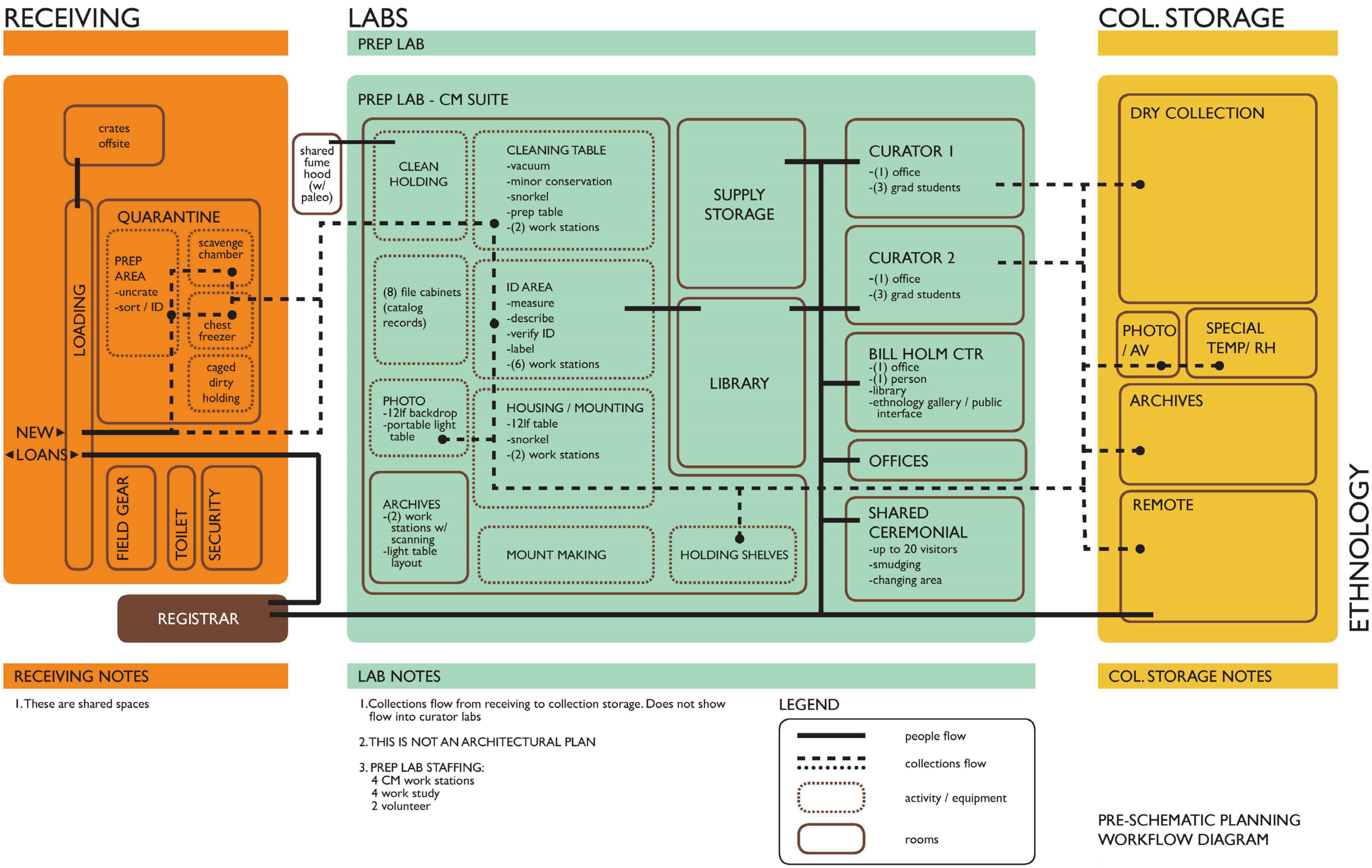
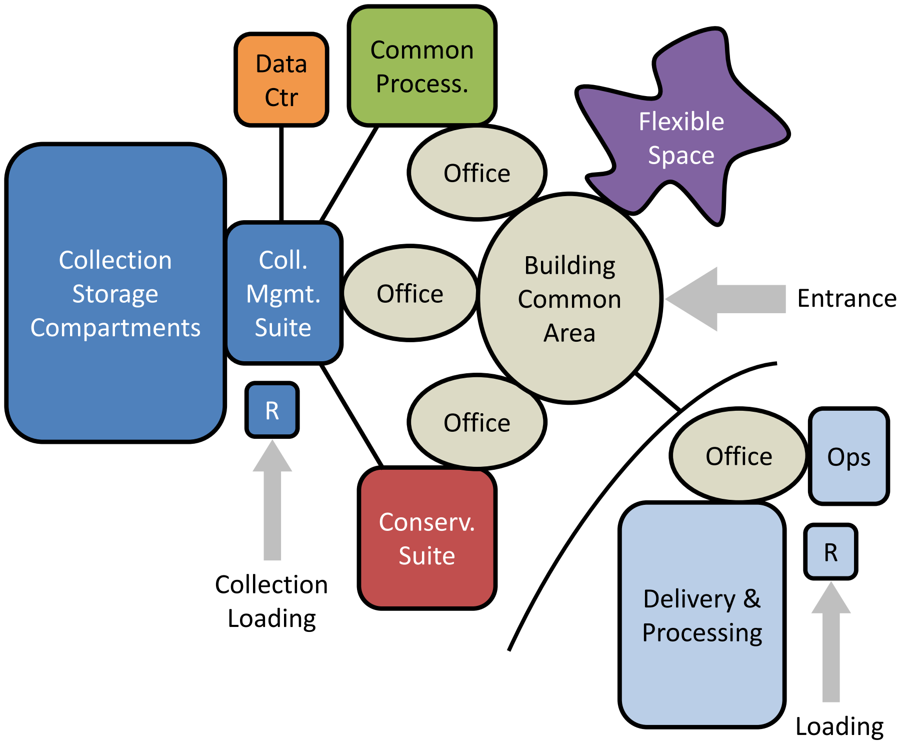


FIGURE 13.3. Predesign workflow diagram from a predesign brief. Credit: Walt Crimm

FIGURE 13.4. Adjacency diagram indicating preferred relationships between spaces. Credit: Walt Crimm



  - Building space program of all spaces identifying the net area required for collection care activities. Net area is the area within each space. Gross area (determined by the design team) is the area of the entire building, which includes hallways, stairs, and space for building systems.
- Space by Space Information
  - Narrative description of space use by collection team.
  - Collection team criteria:
    - Staffing changes over the project time horizon.
    - Anticipated projects to improve preventive conservation outcomes (e.g., new mounts or housings).
  - Criteria for design team:
    - Volume of collection to be accommodated with an acceptable height above the floor to allow safe collection access.
    - When known, weight of collection per cubic volume (foot or meter) to define weight to be accommodated.
    - Environmental conditions, lighting, fire protection, IT, security.
    - Major collection care equipment (e.g., conservation equipment).
    - Collection storage furniture standard by collection type (e.g., cabinet or shelving).
    - Finishes for cleanliness and pest management.
    - Staff responsible for oversight.

- Graphic diagrams:
  - Too often formulas are applied on a per-square-foot/meter basis that may not be applicable to an institution's staffing and volunteer levels, equipment needs, and work protocols. Test fit diagrams provide clarity that staff has adequate working space and that collections can be safely processed, housed, and stored. Per figure 13.5, a hypothetical space for a collection care area shows the linear footage of work surfaces, numbers of seats for staff/volunteers, major equipment locations, and the separation of functions based on a preventive conservation approach.

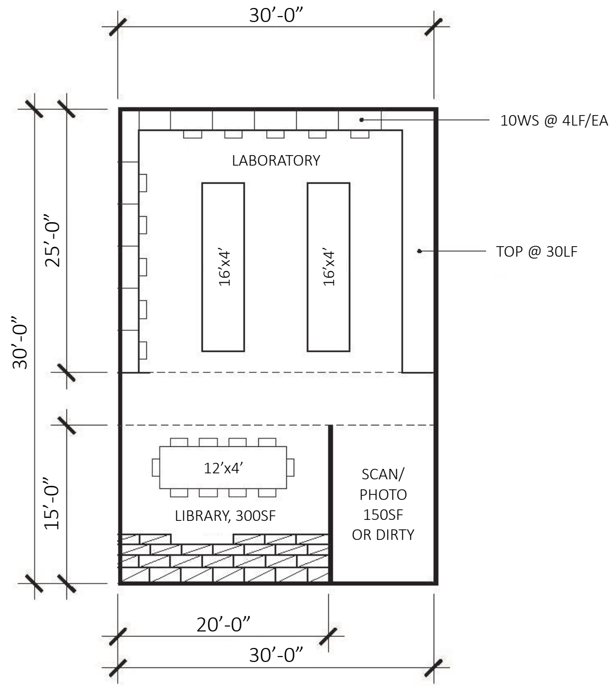


FIGURE 13.5. Predesign non-architectural layout of space testing areas relative to equipment. Credit: Walt Crimm

Collection Storage Spaces

- Spreadsheet identifying:
  - Net existing volume of collection and expected volume per square foot/meter)
  - Housing/rehousing impact on volume
  - Growth over time horizon
  - Preferred storage furniture by collection type (e.g., circulating books versus rare books)
  - Total volume of collection over project time horizon to be accommodated
  - Calculation of net area based on acceptable height of collection above floor

Project Schedule

- One schedule to identify each influencer and stakeholder's tasks, from completion of predesign to collection move in, with an emphasis on how the requirements of each task inform the work of the other stakeholders. Include:
  - Institutional leadership tasks: board approval durations, community relationship management, budget approval and fundraising.
  - Collection professional staff tasks: In the case of a database project, this may include evaluation of vendor options, adding short term staff to support information migration, online interface, imaging or scanning. In the case of a building project, working with a design team, move planning, packing, move tracking software, rehousing photography, and move-in.
  - Finding and hiring consultants.
  - Vendor implementation, whether preparation of software and onsite services for implementation or, in the case of a building, for design and construction.

Resources Required

- Estimates of probable cost.
- Cost for additional staffing and supplies to complete internal projects.

Known Risks to the Predesign Study

- Identify key unknowns in the document to recognize potential scope issues that still need to be addressed, which may impact project budget or schedule (e.g., structural loading capacity within a historic building or swing space for temporary relocation of collections displaced by the renovation of an existing space).

Conduct the final review of the predesign brief in the context of the three subsequent phases: design, implementation/construction, and move in or operations. Examine whether the project scope and resources are thoroughly defined and will provide leadership, the board, and the design team with all the information needed. Identify what is undefined or unknown. Ask facilities staff or peers who have been through similar projects to review and discuss the brief to ensure all gaps are addressed. Small gaps in the predesign brief, such as failure to identify phased implementation, can increase costs substantially and, after approval by the board, lead to cuts in scope to pay for the phasing costs.

After the Predesign Phase

As you begin the design phase, use the predesign brief when hiring the vendor or design team to allow them to grasp the project scope and the collection team's level of preparation. The brief should enable them to provide a more detailed proposal with a lower fee because the project scope is well defined. To better understand the skills of the vendor or design team in preventive conservation approaches, ask them to comment on the predesign brief in their proposal and interview.

Once in design phase, the predesign brief is the authoritative guide. Where predesign identifies the problem to be solved, the design phase is where the solution is developed. It is inevitable that the design phase process will identify new issues – some changes are inevitable. All changes, no matter how minor (e.g., changed phasing), should be made in consultation with the stakeholders and influencers consulted in the predesign phase and should be documented as appendices that include:

- Scope change
- Cost impact
- Schedule impact
- Stakeholder sign-off

This process focuses all stakeholders, including the design team, on the requirements of the predesign brief and ensures that the impacts of all changes are mutually understood and agreed upon. This is especially important if the collection team is not represented at every meeting during this phase of work. At the completion of the design phase, measure all design documentation against the brief to ensure compliance. Ask the vendor or design team to identify any areas of noncompliance and inform the collection team of how the issue was resolved.

When the implementation or construction phase begins, maintain the same process. Whether vendor staff are writing code or construction staff are ordering materials, these new stakeholders are removed from the intent of the predesign brief and may not understand the impact of even minor changes. All changes should be documented as requests for information that allow collection staff to remain involved. "Minor changes" may be an extra step in software migration or re-routing piping overhead—changes minor to a vendor or contractor may impact preservation goals.

The move in or operations phase will include a warranty period and is the time for the collection team to test and ensure that the design is performing according to the criteria set in the brief. Test the performance of more complex database interfaces with legacy software that may take years to retire or building system performance during extreme weather events. Immediately document and reach out to the appropriate person to address the problem. After the warranty period is over, any deficiencies will more than likely come at a cost to the institution rather than the vendor or contractor.

Conclusion

Regardless of the size or scope of the project, the best way to ensure that preservation goals are met is by creating a thorough predesign brief with engaged collection professionals and key institutional stakeholders and influencers. Skipping the predesign brief sets the stage for scope, schedule, and budget changes and increases the risk that outcomes of the preservation project will be compromised.

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TECHNICAL NOTE 14: LIFE CYCLE THINKING FOR SUSTAINABLE PRESERVATION PLANNING

Sarah Nunberg and Matthew Eckelman

Introduction

This technical note aims to familiarize cultural heritage custodians with life cycle assessment (LCA) and life cycle costing (LCC) so they can adapt practices after exploring sustainability goals. It provides a general introduction to LCA and LCC, defines each, identifies the issues that they cover, and illustrates how both are used through case studies.

Environmental and cultural heritage conservation are closely aligned: both strive to preserve our wealth, either natural or cultural, for future generations. Humans have clearly altered much of the earth's surface through agriculture, urbanization, and extraction of natural resources. Our activities have led to climate change, widespread pollution, global dispersion of persistent synthetic chemicals, species extinction, and resource depletion, in many cases pushing natural systems beyond their capacity to adapt and inducing long-term planetary changes (Rockström et al. 2009). Our cultural heritage sites and artifacts risk damage alongside natural disasters and potential destruction of the earth's sensitive ecosystems (UNEP 2004).

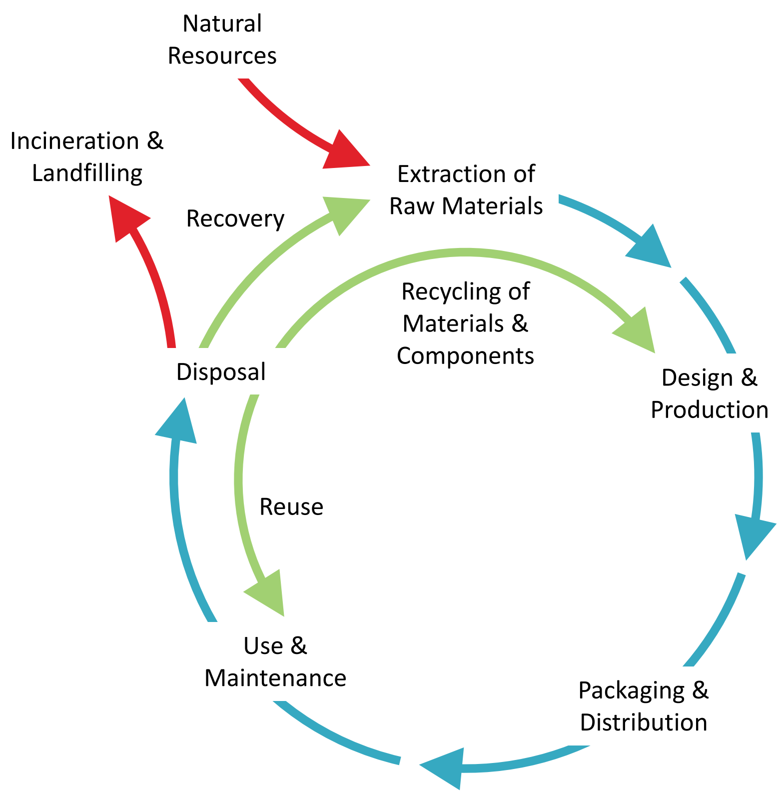
Preservation of cultural heritage is an exemplary act of sustainability. Through carefully and systematically preserving the past, conservators defy the disposable culture that drives climate change. They follow set methods of documentation, long-term planning, and in-depth research, all compatible with sustainable practices and thinking. However, they specify energy-intense storage and exhibition facilities, and in treatments primarily use materials made from virgin petroleum products. In recognizing this conflict in goals, the cultural heritage field has begun to collaborate with environmental engineers to identify sustainable practices through systematically comparing products, methods, and actions from cradle to grave, or production to disposal. These analyses aim to identify areas of greatest impact, referred to as "hotspots," and empower the professional to make informed choices. Industries often carry out such analysis using the method of environmental life cycle assessment (LCA) and life cycle costing (LCC) to create or choose "greener" and more cost-effective products and actions.

In 2012 the American Institute for Conservation of Historic and Artistic Works (AIC) supported a study of three LCAs that examined lighting, environmental management, and exhibition loans (Nunberg, Eckelman, and Hatchfield 2016). This project began as a collaboration between engineers and conservators that led to a 2017–22 National Endowment for the Humanities project, Sustainability Tools in Cultural Heritage (STiCH), which houses a carbon calculator related to preserving, exhibiting, and creating cultural heritage, a library of relevant LCA case studies, information sheets, and relevant educational materials.[1]

1 "Home Page," Sustainability Tools in Cultural Heritage, stich.culturalheritage.org.

LCA is effective in examining the life cycle of a product or comparing one product or action to another. For example, preservationists can use LCA to devise sustainable but effective treatment methods, design sustainable object storage using renewable resources and efficient environmental management systems, and opt for loan management with reduced greenhouse gas emissions. Considering that more than a billion objects are housed in cultural heritage collections, 17 million objects are housed in art museums, and 726,000 museum sector jobs exist in the United States, the resulting impact from cultural heritage preservation has the potential for significant environmental costs.

FIGURE 14.1. System boundaries of life cycle analysis (LCA). Credit: Life Cycle Initiative



Environmental LCA and LCC are decision-support tools used widely to inform design and process choices. They are often used separately, but can be applied in combination. Both tools provide planning approaches that look beyond the immediate term or a five-year budget cycle in a way that aligns with the aims of many cultural institutions and preservation agendas. Both tools are quantitative and employ a "life cycle perspective," meaning that they consider the large-scale and long-term consequences of a decision, and not just the immediate consequences. Figure 14.1 shows the scope of a generic LCA or LCC study, covering the life cycle of a product from raw material extraction and manufacturing to the finished product, its use and maintenance, and finally its treatment and disposal, including possible reuse or recycling.

LCA links product and process decisions with consequences for the environment and human health. Many categories of environmental and health impacts influence sustainability goals, such as energy use, greenhouse gas emissions, toxicity, and so on. LCA enables users to quantify multiple categories of impact simultaneously. In this way, LCA leads to a multi-criteria decision that can help professionals evaluate their actions and the materials they use, identify the least sustainable aspects of each option, and explore alternatives. LCC, on the other hand, only considers one metric, economic costs, but it also takes a holistic perspective to the costs and benefits of a decision. Specifically, LCC includes both costs and benefits that occur in the present as well as those that will (or are likely to) occur in the future. LCC thus provides a way to balance economic trade-offs over time, which can facilitate the consideration of options that are initially expensive. LCA and LCC are frequently used together to include both environmental and economic information in decision-making.

Life Cycle Assessment

The development of life cycle assessment began in the 1960s and 1970s and initially focused on quantifying energy use and efficiency savings (for a history of LCA, see Curran 1996). LCA methods have since undergone several waves of development and formalization, and new data and scientific models are continually being incorporated to improve the accuracy and representativeness of LCA results. LCA tools are used around the world by companies, governmental agencies, NGOs, and scientific researchers, and have been applied to thousands of products and processes across a wide range of sectors. For example, the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) launched an international program in 2002 to encourage further understanding and knowledge of LCA. They provide a comprehensive and easy-to-use range of presentations and publications to educate the layperson in the use and value of LCA.[2] Other open-access efforts include the International Life Cycle Database system (ILCD) handbook and USEPA resources.

While the goals and context of each LCA study may differ, many common protocols and standards have been codified to provide a common methodological platform for all LCA research. The most important of these consensus standards is the series promulgated by the International Organization for Standardization (ISO).

LCA Standards and System Boundary

The LCA standard ISO 14040 describes the principles and framework for LCA including: (1) definition of the goal and scope of the LCA, (2) the life cycle inventory analysis phase, (3) the life cycle impact assessment phase, and (4) the life cycle interpretation phase.

The scope of an LCA depends on the goals of the study and the product options in question. A *cradle-to-grave* analysis encompasses the life span of an object or action from first manufacture to use and final disposal (see figure 14.1). A *cradle-to-gate* analysis examines materials or actions only up to the point of final manufacturing, and does not include the product's use or end of life. For example, examining coffee beans from cradle to gate considers growing the coffee bean, including fertilizers and other agricultural inputs, harvesting, transporting, and roasting the coffee bean, while cradle to grave would examine everything in the cradle-to-gate study along with sale, making the coffee, cleaning the cup, and disposal of the coffee grinds. Whether a study is a cradle-to-gate or cradle-to-grave analysis of an object or action depends on the extent of the *system boundary* defined for the study.

When analyzing the act of exhibiting an object of art, the system boundary may include conservation; manufacture of exhibit furniture, condition reporting, art transport and the courier; crate construction and packing materials; art storage and the associated energy for environmental management (HVAC system);

2 "Home Page," Life Cycle Initiative, http://www.lifecycleinitiative.org.

gallery preparation, including exhibition cases, vitrines, gallery wall construction, and paint finishes; environmental management of the gallery; administration processes involving report writing, travel arrangements, and associated energy through computer use. The energy and resources expended in making the art object or the impact of building the museum that houses the objects may or may not be included.

Through establishing system boundaries, LCA helps to track performance of a product or action by structuring or organizing the relevant parts. Definition of the system boundaries will depend on the goals of the study and the options being considered. Because the scope of an LCA must be designated by the practitioner and the client, LCAs are often product or project specific, such that the product's practitioners or commissioner have discretion in choosing which types of environmental impacts are most relevant to the decision at hand.

Case Study: Removal of White Paint from a Wooden Sculpture Installation

To conduct an LCA, a series of steps are followed to accumulate, organize, and process information. For example, in an LCA study of a conservation treatment, four cleaning systems were considered to remove titanium white poly(vinyl acetate) (PVAc) restoration paint from original titanium white alkyd paint on a sculptural installation that covers five walls of a public room in New York City. This case study examines the environmental impact resulting from use of solvents. Given the square meters of paint removal, the treatment choice will produce significant amounts of waste; less toxic choices will result in less environmental and human health impact. Although it is treatment oriented, and thus specific to conservators, the comparison it makes between the use of virgin petroleum-based products and less impactful products is noteworthy and useful as an exercise to understand LCA and its components.

Goal and Scope

In an ISO 14040-certified LCA, the first phase is the *goal and scope*, which defines and describes the product, process, or activity, and both establish the context in which the assessment is made and identify the boundaries and environmental effects to be reviewed for the assessment. The *goal* of the paint-removal LCA was to identify the aspects of the cleaning systems that contribute most to toxicity and overall environmental impact so that, through understanding the systems, a minimum impact treatment could be devised. The *scope* covered all life cycle stages (cradle to grave) of the four cleaning systems with a system boundary, including raw materials for making each solvent/cleaning system; electricity consumed in the production of the solvents; transportation of the materials from the manufacturers to New York City; and waste disposal, including the removed PVAc paint. Because the study focused only on the solvent, all other tools involved in cleaning were excluded, such as tools used to apply the cleaning systems (e.g., swab sticks, sponges, or brushes) and tools to clear the surfaces of swelled PVAc paint (e.g., spatulas, brushes, sponges, or cotton wool), as these are assumed to be common among the solvent options. The system boundaries examined in this LCA are illustrated in figure 14.2.[3]

Within the goal and scope, the functional unit, or the basis for the study, is defined. Different cleaning solutions have different efficacies, and this is essential to take into account so that product options are compared according to their performance, thus ensuring a "like to like" comparison. In the paint removal project the functional unit was defined as cleaning restoration paint from 10 square meters of the sculpture. Also defined in the LCA is the reference flow, which describes the exact amount and type of materials that are necessary to provide the function specified by the functional unit. In the paint removal LCA, four cleaning options were evaluated, with the following reference flows:

3 Parts of the LCA relevant to the paint removal case study are included in the body of this technical note. Additional areas that might be studied are addressed in the glossary.

- 3.2 g water buffered to pH 8.5
- 4.2 g 1% triammonium citrate
- 4.2 g distilled water
- 4.2 g 2-propanol[4]

Life Cycle Inventory

Next, a life cycle inventory (LCI) was developed based on the four cleaning options listed above. Each material quantity in the reference flows was linked to a matching material listed in the ecoinvent Life Cycle Inventory database, which is a commercially available dataset that contains cradle-to-gate (supply chain) information on the production of thousands of raw materials and processes. For example, the LCI database record for 2-propanol lists all material and energy inputs and emissions associated with the entire chemical supply chain for 2-propanol, including oil extraction, petrochemical refining, packaging, and transportation.

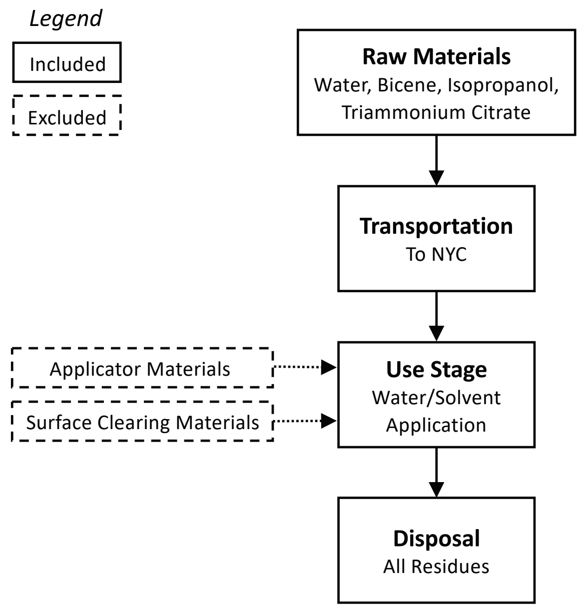


FIGURE 14.2. System boundary for removing PVA restoration paint with isopropanol, deionized water, buffered water using bicine, or triammonium citrate 1% (after Sullivan, Li, and Madaka 2016).

Life Cycle Impact Assessment

LCA is a multi-criteria model, meaning that it computes results for several types of environmental impacts in order to avoid "burden-shifting," or creating new, unintended environmental problems while solving another. For example, a cleaning system that has extremely low greenhouse gas emissions may be highly toxic. Conservators ideally should have as much environmental information as possible when choosing among different options, so that they can consider their choices in a holistic way.

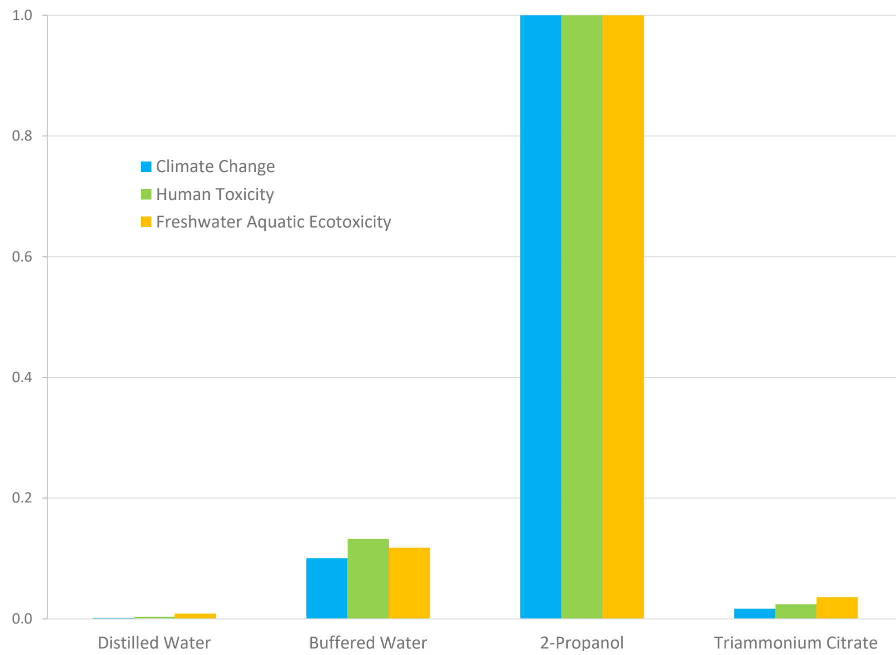
The life cycle impact assessment (LCIA) phase translates each of the emissions in the LCI, and estimates the effect that each emission will have on the environment. Assessment models have been developed for a range of *impact categories*, or types of environmental concerns. The most common impact categories include climate change, ozone depletion potential (related to the ozone hole), smog formation (urban air quality), acidification (acid rain), eutrophication (water quality), human health toxicity cancer/non-cancer potential, ecotoxicity (see the glossary for definitions). This is the core list of impact categories developed by the U.S. Environmental Protection Agency in their TRACI (Tool for the Reduction and Assessment of Chemical and other Environmental Impacts) LCIA model. This tool was used in the paint removal case study LCA and three environmental impact categories were selected: climate change, human toxicity, and freshwater aquatic toxicity.

Results

The LCA results are shown in figure 14.3, scaled to the highest impact option for each environmental category. The results clearly show that 2-propanol has the highest impact for all of the environmental impact categories considered, meaning that it is the worst choice concerning cleaning systems with

4 The four systems were included in this study, although the bicine at 8.5 pH would be too high a pH for contact with the alkyd paint during cleaning, and the triammonium citrate at 0.5–1% in distilled water was used in practice. Each system was calculated at nearly equal amounts for this study; in actual cleaning to remove the restoration paint, similar amounts of each cleaning system were also required due to the method of application (using Nanorestart PG 5 gels).

FIGURE 14.3. Relative results scaled to highest-impact option for each category (=1). Credit: Sarah Nunberg and Matthew Eckelman



environmental impact. In particular, the life cycle toxicity of the 2-propanol was many times higher than the toxicity of the other systems, indicating that the water-based systems result in significantly less climate change and human health impacts than the solvent-based systems. This case study presented no inherent trade-offs, as the four options had the same rank order of preference for each type of environmental impact considered, but often this is not the case and trade-offs must be weighed before making a decision.

Other LCA Studies for Conservation

In another example, LCAs have been used to examine the carbon footprint of loans, and have identified the courier as an unexpected hotspot (Lambert and Henderson 2011; Nunberg, Eckelman, and Hatchfield 2016). Given that the courier causes the highest greenhouse gas emissions of all actions involved in packing, transporting, and exhibiting an object, reducing the number of couriers who travel each year (even by 15%) would significantly reduce the carbon footprint of loans. Because couriers are essential to the loan process, they cannot be removed completely, but COVID-19 travel restrictions have led to bookend couriers and new approaches to the oversight of exhibition installation.

The STiCH website also includes several LCA case studies. For example, a case study on crates compared various crate materials and designs, finding a significant carbon benefit in using durable (100-200 uses) rather than single-use designs, even though the durable crates are substantially heavier. Other case studies compared options for backing boards and anoxic treatments.

Cultural heritage institutions have begun to analyze individual spaces, exhibits, or even entire institutions, and to record these results in sustainability reports. For example, in 2020 David Zwirner gallery commissioned Atelier Ten to do a carbon footprint of an exhibition for Harold Ancart, finding that the largest sources of emissions were the lighting and environmental controls for the gallery itself. Carbon calculators like that of the Gallery Climate Coalition (GCC) and the STiCH project are making it easy for cultural heritage professionals to make initial carbon footprint estimates.

Use of LCAs

Application of LCAs to cultural heritage preservation allows for a new evaluation of conservation and collections management. Identifying hotspots, or the aspects of an action or material that contribute the greatest impact, leads to educated, thoughtful choices concerning the environmental and human health impacts of systems and products. Although the practitioner cannot always entirely remove hotspots from an action, processes can be altered based on the information the LCA reveals, reducing impact. Understanding the environmental impacts related to synthesis, use, and disposal of cleaning systems, such as the paint removal case study described above, can influence the solvent choice for a treatment, the application methods, extent of room ventilation, respirator choices, and waste disposal options.

Life Cycle Costing

Economic analysis is central to informed decision-making in every business and institution. Many decisions are made using present-day cost data that are readily available, at both the product and the service or process level. What differentiates LCC from "simple" economic analysis methods is that LCC considers how economic costs and benefits change over time. The longer the time frame of a design or equipment decision, the more important it is to use an LCC approach. LCC is commonly used to answer questions about how best to invest today in order to realize benefits in the future. Typical questions include: Will this new HVAC system pay for itself? Should we store objects on-site or off-site? What is an (economically) optimal schedule for cleaning or maintenance? Cultural institutions are often intended to last for long time periods, which connects directly with the benefits of LCC approaches for the institution's overall mission and collection preservation. The following tables and explanations demonstrate LCC applied to the common question in museums of whether or not to switch lighting systems.

Case Study: Gallery Lighting

Humans tend to focus on short-term rather than long-term consequences of decisions (Ainslie 1975). When making decisions, this trend is most commonly manifested by focusing only on the first cost, or initial/purchasing cost of a decision, and ignoring costs that are incurred later on. This can lead to decisions that turn out to be more expensive over the long term.

For example, consider a museum deciding between halogen and LED lighting systems. LED lamps are about three times as expensive as halogen lamps when normalized for light output (measured in lumens). If the halogen bulbs cost USD$2,000 in total, then choosing these over the LED bulbs ($6,000) will save $4,000. However, the lighting systems require more than just lamps to operate. Including the tracks and labor to install the systems results in the following table of first costs (table 14.1).

It is obvious that the halogen track lighting is the more economical option, saving $9,000 versus the LED system. But these first costs are not the only costs; there are also maintenance costs for the system. Now suppose that the halogen bulbs have to be replaced annually, which entails both buying and installing the new bulbs and properly disposing of the old bulbs.

First, we must decide on a *time horizon* for our investment decision, based on the equipment and where it is being used. If the museum exhibit is expected to be in place for 10 years, then we can choose a time horizon of 10 years for the lighting system decision. Current LED bulbs have rated lifetimes of up to 25,000 hours, or just over 11 years for an exhibit that is lit 6 hours per day, 7 days a week, assuming they perform

TABLE 14.1.

Installation costs for lighting systems. Credit: Sarah Nunberg and Matthew Eckelman

Costs	Option A: Halogen	Option B: LED
Tracks & Ballasts	$15,000	$20,000
Installation	$3,000	$3,000
Initial Bulbs	$2,000	$6,000
Total	**$20,000**	**$29,000**

according to manufacturer specifications. So, no replacement of the LEDs is necessary in our time horizon. Now, the overall costs are those in table 14.2.

TABLE 14.2.

Initial and maintenance (nominal) costs for lighting systems. Credit: Sarah Nunberg and Matthew Eckelman

<table>
<tr><th colspan="2">Costs</th><th>Option A: Halogen</th><th>Option B: LED</th></tr>
<tr><td rowspan="3">Initial</td><td>Tracks & Ballasts</td><td>$15,000</td><td>$20,000</td></tr>
<tr><td>Installation</td><td>$3,000</td><td>$3,000</td></tr>
<tr><td>Initial Bulbs</td><td>$2,000</td><td>$6,000</td></tr>
<tr><td rowspan="3">Annual</td><td>Replacement Bulbs</td><td>$2,000 x 10</td><td>$0</td></tr>
<tr><td>Replacement Labor</td><td>$1,500 x 10</td><td>$0</td></tr>
<tr><td>Disposal Costs</td><td>$20 x 10</td><td>$0</td></tr>
<tr><td colspan="2">Total</td><td>$55,200</td><td>$29,000</td></tr>
</table>

Over our 10-year time horizon, the total maintenance associated with the replacing the halogen bulbs totals $35,200, much more than the initial cost of the system! Obviously, the LED system is now economically preferable. But we must consider one additional cost: that of the electricity needed to power the lights. This is called an *operational cost*.

In order to estimate operational costs, the amount of electricity each lighting system requires over a year needs to be established. One reason why LED lamps are gaining market share is their energy efficiency: a typical LED lamp has an output of 75 lm/W (lumens of light per watt of electrical power), whereas halogen lamps produce approximately 25 lm/W. This means that, in order to deliver the same amount of light to our exhibit, the halogen system will use three times as much electricity as the LED system.

Let’s assume that the LED system is made up of four hundred 750 lm bulbs that cost $15 each (totaling the $6,000 initial bulb cost), and that the same number of 750 lm halogen lamps would cost only $5 each. Using the energy efficiency values above, the LED bulbs require 750 lm/(75 lm/W) = 10 W of power, while the halogen bulbs each require 30 W. For the lighting system to operate for six hours per day every day, the total amount of electricity for the LED system is:

(6 hrs/day) × (365 days/year) × (10 W/lamp) × (400 lamps) = 8.76 million watt-hours.

In more common units, this is 8,760 kilowatt-hours (kWh) of electricity every year. An average electricity price in the United States for one kWh is 10 cents, so the annual cost of electricity for the LED system is (87,600 kWh) × ($0.10/kWh) = $876. This means that the annual operational costs of the halogen lighting system are three times this value, or $2,628. Now, our table of costs becomes that in table 14.3.

TABLE 14.3.
Initial, maintenance, and operating (nominal) costs for lighting systems. Credit: Sarah Nunberg and Matthew Eckelman

Costs		Option A: Halogen	Option B: LED
Initial	Tracks & Ballasts	$15,000	$20,000
	Installation	$3,000	$3,000
	Initial Bulbs	$2,000	$6,000
Annual	Replacement Bulbs	$2,000 x 10	$0
	Replacement Labor	$1,500 x 10	$0
	Disposal Costs	$20 x 10	$0
	Electricity Costs	$2,628 x 10	$876 x 10
Total		**$81,480**	**$37,760**

The LED system is now looking even more economically attractive.

Payback Period

Simple payback period is a measure of how quickly an initial investment pays for itself, typically measured in units of months or years. As illustrated above, the LED lighting system costs more initially but has lower maintenance and operating costs over time (assuming these costs do not change—more on this in the next section). Suppose a museum already has a halogen lighting system and is considering switching to LED. Using the table values, buying a new LED system will cost $29,000 up front, but will save $5,272 every year. (Avoided annual halogen costs are $2,000 + $1,500 + $20 + $2,628 = $6,148, minus the annual LED costs of $876.)

So the payback period is:

Payback period = (Initial costs) / (Savings/year) = $29,000 / ($5,272/year) = 5.5 years.

What constitutes a "good" payback period will vary by both institution and the type of project. But regardless of context, the payback period of a favorable investment must always be less than the expected lifetime of that investment; otherwise, the investment will lose money.

Inflation

Thus far we have assumed that maintenance or replacement costs do not vary in time, but of course this is not realistic. The cost of goods and services changes due to shifts in market conditions (supply and demand), and also to inflation. The price of milk today is higher than it was 50 years ago when measured at face, or *nominal*, value. So, when doing LCC calculations, it is important to include estimates of inflation in future costs. Inflation in goods and services is tracked by the US Department of Labor. One of the most popular values to use is the Consumer Price Index (CPI), which currently shows urban consumer prices increasing by approximately 2.5% per year. The further into the future, the more inflation will increase costs—their increase is *exponential*.

Future costs can be calculated based on present costs, the number of years in the future, and an annual inflation rate. Using the CPI value of 2.5% annual inflation, replacement halogen bulbs should be listed as costing:

- $2,000 × 102.5% = $2,050, after year 1;
- $2,050 × 102.5% = $2,101.25, after year 2; and so on until
- $2560.17, in the final year, 10.

Expressing costs in this way, taking inflation into account, is called looking at inflation-adjusted, or *real*, values.

Time Value of Money

A final core concept in life cycle costing is the time value of money or, more colloquially, the idea that a dollar today is worth more than a dollar tomorrow. Why? Because we can take a dollar today and invest it, and have more than a dollar tomorrow. This holds as long as there is a way to earn a positive interest rate, for example in a bank savings account or by purchasing government bonds. This nominal interest rate *compounds*, as does inflation, so that money that we presently invest will have a future value that increases exponentially with time. For LCC, we typically want to know what future costs are actually worth in today's dollars, so we can rearrange this equation to show that future costs F are worth P today by *discounting* them to the present. As long as interest rates are above zero, this means that future savings in maintenance and operations are worth less than they first appear in our tables above because they must be discounted to reflect their value in the present.

Real Interest Rate

The final step is to combine inflation rate and interest rate. The inflation rate serves to increase future costs relative to the present, while the interest rate serves to decrease future costs when discounted to today's dollars. The effective interest rate that accounts for both inflation and interest is called the *real interest rate*, and can be approximated as the difference between the interest rate and the inflation rate. Under normal macroeconomic circumstances, the nominal interest rate is greater than inflation, so the real interest rate is greater than zero.

This real interest rate can be used in our LCC for museum lighting options. Considering an example of a safe investment with a nominal interest rate of 4%, the real interest rate is: 4% − 2.5% = 1.5%. This value can then be used to discount the future maintenance and operations costs. For the replacement halogen bulbs over a 10-year project period, the costs in *present value* are seen in table 14.4.

Thus, instead of costing $20,000, the actual cost of the replacement halogen bulbs over 10 years is lowered by more than $1,500 due to the combined effects of inflation and interest rates.

Putting it all together in the LCC example, the final present value cost table looks like table 14.5.

The discounting does not change the preference of the LED over the halogen lighting systems, as future costs for both systems are being discounted using the same rates. The discount rate will affect the payback period, however: as discount rates increase, future cash flows are worth less in present value, decreasing the financial benefits of a project, and so the payback period increases.

TABLE 14.4.
Present value costs of future bulbs. Credit: Sarah Nunberg and Matthew Eckelman

Year	Discounted Costs
Initial Bulbs (Year 0)	$2,000 (No Discounting)
Year 1	$1,970
Year 2	$1,941
Year 3	$1,912
...	...
Year 10	$1,723
Total	**$18,444**

TABLE 14.5.
Complete present value costs of lighting systems, life cycle costing example. Credit: Sarah Nunberg and Matthew Eckelman

Costs		Option A: Halogen	Option B: LED
Initial	Tracks & Ballasts	$15,000	$20,000
	Installation	$3,000	$3,000
	Initial Bulbs	$2,000	$6,000
10-Year Discounted	Replacement Bulbs	$18,444	$0
	Replacement Labor	$13,833	$0
	Disposal Costs	$184	$0
	Electricity Costs	$24,236	$8,078
Total		**$76,697**	**$37,078**

Use of LCCs

As illustrated by this example, first costs, operational costs, and maintenance costs all play a role in preservation and exhibition of cultural heritage. First costs are nearly always considered in project budgets, but neglecting future costs in decision-making can potentially lead to unexpected outlays or choosing options that are more expensive in the long run. Discounting of future costs and revenues is not always necessary, particularly when considering short-time horizons of a couple years or less, but for projects with longer time horizons, and in situations wherein high interest or inflation rates prevail, discounting is standard practice.

Conclusion

In planning for the preservation of our cultural heritage, we can accomplish the essential goal of lowering our environmental impact while improving our methodologies and reducing costs. Through evaluating each of our routine actions and then identifying the aspects most harmful to the environment and to our own health, we can then make educated and effective changes toward sustainable goals. When selecting materials, equipment, or approaches, there is always a need to demonstrate financial viability. Cultural institutions with limited resources may have several competing priorities that draw from the same resources. Demonstrating the economic feasibility or benefit of options that are not the lowest cost is often necessary. LCC moves emphasis from short-term initial costs to the ongoing, long-term costs of repair and renewal. This helps identify the essential cost of maintenance, use, and operation, and justifies large initial costs that have environmental and/or economic benefit in the longer term. Cheaper materials often require more frequent maintenance and have a shorter life span, so they impact negatively on the broad mission of the institution.

Planning for collection preservation necessarily involves the consideration of long time scales, wherein expected lifetimes of objects may be measured by decades or centuries. Consideration of the global environmental needs, and the economic viability that might justify those choices, can be better facilitated with the appropriate tools and data to present options that represent long-term planning. Conservation professionals are constantly faced with decisions regarding which products or processes to use, or which investments to make, in order to best preserve cultural heritage, while hopefully also striving for environmental sustainability. Life cycle assessment and life cycle costing can aid in decision-making and contribute to a more systematic approach to preserving collections in a sustainable way.

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TECHNICAL NOTE 15: NEGOTIATION AND CONSENSUS BUILDING

Jane Henderson

Introduction

We all negotiate all the time: even something as simple as getting to work in the morning involves types of negotiation, from access to domestic facilities in the morning to traveling around our locality. We negotiate a space and a place for ourselves and most of the time this works well. We take a shower in good time to leave the house and we move aside on a path to let a buggy or bike go past. It works because we exchange information about who needs to leave the house first (communication); we recognize that at some point we might have the buggy (empathy); and we calculate that the cost of moving aside is likely much lower than that of going off the path for the other party (cost benefit). Negotiation is a normal part of our lives, it doesn't have to be hard, confrontational, verbal, or motivated by power or money. In the museum context we negotiate every day, whether deciding how many visitors can enter a historic room or managing the carbon footprint of a traveling exhibition.

Definitions: Negotiation and Consensus

Negotiation is comprised of two parties with different perspectives meeting to resolve that disparity. The traditional image of a negotiation is a power play with two sides arguing over a measurable outcome. In such situations, the negotiation will be deemed a success if your "side" wins. This may be at the expense of buy-in or future cooperation. Negotiations have many forms and outcomes; when the outcome is a meaningful agreement, this can be considered a consensus.

Consensus arises when a group recognizes its multiple concerns and uses them to create solutions that deliver value to all, or most of, the group. Consensus is not the same as complete agreement, but a consensus should address people's most important concerns. To achieve consensus, deliberation and a diversity of opinions are needed, ensuring that everyone has been heard. A forced "consensus" will not generate buy-in to the outcomes and this matters if many people are needed to deliver the solution. It means that even if a deal has been agreed upon, it may not be delivered.

When groups work together to find solutions they benefit from the "wisdom of the crowd" (Sigman and Ariely 2017). To gain this benefit it is essential that all participants advance their own perspective and are not heavily influenced by others, nor do they conform to a "group think" solution advocated by a charismatic or powerful figure.

Consensus is often a goal in the nonprofit sector and other values-led organizations, whereas a "winner takes all" perspective may be more common in commercial settings; however, modes of negotiation are neither fixed. Consensus building takes time and normally requires flexibility from all parties. Quick decisions are needed on occasion and leaders who can make those decisions will be respected; and at times one or more party will not be prepared to compromise their position. Values-led organizations may identify issues on which they are not prepared to compromise. Consensus is likely to operate best in a period of social calm and minimal change. Under exceptional conditions, such as times of crisis or other rapid changes, someone with a creative approach or a distinct way of describing the world might be the best person to find a solution.

Power and Consent

Negotiation, influence, and consensus building are not critical skills if other parties can be controlled. This control eliminates the option to refuse a request—however it manifests. The power to compel action can stem from a range of circumstances, such as:

- financial (they pay your fee);
- institutional (they are your boss);
- moral (they are a thought leader); or
- personal (they are a close relative).

Such relationships may achieve results, but they can also derail consensus. For example, if a negotiation has resulted in withholding the remainder of a fee because the air handling has not been installed to specification, or if staff are on a formal written warning for persistent poor handling of the collections, then negotiations are failing.

Following someone with moral leadership may make you want to concede your position, especially if they note that their position coincides with that of someone with desirable characteristics. When someone with whom you have a long-term, positive relationship makes a request, you may concede to protect that relationship. In these cases, concessions may arise without rancor despite a lack of choice. These forms of personal power are available to everyone in an organization—even the most junior of staff. Associating outcomes with positive attributes and being someone that people like helping is a sensible strategy for the relatively powerless.

Core Concepts of Negotiation

Negotiation is a human activity. For all the rules, guides, and tricks the negotiation will come down to how people work together.

Empathy

Empathy is not necessarily about agreeing or sympathizing with another person's position; it is about understanding it. Empathy is a powerful negotiation tool because most decisions have an emotional component. Former FBI hostage negotiator Chris Voss offers a practical concept of "tactical empathy" (Voss 2019), a process of seeking to understand without necessarily actually empathizing. Plenty of preparation can be undertaken to build tactical empathy, through researching the priorities and beliefs of your target.

Do the Research

Good negotiation starts with research on the individuals or teams with whom you will work. Candidates who are successful in job interviews are usually the ones who have done their homework and have familiarized themselves with the organization's priorities, plans, and activities. A greater understanding of those you seek to influence allows a greater understanding of the qualities they value, so desired outcomes can be aligned with these desirable attributes. For example, knowing that a facilities manager supports sustainability means any advocacy on the ideal relative humidity set points should be framed by the concept of energy efficiency.

Expertise

Expertise, when respected, is influential. Individuals may see themselves as experts but in terms of influence expertise is situational, not fixed, and will not carry from one topic to another. Expertise depends on context, and on any given topic one person's expertise will be compared to another person's. Absolute expertise is not as important as how the other party judges your knowledge on a given topic against their own (fig. 15.1).

FIGURE 15.1. The listener evaluates your expertise in comparison to their own on a specific topic. Image by Designworld Ltd

Learning how the target of your negotiation self-assesses (their self-schema) will help to establish how they will evaluate you. Understanding their role descriptions (schema) for you will also unlock powerful negotiating tools. Do they consider your organization or profession to be difficult, inflexible, or soulless; do they see you as an idealist, a bean counter, a dreamer? It may be necessary to counter one's perception with brief but highly relevant evidence of your expertise. At its simplest you may only need to use the correct vocabulary to dispel their preconceived notions about you. Sometimes conforming to a stereotype can increase your advantage. In whatever way you choose to respond to their schema, a correct diagnosis of it should inform your actions.

Long-Term Relations

Consensus decision-making is a creative and dynamic way to reach an agreement and break down any entrenched opinion. While competitive negotiations can be "won" with anger, neutral negotiation allows for innovative, collaborative solutions.

To maintain positive long-term relationships when negotiating in an institutional context, ensure that everyone gets something out of the process. Imagine a space-allocation negotiation when planning a new archive. The number of square meters of storage that the collection needs for twenty-year growth is known. Halving that to "achieve consensus" is a poor outcome. In contrast, consensus may arise from reframing the problem in a way that recognizes everyone's interests. An advocate for building-storage-space growth might agree that the growth space would be built to collection standard (security, environment, floor finish, etc.) but could, in the short to medium term, be utilized as an income-generating space.

Agreement may not always be possible on all issues, but relationships can be protected. Imagine a negotiation about whether to install a pitch or flat roof over a collection space in a rainy, temperate climate. The conservator may wish to insist on a pitch rather than a flat roof but can be self-aware enough to weigh the impact of the disagreement on future relationships while still seeking a win. Such mitigation might take the form of increased advocacy, such as visits to sites with flat roofs to discuss their maintenance, conceding ground elsewhere (e.g., designing a denser storage pattern to reduce cost), or simply acknowledging rather than dismissing the rationale for a flat roof.

In any intra-institutional context, negotiation will be part of a long-term framework for relationships and will have long-term impacts. The duration of a relationship may not be related to the duration of the current negotiation. Having a clear understanding of the duration of the engagement will help generate positive outcomes. For example, in planning gallery lighting a conservator might overturn a lighting design decision by going over the lighting designer's head to a manager. However, if both conservator and designer must work together on several more exhibitions this quick win might sour the relationship, making future negotiations harder. Any cost-benefit calculation must consider the long-term, not just the immediate win.

Upon entering a negotiation, it may become apparent that past encounters have soured current relations. Discovering the schema that "people from your department are difficult," for example, might illuminate otherwise puzzling behaviors. This longer-term impact can emerge from the outcome of the first negotiation or from behavior during and after the initial negotiation. Humiliation, power plays, preening, and overt displays of victory are all hallmarks of short-term negotiation. Putting in measures to protect other people's ego will help ensure that all parties feel heard in the projects and will then be more likely to subsequently share the implementation of the agreed outcomes.

Goals and Goal Sharing

Goal definition is a powerful tool in negotiation and influence. An ability to define your own goals, and the goals of those around you, will increase opportunities to influence negotiations. The goal-definition process can start from one person devising personal goals and may lead to a collective attempt to form a common set of goals. In considering goals, the distinction between outputs (what you want delivered) and outcomes (what you want to happen) is useful to consider (fig. 15.2).

If people are instructed how to perform a task through a series of rules, they can be trained to follow the instruction without question. In some situations, this is necessary: for example, in a post-disaster recovery in which people are allocated to workstations, a strict implementation of the recovery protocol might ensure the most effective response. On other occasions overtly following the rules can be less constructive: for example, in trying to follow a salvage plan that has not been updated to cover the new temporary exhibition gallery.

In situations that require more complex decision-making, goal sharing helps others to deliver what you want rather than what you've asked for. If everyone understands the common and agreed goals, they can adapt their responses to deliver those outcomes. For example, if a team in a building project notices that a bund installed to help with flood risk management introduces stepped access to the main store, they may flag this as a potential problem. If, on the other hand, the project has been rigidly instructional they might take satisfaction in following the rules regardless of the outcome.

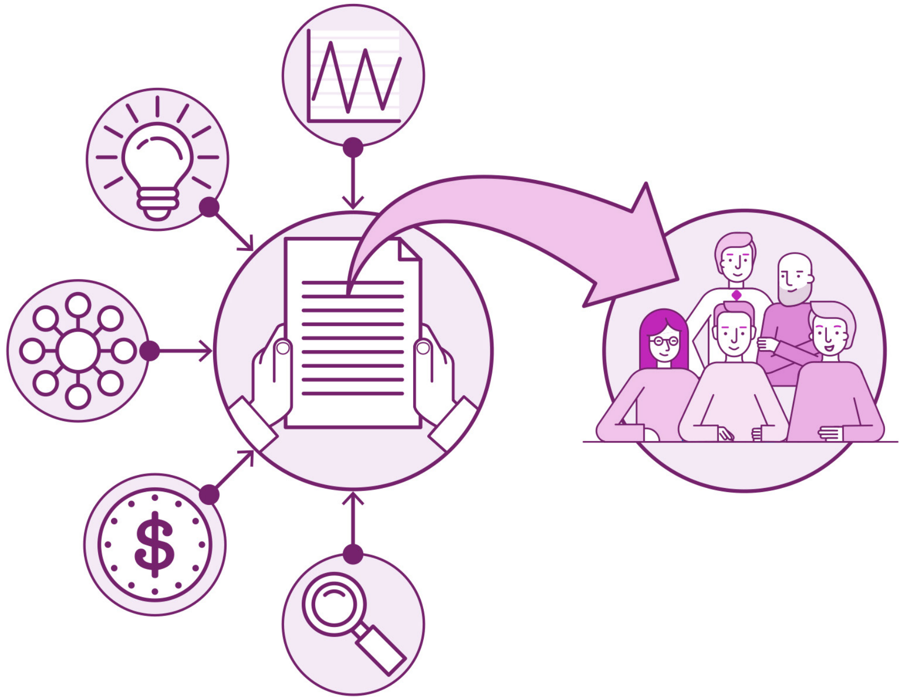

FIGURE 15.2. Outputs (a report) and outcomes (a happy team). Image by Designworld Ltd

Sub-Goals

Taking time to clarify and formally record your main goals and sub-goals at the outset will improve your negotiation position. A main goal might be buying the highest specification shelving system or minimizing the rate of heat transfer through the building shell. To support negotiation plans it is beneficial to identify sub-goals. Questions like the following will help to achieve this:

- What do I want to happen in the longer term?
- What are my restraints (budget/time/legalities)?
- What longer-term relationships do I have to work on?

Sub-goals will normally outnumber main goals and may initially feel less mission critical. Sub-goals might include staying on budget, building better long-term relationships, achieving a sustainable solution, or reserving time for your other job roles. Formally acknowledging both main and sub-goals should help to avoid a negotiation that focuses on achieving a central concern at the expense of future working relationships.

Satisficing

One way to encourage positive outcomes is Herbert Simon's classic social theory of "satisficing" (Barros 2010). From an economics perspective, satisficing is the acceptance that the best outcome is one that leaves everyone satisfied rather than one that measures success by the optimization of a single measurable quantity. In psychology, satisficing is defined as the acceptance of a "good enough" solution, in which a select range of outcomes is reviewed and one that is good enough is selected. This solution may at first appear less than ideal—but it pragmatically describes how most people live their lives. We often select our home, job, or even a life partner from eight to twelve options on the basis that it will satisfy our primary needs. Rather unromantic in description, satisficing leads to the optimization of sub-goals. Satisficing helps the negotiator avoid all-consuming battles over one "win" while neglecting other opportunities and the chance to make progress on a good enough solution. Leaving other people satisfied will help build long-term productive relationships and generate consensus.

Tips for Negotiation

Negotiation Styles

Most negotiation books offer advice on between three and five styles of negotiation. These can be described as such:

- Hard negotiator—competing to win
- Soft negotiator—seen as considerate or intelligent
- Principled negotiator—seeking the goal of equanimity

Principled negotiators attack the problem, not the people. They avoid becoming entrenched in any specific position from the outset and they find ways to manage the process of agreeing on an outcome.

The Harvard Law Approach

A leading voice on effective negotiation comes from Harvard Law School's concept of a mutual gains approach (Susskind 2014). This formalized approach is reflected in many other guides, and a comprehensive heritage-based application can be found in Stacie Nicole Smith's chapter "Consensus Building for Cultural Heritage Place Management" in the Getty Conservation Institute publication *Consensus Building, Negotiation, and Conflict Resolution for Heritage Place Management*. The Harvard Law guidance notes that consensus building will always involve several critical steps:

- *Convening*: Ensuring that people come together with shared expectations of how the negotiation will work.
- *Clarifying responsibilities*: Identifying roles such as whose job it is to record outcomes or to move the discussion forward.
- *Deliberation*: Taking time to approach a unanimous decision, undertaking joint fact finding, listening carefully, and finding an agreement that addresses the participants' most important issues.
- *Conclusions*: Formally identifying where an agreement is emerging across all the critical issues.
- *Delivery*: Ensuring that participants are prepared to commit to what has been said and who will take that forward.

The Harvard Law approach is highly likely to feature in any work-based negotiation training. The guidance presupposes that the reader already has a "seat at the table," but understanding the phases of a formal negotiation can help negotiations across a range of contexts.

Confidence

Confidence and power are independent variables in a negotiation. Developing a confident position aligned with goals and sub-goals will improve opportunities for the negotiator to coalesce opinions. Often those with extreme views will be the most confident in articulating their position, while others who are unsure of their opinions and thus have low confidence, may not be heard. A person who is confident that a consensus position will work is more likely to find a mutually acceptable solution. For example, confidently asserting that conservation and access are complimentary, and that the question is simply to find out how, is a way to guide a discussion toward consensus.

Planning to Optimize Impact

Regardless of the length of the formal negotiation period, time spent planning will help optimize outcomes. Time spent researching and planning will also help manage any anxiety associated with the process. Even if the formal part of a negotiation lasts only an hour, it is wise to spend the preceding week preparing. The "elevator pitch" concept is about preparing a perfect and succinct statement of advocacy to be held in reserve in case a serendipitous opportunity arises. Having a brief, compelling, engaging, and interesting summary of your position is a way to prepare for negotiation even when you do not have a seat at the table.

Clear Communication

When negotiating, ensuring the clarity and coherence of your message is vital. Expressing your request in terms that can be comprehended, and are relevant and important to the other party, will facilitate the request's advancement. A common error in a negotiation is overwhelming others with too much information that the other parties find irrelevant. This results in failed communication because the other side does not understand your message. For example, a conservator may be concerned about the relocation of collections to storage in a poorly maintained building. Raising concerns around energy use and staff welfare, rather than material response to humidity, may be more effective when meeting with the director, whereas a detailed discussion on U-values might be welcome in a meeting with the estates manager. Learning the areas in which the other parties consider that they have expertise is more powerful in identifying a common framework for consensus than showcasing your knowledge. For negotiation and influence purposes, not being understood is far less important than not understanding.

Small Group Discussions

Small group breakout discussions work because they help to prevent people from lining up behind specific positions. Talking and then preparing a group recommendation encourages three critical skills for consensus building: active listening, summarizing, and synthesis (table 15.1).

TABLE 15.1.
Key stages in consensus building. Credit: Jane Henderson

Stage	Involves	Benefits	Group Size
Active Listening	Everyone listening & talking	Ensures participants understand multiple perspectives on the topic & creates a sense of co-ownership in the process	Best in small groups to ensure all voices heard
Summarising	Capturing all the perspectives & represents them	Does not require agreement as all views represented but will provide a clear sense of other people's views, priorities, & needs	To the whole group
Synthesis	Clarifying emerging commonality & expressing any unresolved differences	Helps focus minds on the emergent common ground, examine outstanding problems, & work towards building a proposal that aims to address the priorities & needs of everyone	Smaller or medium size groups

This technique can be used formally in meetings, but the benefits of the approach can be sought informally by anyone who has not yet been invited to negotiate. Even away from the negotiation table, people who want change can work their way around stakeholders, listen to them, and then attempt to articulate their opinions on topics related to their own negotiation goals. Allowing discussions to flow and avoiding the creation of fixed positions will help provide insights into the range of opinions in your domain. Presenting concepts and values to your colleagues will increase the sense that you are taking their ideas onboard. Synthesizing multiple concepts, priorities, or values will force you to look for overlaps or common concerns. This can be accomplished even with no current prospect of participating in a formal negotiation. It helps prepare for the invitation to negotiate or to seize the moment if the "elevator pitch" opportunity arises. Being recognized as a person who can articulate a range of perspectives may even increase your chances of being invited to the negotiation table.

Managing Negotiations

Most advice on negotiations starts with the assumption that the parties have already agreed to talk, although they do not assume that every party has equal power or stakes in the outcomes. When individuals want to engage but have no leverage, they should follow the advice above on preparing for negotiations: listen, plan, and set goals to be ready when opportunities arise.

To set up a fruitful negotiation, devise and share a framework that explains how the exchange will work. If you are attending a negotiation but this information has not been provided, ask for it. Clearly defined roles bring a degree of certainty to the process whilst protecting the opportunity to be open to different options and solutions. If a negotiation is well convened everyone will arrive with shared expectations of how it will progress. If everyone is clear on how the discussions will be managed and feels confident that they will be heard, they will make an effort to listen to others. The Harvard Law approach encourages the creation of rules for a consensus-building process (table 15.2).

TABLE 15.2.
Issues to address and clarify for formal negotiations based on Harvard Law guidance. Credit: Jane Henderson

Consider	Ask Yourself
Who will manage the discussion?	• Will they set the agenda? • Will they move the discussion forward at intervals?
Will there be note taking?	• Will it record everything said during the discussion? • Will they create an action list at the end?
Will there be rules of engagement & ways to formalise agreement?	• Ask all parties to agree to a proposal if they are broadly happy with it • Ask those who disagree to suggest improvements not disapproval • Agree to stopping points during the discussion
Do you have success criteria?	• Agree to a minimum threshold for consensus • Agree to a satisficing approach

Within the group at least one person should be in a facilitation role, which entails keeping the conversation open and restating that a positive outcome is achievable. Their role is to express emerging consensus and formulate it in terms that others can respond to. This may generate multiple solutions and the group may choose to eliminate some and develop others. If there is no facilitator, relatively powerless individuals may increase their leverage by taking on some of these attributes.

Part of consensus building is to draft positions that everyone can agree with. On the road to consensus a proposal inevitably will be made that some participants feel does not speak enough to their perspective. In a negotiation it is possible to force a vote and take a win at fifty-one percent. Such a route can achieve desired outcomes but may not generate harmony or consensus. In a consensus mode, all parties revisit the proposal and consider whether the remaining concern can be addressed without foregoing anyone else's principal issues.

Breaking a Deadlock

If problems arise during a negotiation, revisiting the goals may help to re-open the conversation. Debating goals rather than options will help to depersonalize discussions, and will encourage people to let go of single trains of thought, and this can break deadlocks. If the discussions stall, pose big questions about the original goals: Are they still valid? Do all parties still agree to them? If not, should they be reset? Can the outcomes be preserved with a different output?

Using Creativity

A negotiation can achieve a result in which one side wins and the other loses, but this will not build consensus. Rather than approaching a problem as a competition, exploring the issue—perhaps through creative work practices—may offer a richer solution by reframing the issue to expose previously hidden options. Some advisors recommend using creativity in negotiation. This could be creative acts such as drawing a problem, building clay figures, playing roles, performing trust exercises, and so on—although these activities make some people recoil in horror. Nonetheless, creativity is important in resolving intractable problems, so finding new ways to undertake an exchange and free up mental space for new ideas is a useful approach.

Meeting Strategies

When highly creative meeting formats are not desirable it remains possible to break out of familiar habits and work patterns. Some approaches are described below. Several can be undertaken at once and may be pursued in a more or less formal manner.

1. An active listening exercise in which everyone in the group speaks on their perspective for a substantial period (maybe six or seven minutes) without interruption, note taking, or questions; questions are not asked, as they steer the conversation in the direction of the listener.
2. A change in the discussion from what people want out of the situation to patterns of cause and effect that are not working. The discussion can then move on to desirable cause and effect patterns.
3. Running a three-phase "Scan Focus Act" meeting. The first part of the meeting is devoted to a scanning exercise in which all parties discuss their preoccupations within a topic with no attempt to structure or resolve issues. This may introduce new and positive ideas and reveal overlooked perspectives. The next segment is dedicated to reviewing and organizing these priorities. Only in the meeting's final section does the group consider practicalities of how and who to take actions forward.

4. Capturing (or “pinning”) ideas and solutions to keep discussions open and fluid. Everyone in the group should be able to see these pinned ideas and should be reassured that the points will be revisited once all have had a chance to hear each other and express all the possibilities.
5. Seeking clarity about what everyone wants to achieve at the discussion’s outset. Use your voice to ask for everyone’s opinions. Even if one party is pushing hard for their solution, actively discourage parties from advancing specific proposals.
6. Considering whether pre-meeting site visits or guest presenters may help generate more creative solutions.
7. Introducing a facilitator to the group as a credible advocate for different ways of working.

Nonverbal Transactions

The word “negotiation” often conjures ideas of words or numbers on the table, but negotiation is framed by other important nonverbal transactions. In high-stakes political negotiations every detail is managed to ensure a level playing field, from the number of negotiators in the room to how people arrive, who sits where, and, crucially, who chairs the discussion and records the agreements. These nonverbal transactions are far from trivial; they feed into power dynamics and indicate how much the other side needs to win. When looking to build mutual agreement and consensus, subtly leveling the playing field is vital.

Museum staff who have worked with participatory models of engagement will be able to draw lessons from these practices in managing the nonverbal impacts within a negotiation. Follow the good practice protocols from your coproduction approach to community engagement. Keeping the tone positive, meeting at reception and arriving at the negotiation space at the same time, and making sure everyone has the agenda and papers in good time are simple actions that are all too easily forgotten. Good introductions, considerate seating, adequate rest breaks, and a measured agenda will promote the coproduction of solutions.

Discrimination, Bad Behavior, and Other Things We Don’t Like to Talk About

A negotiation hampered because one side does not respect the credibility of the others will create a harder position from which to negotiate going forward and will render consensus building nearly impossible. If the lack of respect stems from discrimination then seeking support from Human Resources (HR) or trade unions may be necessary. Escalation to HR may entrench divisions so may be the best option only when behavior is unacceptable. As a member of a team, be prepared to challenge discrimination and support colleagues who call it out. Because credibility is issue-relevant, and people have “schema” (a sense of what a person like you will think and do), finding out more about others is an effective tactic. Although it is offensive to be treated as less than competent, it is useful to know from what a person’s prejudice stems. Taking active steps to establish issue-relevant credibility may help. This can be done by demonstrating relevant and focused knowledge of the topic at hand, or by staying focused on your specialized area and tightly framed expertise. Using the credibility of other sources to bolster an argument can be achieved by steps as simple as referring to ASHRAE standards or noting that you are following the rules of your funder or a legislative requirement. Advice can also be outsourced by seeking peer influencers, for instance, going on fact-finding missions to organizations that have undertaken a similar and now proven successful project. The careful management of such visits, the choice of whom to meet, and the questions asked may even help those you are negotiating with to come up with the solutions you desire.

If the only goal in the negotiation is to win, this can lead to behavior that is manipulative, aggressive, or dishonest. If the relationship is long-term, most of these strategies will have negative consequences. A calm and dispassionate approach that de-escalates aggression has been shown to be more effective in delivering outcomes that are broadly supported, and most importantly, enacted effectively. Focusing the debate on why everyone is at the negotiation and describing their interests in the process, rather than on their solutions, is a useful way to keep a discussion on target. By focusing attention on the topics at play the discussion becomes less personal and the opportunities to allow a broad-ranging and creative discussion are increased.

If a "win at all costs" negotiation tactic is used against you without any consideration of your needs don't feed it. Conceding in the hope of appearing reasonable will most likely generate more of the same behavior. If it is not possible to change the terrain of the discussion then focus on your own needs and concentrate your efforts on how to maintain them under pressure. De-escalating aggressive behavior with humor or empathy may reduce the pressure, but if manipulation tactics are becoming oppressive, create space to think by engineering an artificial break—for example, to consult your boss or team.

Failure Is an Option

In some negotiations, even those built around consensus, some people may not achieve their outcome. The concept of satisficing is useful to help mitigate the consequences and identify measures to reduce dissatisfaction. Mitigation can be as simple as the meeting chair formally recording objections or guaranteeing a review period when ideas can be revisited. Participants in the negotiation can ask the "losing" party if they felt heard to acknowledge that this party's position was considered. Beyond the scope of the formal discussion, other unrelated things may be done to reduce the sting, and the consequent damage, to long-term relationships. Perhaps the pain of losing a debate on the air exchange rate in the showcase specification can be minimized by ensuring that the party is invited to the gallery launch and their role acknowledged.

If you find yourself in opposition to the emerging solution perhaps some flexibility on your part can unlock flexibility elsewhere. Some negotiation advisers suggest that you should revise your position if the outcome on the table is better than the impact of no agreement. This might make sense in a debate on costs but may be less effective on issues that are matters of principle. If the context of a negotiation is the per diems of registrars, taking the best offer might make sense, even it is half of your starting position. If the context is a restitution of human remains, then the originating community may not want to negotiate the return of half of their ancestors' remains. If no agreement is possible without compromising a principle, it may be better to acknowledge this and walk away. A high-principle/high-risk strategy approach privileges a future but as yet uncertain opportunity to revisit the issue over a present opportunity to form an agreement. When individuals frequently lose a high-principle/high-risk position they should attempt to diagnose the cause. It may result from unequal power distribution, or from neglecting the needs of others under the guise of altruism: a party acting on behalf of the collections, for example, does not guarantee that they are correct (fig. 15.3).

Disagreement

Total agreement is not always possible. Those who disagree with the consensus or negotiated solution can be categorized into three types.

- Those who recognize that a solution, while not ideal, works and are prepared to contribute to its implementation.
- Those who do not like the decision but can tolerate its implementation.

FIGURE 15.3. "Won't anyone think of the collections?" Image by Designworld Ltd

- Those who actively disagree with the proposal and, if not managed carefully, will act to block the implementation of any agreement.

Considering the type of disagreement is worthwhile as it may offer a valuable perspective. Although consensus is gratifying, in times of upheaval the mavericks with dissenting voices may be more likely to find solutions. Maintaining a diverse team makes your group more resilient, so value everyone's distinct perspective.

If you find yourself constantly in opposition and realize that your values simply do not align, you might see this as a chance to refocus your career and assume a different role in which you can have a positive impact. In any situation in which you have attempted to negotiate or influence on a topic that is a personal red line you must be prepared that you might lose. Sometimes waiting and watching without destroying working relationships will create chances to rectify the consequences in the future.

Record the Outcome(s)

With consensus should come a commitment to deliver. The value of consensus-based negotiation should be a high degree of traction from those involved to make it happen. Time invested should lead to buy-in and action. This commitment can be reinforced with the simple procedural work of agreeing on actions, recording, and distributing them. Having a formal sign-off will increase pressure to deliver them. Formal and public reviews of the action plan will be influential in focusing people on their part of the delivery. If your group has agreed on goals and tasks, restate these at the outset of any follow up; they will serve as a reminder of why actions were agreed upon and will form a baseline if proposals must be revisited due to changing events.

Conclusion

When a problem must be solved, individual leaders can dictate and implement a solution they have chosen or they can negotiate one. Leadership is addressed in the next technical note, but not all leadership has to be based on consensus and not all solutions must be negotiated.

Negotiation and consensus building take time: diversity and deliberation are needed to build consensus and people must have the space to express their priorities, their thoughts on the topics at hand, and their feelings about other people's ideas. In situations where many people have a stake in the outcome and in delivering the solution, this early investment of time and energy to create consensus will repay in the successful delivery of the project, and will help build a satisfied team.

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TECHNICAL NOTE 16: THE ART OF DIPLOMACY: HOW EFFECTIVE LEADERS DEVELOP STRATEGY, COMMUNICATION, AND INFLUENCE

Bob Norris

> Leadership is the art of getting someone else to do something you want done because he wants to do it. —*Dwight Eisenhower*

Introduction

Museum professionals and those in nonprofit organizations are constantly called upon to lead projects without the organizational authority to advance or make decisions. They often see the need for institutional change but find the path forward blocked and/or hidden. Many of these professionals lack formal leadership training or have not had mentors to foster their success. To be effective leaders, individuals need to fully understand and apply influencing skills; embrace leading communication practices; understand situational leadership techniques; and use the "art of diplomacy" to influence and demonstrate effective leadership.

The Art of Diplomacy: Leading with Influence

The term "diplomacy" can be described in various ways:

- The art and practice of conducting negotiations
- The methods and forms usually employed to reach agreement
- Applying dexterity or skill in securing advantages for you and others
- Tact to produce no ill will in reaching decisions for the betterment of the activity at hand

Diplomacy in the context of leading with influence is very similar to how Eisenhower defined leadership in the epigraph above. Authority in any organization comes from three sources: (1) position, (2) relationships, and (3) a value-based personal approach. Influence is present in all the sources, but very important in the last two.

Leading with influence demands that individuals understand what sources they need to leverage to make an impact on decisions. Most people do not have a position that allows them to make strategic decisions. Therefore, they have to rely on building relationships and utilizing personal influencing skills to ensure their point of view is fully understood and impacts the outcomes that are desired. The key to building strong relationships and personally connecting with individuals is effective communications planning and delivery of messages.

Influence is an extension of the authority needed to make a difference. It is the motivator that people can use to change behavior or attitudes. Unlike direct authority, influence can produce the desired effect without the need to use force or in a control directive such as a command. (Do this or else!) Influence can be used to convince them to pursue a course of action to make an impact.

Hence, effective use of diplomacy is based on how well you influence and communicate what you want to happen, or "the what." The art of diplomacy in a leadership context is grounded in the "how"—how to apply the dynamics of influencing through a plan that communicates how to address and engage with the needs of key stakeholders.

This technical note addresses three core areas that are essential to effective leadership: leadership behaviors that are essential for success; effective communications; and influence without authority. Mastering the methods outlined here will enhance leadership skills.

The Influential Leader—Leadership Behavior and Skill Essentials

Over the last forty years, countless leadership books, surveys, and opinions on what makes a good leader have appeared. A composite review of surveys provides an ability to identify essential and effective leadership skills and behaviors that create an understanding of the qualities needed to be a good leader. The most important qualities for leadership effectiveness are:

1. Communicating/listening to project empathy and passion (skill)
2. Trusting in employees or colleagues to do their jobs well (behavior)
3. Coaching and working collaboratively to develop learning and development (skill)
4. Using common sense intelligence in listening to and interpreting diverse points of view (behavior)
5. Promoting teaming as a vehicle to drive results (skill)
6. Maintaining an even temperament—calmness in the face of a storm (behavior)
7. Displaying flexibility and agility to continuously understand the need to change (skill)

Leaders are made, not born, contrary to the popular belief in a "great" individual theory. A 2013 study published by the American Psychological Association found that "leaders often operate in dynamic and complex social environments that require them to acquire strong perceptive and adaptive abilities in order to make good decisions and be effective" (Hannah et al. 2013). A number of additional studies support the theory that critical leader skills and traits are realized or acquired through the environment in which the individual has lived and/or operates on a daily basis.

The essential skills and behaviors listed above are learned typically through activities or experiences that impart an understanding of the "how" and "when" to apply the skills. Training reinforces the acquired skills and behaviors. A high-level view illustrates how to obtain and/or enhance leadership skills or behaviors (fig. 16.1).

Skills are fostered by providing the organization's associates the ability to experience and learn from situations in which they are placed to lead or participate to accomplish organizational goals. Experiences that contribute to the development of leaders take various forms. Examples include leading or participating in an implementation team that executes tasks and activities; problem solving opportunities that are cross-functional; planning tasks for multiple groups; engaging in research and/or preparedness activities.

FIGURE 16.1. Activities drive behaviors to create and modify the culture of the organization and/or group. Credit: Bob Norris

Leaders should be understood not only as individuals who hold high positions in organizations but also associates inside the organization who command a presence and/or emotional "pull" through factors such as intellectualism, experience, personality, charisma, and/or their ability to accomplish things. In essence, they lead by example. This could also be an individual who lacks organizational stature but to whom others gravitate and/or admire. These "informal" leaders (without the title or senior hierarchical position) are just as important for an organization to help motivate others and to ensure the work is done in alignment with strategies and objectives. Influence techniques apply directly to informal leaders.

At its core, leadership is inspiring people to follow. Good leaders provide their followers with the opportunity to maximize their efforts and to achieve the organization's goals and objectives. The bottom line is that leadership is all about helping others to succeed, whether leaders are formal or informal.

The decision to respect someone as a leader is based on observing what the leader does to understand who the leader is as a person. This observation allows people the insight to determine whether the leader is honorable and trustworthy or a self-serving individual who misuses authority and/or is hypocritical to accepted values and beliefs.

What makes a person follow a leader? This question is constantly asked when evaluating effective leadership. Most people want guidance from someone whom they respect and who can communicate with compassion a clear sense of direction or vision. To gain respect, the leader must be seen as ethical. Studies have shown that trust and confidence in leadership, regardless of position or role, are reliable predictors of success in achieving results for the organization or group and its strategy.

Core principles are integral to a leader's success. A respected leader concentrates on three areas that will result in effective leadership:

- *"Be": who she/he/they is/are*. The leader's beliefs, values, skills, and behaviors that assist in producing the organization's results by motivating its people to achieve and even go beyond expectations.
- *"Know": what she/he/they know(s)*. Breadth and depth of experience in terms of key jobs, critical tasks, and human nature/common sense in "moment of truth" situations.
- *"Do": what she/he/they do(es)*. The ability to inspire and influence implementation; to assure others that you have "walked in their shoes"; and to provide the direction and guidance that are central to the mission—to provide an overall vision.

Maintaining and demonstrating strong, ethically based convictions endows leaders with the credibility and integrity to encourage others to follow. A formal or informal leader who can enact the aforementioned core principles, demonstrate personal accountability, and create a desire in others to strive for excellence and to continuously learn and improve possesses the essentials necessary to be a successful leader.

The Servant Leader Model

Numerous leadership models have been developed and/or outlined that are essential to effectiveness and success. A very fitting model for nonprofit oriented organizations, like a museum and other arts organizations, is servant leadership.

This model encompasses a set of practical philosophies that support leaders who choose to serve their constituencies first, and then to lead as a way of expanding service to their other key stakeholders. Servant leaders may or may not hold formal leadership positions. Leaders in this context can gain their role based on their position in the institution's hierarchy or can "lead from the middle" (i.e., someone appointed to or volunteering to be a team leader), thus serving as an "informal" leader.

The servant leader model attempts simultaneously to enhance the personal growth of workers and to improve the quality and caretaking of the institution through a combination of teamwork and community, personal involvement in decision-making, and ethical and caring behavior. As with other leadership models, this one is defined by core values: listening, empathy, healing, awareness, influence, conceptualization, foresight, stewardship, commitment to the personal growth of those involved, and community building.

These values on a basic level grant the leader a set of principles that will inspire others to strive for excellence. The servant leader's focus is to ensure that the operating environment is safe, encouraging, and fair.

The model is self-evident if the leader holds a position on an organizational chart. If the servant leader leads from the middle, key principles must be considered:

- *Direct Debating*: Facilitating open and honest discussions—putting facts on the table and actively and respectfully working through what needs to be addressed regarding deliverables.
- *Mindful Listening*: Remaining quiet when others are talking and actively listening to ensure that key stakeholder needs and requirements are fully understood. This entails using both your ears and your eyes to attain an understanding of the situation.
- *Walking in Others' Shoes*: Fully understanding the dynamics of the situation for those you are leading to ensure that the demands meet your colleague's capabilities and capacity for success.
- *Valuably Failing*: Acknowledging that "risk" is part of all we do. Leaders will encourage and empower their colleagues to take a chance, be innovative, create, and make things happen, and if these things don't work, the leader will review the results and adjust as necessary to learn.
- *Action-Based Decision-Making*: In other words, rolling up one's sleeves and "getting dirty" in order to complete tasks and activities. The leader in the middle is engaged with their colleagues challenging, nudging, celebrating, coaching, sharing decision-making. This encourages the leader to have candid conversations and take genuine measures to ensure that the team succeeds.
- *Influencing Engagement*: Not directing, dictating, or doing the work of colleagues but rather allowing them to take initiative and work through issues. The leader creates leverage points to encourage their colleagues, cajole, and care for what they are building, what they are doing and, how they do it.

An essential part of being a servant leader, regardless of position, is to teach, mentor, and provide guidance to your employees or colleagues so that they can succeed. Your success as a leader is fully focused on your team or group of colleagues achieving results to meet goals and objectives.

True servant leaders put the welfare of the group ahead of their own self-interest. They know their team and how to influence their team through motivation to exceed expectations. If these core values are enacted, leaders will enhance the capability of their organization by guiding the actions of others to achieve success.

Key Leadership Qualities

There is no standardized model to be an effective leader. A person's attributes and personality will help shape how they lead, and how they can influence others to engage and to meet goals and objectives. A leader's personal traits are established by their activities, and the behaviors and skills acquired in or molded by the environment in which they have lived and operated. Effectiveness as a leader is directly proportional to how well the key qualities are expressed and value is delivered to their constituencies.

These qualities define and measure the success of a leader:
- Maintaining and demonstrating strong convictions
- Developing, communicating, and reinforcing a clear, winning vision
- Building trust through transparency and integrity
- Creating and promoting a high-performance culture through their own visibility
- Believing in service to people—the leader coaches, teaches, empowers, grows
- Convincing rather than controlling
- Building commitment rather than imposing compliance
- Learning continually

Expressing these qualities reinforces the individual's personal values, how individuals respect and value others, and the essence of the personality that they bring to the role.

Communication Strategies and Principles

To effectively influence, a leader must develop an effective communication strategy and then execute on that strategy. The critical part of communications is the up-front planning needed before execution. A successful leadership role requires a communications plan focused on delivering messages in alignment with the needs of the critical stakeholders.

Communication needs to be addressed as being multidirectional. A common mistake by leaders is viewing their communications as unidirectional—communicating in a "command and control" style rather than engaging, asking open-ended questions, and listening. The use of the "bully pulpit" is generally ineffective in building commitment. Active listening is essential for leaders to connect with and influence their followers to identify expectations and requirements. It helps build relationships.

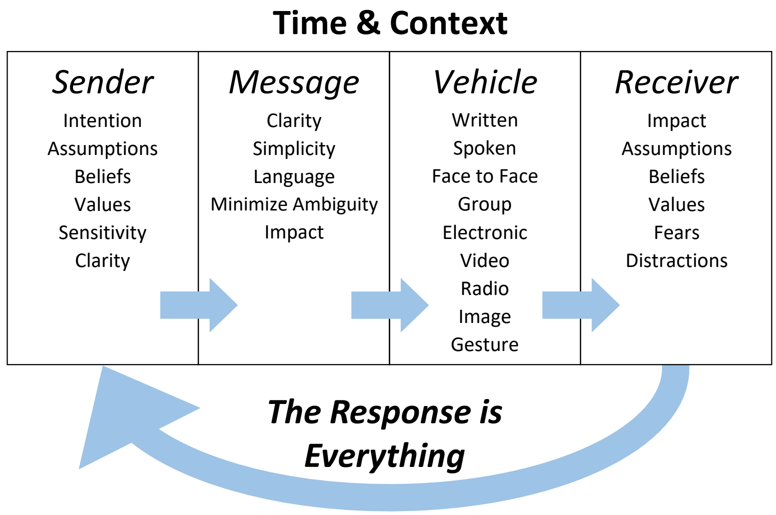
When strategically planning for effective communication, it is all about the messaging. Messages need to be: (1) continuous, (2) candid, (3) consistent, (4) concise, and (5) contextual. If these five essential principles are followed, the receiver's understanding of the communication increases significantly. A leading practice to deliver messages is the "rule of three." This delivery technique is based on the progression of a series of messages to help ensure that what you need to communicate is well understood by the receiver.

Rule of three delivery outcomes are as follows:

1. The message is heard by the receiver.
2. The message is acknowledged by the receiver as being relevant and meaningful.
3. The message is well understood and actionable.

Communications can go bad if the needs of the receiver of the messages are not heeded. This lack of recognition leads to ambiguity and interpretation by the receiver. The sender needs to execute this high-level flow across a time frame with a specific context (fig. 16.2).

FIGURE 16.2. Communications can be thought of as a process from a message's sender to its receiver. Receiving feedback is an essential element for improving a leader's ability to communicate. Credit: Bob Norris

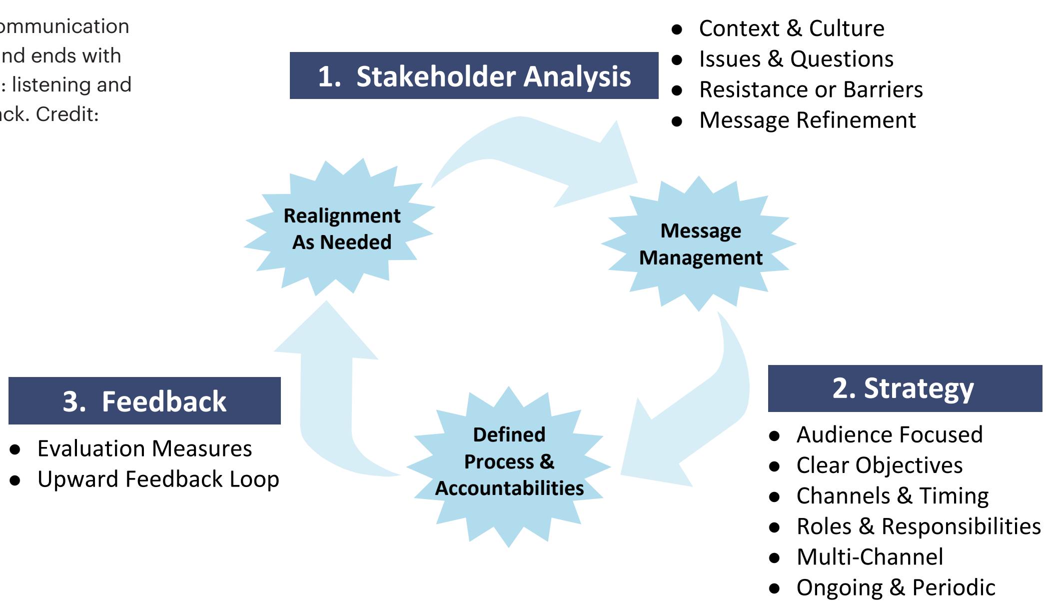


Planning

A communications plan is the result of a group of connected activities. The approach is illustrated in figure 16.3. Focus on identifying the key stakeholders and their needs. A stakeholder assessment asks questions, raises issues, and notes resistance points to help shape the "what" and "how" of the messaging required to influence stakeholders. Once this analysis is done, the next step is to plan out and then execute the communications strategy. The communication effort is complete when feedback is solicited from the stakeholders, either by asking or by realizing actions/results, regarding the effectiveness of the communications.

Stakeholder assessment involves an interview format in which input from stakeholders is sought to probe into the current state of thought relative to the situation, and to look forward to how decisions that impact

FIGURE 16.3. Communication planning starts and ends with the stakeholders: listening and receiving feedback. Credit: Bob Norris



them might be received. Based on the input, a determination is made as to the points of resistance and if stakeholders are willing to follow the leader's direction, or if they are neutral or opposed to the direction. This analysis allows messages to be shaped to influence stakeholders to support the direction that the leader must take to meet goals and objectives.

Communications plans are built with a process mindset (inputs, actions, outputs) that are best defined by the use of a communications plan template (fig. 16.4). The template is an example of how key elements can be addressed in assembling the plan. This template is based on the five aforementioned communication principles and delivered in relation to the rule of three.

Audience: Target Stakeholder Group	Key Messages for Audience	Timing & Frequency Needed	Communication Channels/ Vehicles to Communicate Messages	Owner	Feedback Mechanism

FIGURE 16.4. Communication plan template. Credit: Bob Norris

Communication Principles for Effective Leadership

Critical communications principles should be understood to build, practice, and execute communication strategies. These are:

- *Principle #1*: Leaders need to understand that they cannot attain what is needed from their constituents without effective communication.
- *Principle #2*: Communication is not a "one and done" approach; it must occur in parallel, fully integrated with the overall strategy in the form of a plan. The rule of three is important to achieve this.
- *Principle #3*: Communication should include a rigorous planning process, including assessing stakeholder needs, creating and coaching message delivery, and building feedback loops.
- *Principle #4*: Communication planning in terms of messaging must be continuous, candid, consistent, concise, and contextual.
- *Principle #5*: Communication delivery entails more than selecting tactics according to a prescribed "recipe" of how to deliver messages. Delivery of the communications needs to be varied; it should not be done the same way, using the same vehicle, for all audiences. The approach must be varied to align with your stakeholders' or audience's preferred ways to receive the messages.
- *Principle #6*: Communication is not always to a broad audience; it must be targeted. Effective communication is a two-way process, focused on dialogue with the identified target, who needs to receive and understand the message. If used smartly, the rule of three will ensure understanding.
- *Principle #7*: Communication needs to be measured by the leader to assess its effectiveness.

When executing the communications plan, the individual's communication approach is critical for success. The leader who communicates is accountable and responsible for the messaging based on when and how the message will be communicated. For the messaging to be impactful, the leader should deliver it to the receiver in a form that the receiver will fully understand.

An often overlooked aspect of communications planning and execution is receiving feedback on the effectiveness of the messages. This closes the loop. Feedback improves the ability to communicate. Feedback can be received in myriad ways, including surveys, one-on-one follow-up meetings, and focus groups. Feedback allows leaders to gain an understanding of the messaging's clarity and its value as received by the stakeholder groups. Without measuring clarity and effectiveness, future communications cannot be improved successfully and in a systematic fashion.

The Influence Model at the Heart of the Art of Diplomacy

Influence is the ability to change, direct, or affect the behaviors of others without ordering or threatening them. To be effective, leaders must be open to influence from those they seek to influence. Influencing strategies are defined by the leader's desired outcomes. Outcomes are defined by the agreement of both parties that a "win-win" solution is possible. As mentioned in the introduction and suggested in the phrase "the art of diplomacy," leading with influence is based on encouraging others to arrive at your intended outcome by their own choice.

Influence is based on a key theory that underlies almost all positive human interaction, *the law of reciprocity*—or that others should be repaid for what they do for you. Therefore, at its core, influence is all about trades: providing something of value to one party in return for receiving something that you desire.

In their book *Influence Without Authority*, Allan Cohen and David Bradford (1991; 2005) present an influence model that outlines how leaders can effectively influence decisions and actions to help achieve success through accepted decisions.

The steps in the model (Cohen and Bradford 1991, 20) are:

1. Assume that all stakeholders are friends or allies; this is important until points of resistance are determined.
2. Clarify your goals and priorities to be certain as to what you want to accomplish.
3. Walk in the shoes of the other person(s) who you want or need as an ally.
4. Identify relevant "currencies" that you have to exchange to receive value.
5. Build, nurture, and cultivate relationships that can be beneficial downstream.
6. Influence through give-and-take negotiating or mediating the win-win for each other.

Given the law of reciprocity, the most critical part of the model to help leaders understand how they can influence is the phrase "currencies of exchange." Currencies in the view of Cohen and Bradford represent resources or goods and services that can be offered to a potential stakeholder or in exchange for collaboration and/or support. The authors define the impact of currencies as such: "currencies are the basis for acquiring influence. If you have no currencies in your treasury, you do not have anything to exchange for what you want" (Cohen and Bradford 1991, 36).

Different types of currencies that can be used in implementing the law of reciprocity can be grouped in various categories related to inspiration (e.g., compelling vision); personal connections (e.g., gratitude); position (e.g., reputation); tasks (e.g., resources or organizational support); and relationships (e.g., inclusion, acceptance, friendship) (Cohen and Bradford 1991, 38). Invariably, the leader and follower have more currencies than they realize with which to barter. The individual loses the ability to influence by failing to see the wide range of currency options available to achieve cooperation.

In addition to currencies, another key factor to consider is the leader's respect for the work and team, and expertise or depth of knowledge; positive perceptions in these areas will contribute to the leader's acceptance (and self-acceptance) in this influencing role. In essence, this is the price of admission to influence.

Finally, as noted in the introduction, building both authority and relationships is fundamental to influence. Relationships matter. Influencing is directly proportional to the strength of the relationships you sustain. The better the leader's relationships, the more likely the leader will find the right individuals in the right situation to make the right trades in order to influence outcomes. This can be thought of as the goodwill necessary to obtain what the leader wishes to achieve presently or in the anticipated future.

Approaches to building strong relationships include the following:
- Bringing facts and data to the discussion to support your needs.
- Knowing your colleagues' and your team's strengths—you should understand the culture of your organization.
- Involving all parties in finding solutions through leading with influence.
- Building relationships, which entails anticipating concerns that accompany the fear of losing.
- Seeking solutions that are mutually beneficial.
- Bridging ideas to create unity—consensus strategies motivate cooperation.
- Welcoming conflicting and opposing questions and comments, which create opportunities.
- Seeking opportunities to identify differences and determining ways to resolve the differences.

Summary

Leading with influence involves applying a systematic approach or model to increase the leader's effectiveness. Influence is not persuasion. Influence is not coercion. It should not be perceived as an act of force. The law of reciprocity is at the core of influence; violating this law diminishes the leader's influence. Remember that influence is all about encouraging others to arrive at your intended outcome by their own choice.

As you master these key skills and behaviors remember these points:
- Being a leader is about exhibiting behavior and skills that team members respect and trust.
- Communicating messages that are aligned to strategy and plans will make the messages more meaningful to the receiver.
- Effectively employing the art of diplomacy requires the leader to gain a fuller understanding of others' situations and formulate solutions that satisfy all involved in the decision.
- The law of reciprocity is a powerful way to build commitment from those who are following the leader. Assess the currencies you have to trade and what outcome you as a leader aim to achieve.
- Applying the influence techniques addressed to prioritize goals, identify currencies, and invest personal time developing strong relationships to find solutions that will inspire cooperation, respect, and success.

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CONCLUSION

Cecilia Winter

My first contact with this collection of technical notes was in the classroom, as one of eighteen participants in the inaugural 2017 course *Preserving Collections in the Age of Sustainability*, organized by the Getty Conservation Institute's Managing Collection Environments (MCE) initiative. Shared during the preparation phase of the course, these readings provided me with up-to-date and insightful information on familiar topics, addressed highly complex scientific information, and introduced me to subjects I had never seen associated with collection conservation. The technical notes established a framework of concepts and vocabulary that allowed us to actively engage in discussion with fellow participants, instead of passively receiving new information. At the end of the course, the printed texts continued to serve as reference material, constantly being reread and shared with colleagues.

The MCE technical notes represented the most recent addition to the collection of technical guidance I relied upon and proudly amassed. For the young museologist working with collection management and preventive conservation in Brazil more than twenty years ago, international conservation guidelines and handbooks that could be found online became invaluable resources to implement "best practices" for collection care. Over time, however, I realized that many of these prescriptive practices were impossible to implement in many of the contexts in which I worked, and these readings eventually became the bearers of a great amount of professional frustration.

In my current role as a researcher and educator at the GCI, my excitement in helping realize the MCE technical notes as an online publication—reaching far beyond the 2017 and 2019 course cohort and connected colleagues—is only exceeded by the significant shift in the way recent technical guidance is constructed and presented. While they convey dense technical information, the context of how and when to use this information is equally vital. A reader might even ask if the term "technical notes" understates its content. It is clear that the collection environment topics discussed throughout the MCE technical notes range beyond just a technical matter; they touch upon subjects related to management, communication, negotiation, and organizational structure.

This shift in technical guidance also reflects changes in the way we make decisions related to collection conservation. Initially, our choices were driven by a desire to make objects deemed worthy of preservation "last forever." This need to prevent change at all costs led to the formulation of strict recommendations and a codification of what was considered "best practice," no matter how this limited access to the collection, marred the building fabric, strained staff and budgets, and impacted the environment.

Over the last two decades, a risk management approach has been introduced as a means of developing context- and value-based collection care policies. Risk management allows for the weighing of cause and effect to prioritize mitigation strategies. An important impact of this approach was the application of cost-benefit analysis and the resulting recommendations that resources be directed toward the reduction of the most acute risks, which may not be related to climate. In fact, a possible risk assessment outcome is the realization that climate issues do not pose a relevant risk to the collection and that no action is necessary.

Then why dedicate a course and publication to understanding climate-induced risk? The focus on temperature and relative humidity is not because they pose the greatest risk to a collection, but rather because of the significant investment of effort and resources required for their tight control. The importance of the subject is also demonstrated by the fact that in recent years the collection environment has become the center of conservation debate. Bearing in mind that broadening the acceptable environmental range of mechanical HVAC systems can be an effective means of reducing carbon footprint, this discussion was intensified by the need for the cultural heritage sector to consider its own contributions to climate change.

In 2021, the Joint Commitment for Climate Action in Cultural Heritage, agreed to by IIC, ICCROM, and ICOM-CC, recognized that "the climate crisis represents one of the greatest threats to [cultural] heritage in a world with depleting natural resources, growing inequality and social injustice. In response to these challenges, it is incumbent on all of us to adapt, innovate and pioneer change." This statement demonstrates the importance of sustainable practice by collecting institutions to impact climate change, whether this be self-imposed or mandated by government regulation.

By developing environmental management strategies that apply context-based risk management, including life cycle and life cycle costing assessments, we can begin to grasp ways in which conservation decisions play an active role in financial and environmental sustainability. Similar tools or methods for evaluating and comparing levels and quality of access and use of collection, however, do not yet exist. But we can start addressing inequality and social injustice by recognizing that conservation of and access to objects are not conflicting actions; the maintenance of value and significance of objects and collections is dependent on public and community engagement.

Implementing change is not an easy task. This is particularly true when addressing complicated subjects, and for a field traditionally prone to unconditional safety and risk aversion. The MCE technical notes do not aim to eliminate uncertainty or propose a new set of safe numbers; they provide the reader a path toward unpacking the complexities, defining degrees of uncertainty and risk, and navigating the resulting challenges. Realizing and maintaining this change also requires readers to engage their own perspectives and experiences from practice; this is a crucial step in the application of new information, tools, and skills, and for promoting discussion in which selected strategies must be appropriate for the institution and its collections and building.

And, hopefully, the greatest achievement of this suite of technical notes will be to facilitate the cooperation of collection care and allied field professionals, inspiring them to think and practice preservation beyond loss mitigation at all costs and toward maximizing the value and benefit of cultural collections to people both present and future.

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Glossary

Accuracy: The degree of agreement between the instrument or system value and the true value of the variable being measured. This is important if it is necessary to compare subtle differences in readings from devices at different locations.

Acidification potential: Environmental impact category for life cycle assessments (LCA) that measures emissions that increase acidity of water and soil when deposited, most commonly in the form of acid rain.

Agents of change or deterioration: A conceptual framework to categorize the main causes of change, loss, or damage to collections. The most common format is the Canadian Conservation Institute's (fire; incorrect relative humidity; incorrect temperature; light, ultraviolet & infrared; pests; pollutants; physical forces; thieves and vandals; water), first published by Stefan Michalski in 1990 and later expanded to include custodial neglect (now dissociation) by Robert Waller in 1994. This framework is a major influence on the applied practice of preventive conservation and collection management, especially risk management for cultural heritage collections.

Air handling unit (AHU): Commonly referred to as an AHU, this equipment is composed of a metal container with a fan or fans and other necessary equipment to perform one or more of the following functions: circulation, filtration, heating, cooling, heat recovery, humidifying, dehumidifying, and mixing of air. Air handlers are normally connected to a ductwork ventilation system that distributes the conditioned air through the building and returns it to the AHU.

Anisotropic: A material in which properties such as Young's modulus, ductility, yield strength, and high-temperature creep rate are directionally dependent.

Box plot (or box and whisker plot): 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.

Buffer spaces/zones: An unconditioned part of a building that can act as an effective air barrier and insulation space in a building envelope.

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 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.

Burden shifting: What happens when the choice of one activity may reduce the environmental impact in that phase but increase in other phases of the production or distribution of a product/material. Another kind of burden shifting is when a new, unintended environmental problem is created while solving another (e.g., a cleaning system that has extremely low greenhouse gas emissions may also be highly toxic).

Calibration: Establishing the accuracy of a device through comparison to a known standard and documenting the deviation or adjusting the device to within a range of acceptable accuracy. Calibration is done both prior to and after the use of a device; for long-term monitoring programs, calibration should be checked at the beginning and end of the campaign and at specified intermediate intervals.

Capillarity: The process of a liquid flowing in a narrow space without the assistance of, or even in opposition to, any external forces like gravity. It occurs because of intermolecular forces between the liquid and surrounding solid surfaces. If the diameter of the tube is sufficiently small, then the combination of surface tension (which is caused by cohesion within the liquid) and adhesive forces between the liquid and container wall act to propel the liquid.

Causality: The influence by which one event, process, state, or object (a cause) contributes to the production of another event, process, state, or object (an effect) where the cause is partly responsible for the effect, and the effect is partly dependent on the cause. *See also* correlation.

Change: From the moment of their creation, buildings and objects' materiality undergoes a series of physical and chemical processes that result in changes of state. Most of the changes are inevitable, some are deliberate, and others are the results of accidents. Some can be perceived as unwanted, while others are seen as desirable. Several factors related to the environment, use, and treatment can influence the rate of those changes. Change mechanisms can be classified into three groups: physical, chemical, and biological. *See also* damage.

Climate: The description of the average pattern of weather for a particular region and time period, usually taken over an extended period such as thirty years. It takes into consideration data of precipitation, temperature, relative humidity, solar, and wind speed and direction.

Climate control system: All elements used to manage the interior climate, with a typical 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.

Climate zone classification: Climate categorization protocol that promotes consideration of realistic environmental goals as well as approaches to achieving those goals. ASHRAE Standard 169-2021 uses criteria that are based on temperature, precipitation, heating degree days (HDD), and cooling degree days (CDD) to establish climatic zones, classified using a combination of numbers and letters. Numbers from 1 to 8 stand for: (1) very hot, (2) hot, (3) warm, (4) mixed, (5) cool, (6) cold, (7) very cold, (8) subarctic; letters from A to C stand for: (A) humid, (B) dry, (C) marine.

Commissioning, recommissioning, decommissioning: A quality-control and verification process conducted during the design and after the installation of a new HVAC system to verify and document that the facility and all of its systems and assemblies are planned, designed, installed, tested, operated, and maintained to meet the project requirements. Generally, it is performed by a third-party commissioning agent who was not responsible for the design or implementation. Recommissioning refers to commissioning a previously commissioned system, while retrocommissioning refers to commissioning a never-before-commissioned system.

Consensus decision-making: An effort in which affected parties seek to reach an agreement on a course of action to address an issue or a set of related issues. In a consensus process, the stakeholders work together to find a mutually acceptable solution. *See also* negotiation.

Conservation heating: The use of heating to reduce interior relative humidity. While relative humidity is reduced, the dew point temperature or water content of the air remain unchanged.

Correlation: In statistics, this refers to the degree to which a pair of variables are related to one another, whether causal or not. In general, it is important to look for and analyze correlations, as this is useful for predicting causality, although the existence of a correlation is not enough to infer a causal relationship. *See also* causality.

Cost-effectiveness analysis: A form of economic analysis that compares the relative costs and outcomes (effects) of different courses of action. In conservation, it is often used after a risk assessment and analysis to compare different recommendations to address the identified risks, seeking the maximization of risk reduction for the investment.

Cradle to Gate: System boundary or scope that includes the production portion of the life cycle of an object or action, including raw material extraction and product manufacturing and assembly.

Cradle to Grave: System boundary or scope that includes the entire life cycle of an object or action, including raw material extraction, product manufacturing and assembly, transportation, product use, and end-of-life treatment and disposal.

Creep: The increase of deformation under the influence of mechanical stresses below the yield point of the material.

Cumulative relative frequency (CRF) plot: A graphical description of the distribution of data for an individual variable by which each data point is paired with its CRF, which is 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 interquartile range (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 reside within a target zone.

Damage: In material science, damage is often defined as material failure or the loss of load-carrying capacity. Definitions of damage in the conservation field are still quite varied, but it is widely accepted that "damage is non-beneficial alteration" or "any undesirable change of state."[1] In an effort to explain why one state is more desired than another, authors have argued that damage is a change that invokes some sense of loss and impairment of value, usefulness, normal function, and the benefit that society can derive from the heritage. This definition reveals how what is considered damage is observer- and context-dependent and that not all material change constitutes damage and not all damage consists of material change. *See also* change.

Deadband or set range: An interval of a signal domain or band, defined by a high and low value, where no action occurs, with the purpose of preventing oscillation or repeated activation/deactivation cycles and potentially saving energy.

Design capacity: The maximum load for which a machine, apparatus, device, or system is designed or constructed.

Design day or climatic design conditions: A parameter used to describe a period of time with maximum conditions that an HVAC system was designed to operate and maintain the desired indoor temperature and humidity.

Dew point temperature: The temperature to which air must be cooled to become saturated with water vapor, and below which dew (liquid condensation) or frost (solid deposition) first forms. An elevated dew point value indicates the presence of more moisture in an air parcel. *See also* humidity ratio.

Drift: The change in a reading for a given quantity over time; drift may be a simple shift of all readings over the entire range, or it may be skewed or nonlinear. Drift is important in long-term monitoring programs and in establishing calibration frequencies. The inverse of drift is stability.

Ecotoxicity potential: Environmental impact category for life cycle assessments (LCA) that measures emissions that cause toxicity toward aquatic organisms.

Elastic and plastic regions: In a material that exhibits an elastic-plastic behavior, all deformations undergone by the material while in the elastic region are reversible, whereas changes of material in the plastic region are permanent.

Equilibrium moisture content: The moisture content at which a material is neither gaining nor losing moisture; this is a dynamic equilibrium and changes with relative humidity and temperature.

Error, random or systemic:

- *Random Error:* Statistical error caused by chance and not recurring. Random error occurs when repeating the measurement gives a randomly different result. To quantify random error, the distribution of a set of repeated measurements is required.
- *Systemic Error:* Occurs when the same influence affects the result for each of the repeated measurements and may not be discernible; it is typically not due to chance.

Eutrophication: Environmental impact category for life cycle assessments (LCA) that measures emissions of nutrients that cause excessive growth of plants and algae, leading to depletion of dissolved oxygen in the water. Emissions are mostly nitrates and phosphates and occur primarily from fertilizer runoff and wastewater discharges.

Exfiltration: The uncontrolled passage of indoor air out of a building through unintended leaks in the building envelope (e.g., cracks between wall sections, wall-floor connections, corners, the roof-wall interface, or around windows and doors).

Facilitated meetings: The conscious act of guiding the meeting process so that it stays on course, to make sure everyone participates and to reach the agreed-upon meeting goals. This helps the group have an efficient and inclusive meeting. It also ensures that everyone can be involved in discussions and making decisions. It combines a series of roles and tasks.

Global warming/climate change potential: Environmental impact category for life cycle assessments (LCA) that measures emissions of greenhouse gases (GHGs) in terms of their radiative forcing, or ability to trap and re-radiate energy to the surface through the greenhouse effect. The main GHGs are carbon dioxide, methane, nitrous oxide, and certain fluorinated compounds. The concentration of GHGs in the atmosphere affect the energy balance of Earth, which in turn determines surface temperatures, sea levels, and weather effects such as extreme storms, precipitation, and drought.

1 Jane Henderson, "Beyond Lifetimes: Who Do We Exclude When We Keep Things for the Future?" *Journal of the Institute of Conservation* 43, no. 3, 195–212.

Guideline: Constitutes a principle or advice that may come from a smaller group or an individual. Guidelines are often the result of an individual or specific group responding to an emergent need for direction on specific matters. *See also* standards.

Hotspot analysis: The examination of all the emissions, resources used, and environmental impacts incurred across the life cycle and assigning which processes contribute most.

Human health toxicity cancer/non-cancer potential: Environmental impact category for life cycle assessments (LCA) that measures emissions that cause toxicity toward humans.

Human or thermal comfort: 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).

Humidistatic control: Mechanical equipment operation controlled by humidity set points.

Humidity ratio: The ratio of the mass of water vapor in a given air parcel to its mass of dry air, 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 mixing ratio. *See also* moisture content.

Hygroscopic material: A material with the ability to adsorb and store moisture from the surrounding air. When the relative humidity (RH) changes, a difference in the vapor partial pressure causes the material to absorb or desorb moisture to reach equilibrium. As a result, the material changes by expanding or contracting in volume, becoming sticky or otherwise altered. The list of hygroscopic materials is long: paper, cotton, wood, nylon, polycarbonate, sugars, and many more.

Hygrothermal: Moisture and thermal energy combined, as in flows or loads.

Hygrothermal behavior: In building envelopes, this refers to the movement of heat and moisture. 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.

Hysteresis: The difference in measurements taken during decreasing or increasing change in value for a variable.

Impact assessment: A formal phase in life cycle assessments (LCA) evaluating the environmental impacts that stem from resource use and emissions that are calculated by the inventory analysis. Impacts are calculated according to scientifically peer-reviewed impact assessment methods, which are based on extensive environmental/ecological modeling. Impacts are assessed for multiple midpoints or endpoints, according to the different environmental impact categories defined in the method.

Infiltration: Uncontrolled inward air leakage to conditioned spaces through unintentional openings in ceilings, floors, and walls from unconditioned spaces or the outdoors, caused by the same pressure differences that induce exfiltration.

Influence: Unlike direct authority, influence can produce the desired effect without the need to use force or commands. Knowing how to influence people from the middle is particularly important for collection care professionals, who, in the majority of cases, do not hold a role of high power within the institution.

Instrument system: A device or series of devices for determining the value or magnitude of a quantity or variable, either directly or indirectly. An instrument system generally consists of a sensor, a transmitting means, and an indicating or recording element.

Interpretation: A formal phase in life cycle assessments (LCA) based on findings of the inventory and impact assessment phases of LCA. In this section results are analyzed, conclusions stated, limitations explained, and recommendations provided. Interpretation evaluates the results of the inventory analysis and impact assessment to select the preferred product, process, or service with a clear understanding of the uncertainty and the assumptions used to generate the results. It also considers the completeness, sensitivity, and consistency in the study. The interpretation reports the conclusions and recommendations based on the entire study.

Interquartile range (IQR): *See* box plot.

Isohumes: Lines indicating constant relative humidity, appearing as curved lines in the psychrometric chart.

Isotherms: Lines indicating constant temperature.

Leadership: In traditional managerial views, leadership is usually portrayed as a quality possessed by one individual due to a role of authority or power, or a list of inherent characteristics or traits that make some people natural-born leaders. Recent studies and theories define leadership as the capacity to inspire people to follow and argue that influencing skills, leading communication practices, and situational leadership skills and techniques can be learned.

Life Cycle Assessment (LCA): A multi-step procedure for calculating or viewing the environmental impact of products and systems from cradle to grave. LCA can assist in identifying opportunities to improve sustainable performance of products through informed decision-making.

Life Cycle Costing (LCC): A financial analysis tool that incorporates costs of a project over its lifetime, not just initial capital costs. Future costs are discounted to their present value using an appropriate discount rate and then added to initial costs to find the total project cost.

Life Cycle Inventory: A formal phase in life cycle assessments (LCA) that compiles all resource inputs and emissions to air, water, and soil that occur during the life cycle of a product.

Loss of value: *See* damage.

Material failure: The loss of load-carrying capacity of a material involving cracking (in brittle state) or permanent deformation (in ductile state).

Measurement: Quantifying the value of a variable using an instrument or device.

Measurement range: The range of values of a measured variable over which the instrument is useful. The useful range of an instrument may be limited by its accuracy or precision, or by environmental or physical factors (such as pressures or temperatures that may render the device inoperable or inaccurate).

Mechanical strategies: Environmental control strategies that require an application of energy to change the psychrometric state of the interior air by mechanical systems for heating or cooling and humidifying or dehumidifying.

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. Unlike the average or mean (sum of values divided by number of values), the median is not skewed by extremely large or small values, and may better represent a "typical" value.

Microclimate: The climate of a very small, restricted, or enclosed area, especially one that differs from the climate of the surrounding area. It may be intentional (e.g., conditions inside frames or cases) or accidental (e.g., conditions inside cabinets or between the wall and hanging painting).

Mission statement: Definition of an institution's focus, purpose, and role, as well as its responsibilities to the public and its collections. Some organizations also choose to develop vision and value statements as a way of extending the concepts expressed in the mission statement.

Moisture content: The mass of water in the material divided by the mass of dry material. *See also* humidity ratio.

Monitoring: Recording and collecting measured data in a systematic, consistent, and repetitive manner with accuracy and precision.

Moving average: Calculation of the average of a specified measured quantity (e.g., temperature or humidity) at a given point in time and over a defined period (e.g., 24 hours, 7 days). A moving average is commonly used to smooth out short-term fluctuations and highlight longer-term trends or cycles. Moving averages, particularly with respect to relative humidity, can be more relevant to objects with slower response times.

Negotiation: A strategic discussion between parties with different perspectives to resolve a discrepancy in a way that all find acceptable. It is a process by which compromise or agreement is reached while avoiding argument and dispute. Negotiations have many forms and outcomes, but an outcome of a meaningful agreement can be considered a consensus. *See also* consensus decision-making.

Nonlinearity: Variation in the sensitivity or input/output relationship for an instrument or system.

Nonmechanical strategies: Environmental control strategies that do not involve energy-driven mechanical intervention. They often use fixed and operable elements of the building envelope to moderate or amplify the effects of external thermal, moisture, and convection loads on the interior environment, or passive solutions, such as the use of silica gel. Nonmechanical strategies often require periodic adjustments, like the manual operation of window shades.

Occupant load: The total number of people who might occupy a building or space at any given time. Occupant load can raise the T and RH of a space and also require more air circulation to maintain the carbon dioxide levels.

Ozone depletion potential: Environmental impact category for life cycle assessments (LCA) that measures emissions of substances that lead to a decrease in the concentration of ozone in the stratosphere, or the ozone layer. This layer of gaseous ozone protects life on earth by absorbing harmful ultraviolet radiation from the sun, and thus helps to prevent skin cancer.

Passive strategies: Often used to describe environmental management features of a building, rather than a building system, such as HVAC.

Percentile: Expression of 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.

Power/interest matrix: A tool used for mapping stakeholders and establishing communication strategies. After identifying the individuals, they are plotted on a grid with four quadrants that map their power and interest in relation to the project. The recommended strategies for those with high interest and high power is to regularly engage, collaborate, and manage closely; for those with high interest and low power, to actively consult and involve; for those with low interest and low power, to keep informed and monitor; and for those with low interest and high power, to consult, keep informed, and maintain interest.

Precision: The degree of agreement between successive measurements for a constant property. Precision is important if it is necessary to draw conclusions from differences in values from the same instrument or system over time.

Predesign brief: A statement of qualitative and quantitative requirements that defines what tasks need to be accomplished, describing the specific outcomes, a prototype development, the scope of the project, the expected schedule and timeline, budgets, possible constraints, risks, and unknowns.

Proofing/proofed fluctuation/object memory: The largest RH or T fluctuation cycles 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 graphic depiction of the suite of 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 identical in content with the psychrometric chart but differs in appearance.

Psychrometric strategies: Application of strategies to modify the environmental conditions of a parcel of air, including cooling, heating, humidification, and dehumidification. These strategies can be mechanical or nonmechanical in nature, and are associated with an overall directionality on the psychrometric chart: movement to the left indicates cooling, movement to the right indicates heating, upward movement indicates humidification, and downward movement indicates dehumidification.

Range: 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).

Relative humidity (RH): 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. Expressed as a percentage (%), 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.

Resolution: The smallest change in a measured variable that will result in a response from the instrument. This is important if it is necessary to measure small changes, though this may be less than the accuracy of the instrument.

Risk analysis: Analysis of the degree of a certain risk, which 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 than others.

Risk assessment: Used by many organizations (alongside 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.

Risk management: A popular decision-making approach in heritage preservation, with various techniques and methods developed and applied in the past decade. The process consists of a cycle with steps such as establishing the context, identifying, analyzing, evaluating, and proposing a plan to treat risks. It also encompasses continuous communication, consultation, monitoring, and reviewing.

Sensitivity: The ratio of the instrument output signal to a change in the measured variable. Sensitivity is important in assembling an instrument system, since the sensor, transmitting device, and indicating/recording device should be well matched with respect to sensitivity.

Sensitivity analysis: A tool commonly used during the interpretation step of life cycle assessments (LCA) to study how the mathematical model reacts when key inputs vary due to measured or estimated uncertainty of the model.

Sensor: Device that responds to change in a variable of interest, producing a signal that changes in value in a known and consistent relationship to the change in the variable of interest.

Service life: The expected lifetime in service, or acceptable period of use. It is the length of time that any manufactured item can be expected to be "serviceable" or supported by its manufacturer.

Set point: A reference condition (typically temperature or relative humidity) set by a control device that activates mechanical air conditioning equipment.

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.

Significance: Encompasses all of the qualities, values, and meanings that people and communities bestow on heritage and endows the heritage with the importance of being preserved. Significance also helps emphasize the potential of collections, creating opportunities for communities to access, benefit from, and enjoy heritage. *See also* value.

Smog formation: Mixtures of pollution in the lower atmosphere produced by the reaction of hydrocarbons and nitrogen oxides when exposed to sunlight. Especially harmful smog components include ozone, peroxyacyl nitrates, and various aldehydes.

Spot reading: A measurement that has 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.

Stack effect (thermal): The movement of air in a building due to differences in temperature. Warm air rises and cool air falls.

Stack effect (vapor pressure): The movement of water vapor molecules due to differences in vapor pressure. Vapor pressure is a function of the amount of moisture in the air as well as the temperature of the air.

Stakeholder map: A visualization that prompts consideration of the sphere of influence of several stakeholders that will help to assess how their interests and expectations should be addressed and managed in a project.

Standard deviation: A measure of how dispersed the data are in relation to the mean. A low standard deviation indicates that the values tend to be close to the mean of the set, while a high standard deviation indicates that the values are spread out over a wider range.

Standards: A means of measuring status or performance for evaluation. They are usually established by consensus and approved by a recognized body with the aim of providing guidance or characteristics that can be repeated or followed to promote order and good practice in a given context. *See also* guidelines.

Stress and strain curve: Stress is a measure of an external force acting over the cross-sectional area of an object. Strain is the measure of relative deformation of a material submitted to a force. The relationship between the stress and strain that a particular material displays is known as that particular material's stress-strain curve. It is unique for each material and is found by deforming a sample at a constant rate and measuring the corresponding load at different time intervals (or different extensions). The same material may also produce different results under varied environmental conditions and rates of loading.

Stress relaxation: A decrease in stress in response to constant deformation generated in the material over time.

Subgrade: This indicates that the interior floor is below the surface of the exterior ground around a building.

Supply and return air ducts: Ducts that conduct air to/from HVAC equipment and the spaces being conditioned.

System boundary: Defines the scope of a life cycle assessment (LCA) study, specifically the processes included and excluded and the emissions considered.

Target conditions/zones: 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 nonpublic), purpose (exhibition or storage), or material composition of objects.

Temperature, dry bulb, and wet bulb:

- *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.

Time series plot: 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.

Transmitter: Converts the signal to a usable form, either digital or analog, and may include the wires or circuitry between the sensor and the indicating/recording element.

Use (original or interpreted): Utilization or employment for a specific aim or purpose. Objects and buildings were often created for a specific original use. Over time, they become valuable and significant for reasons that may be quite different than their original purpose. This can be called an interpreted use. It implies utility, but not necessarily consumption.

Value: Refers to the meanings, positive characteristics, or qualities perceived by certain individuals or groups in objects, collections, buildings, sites, landscapes, and intangible expressions of culture that transform them into heritage. There are many classifications of values, such as historical, aesthetic, artistic, economic, social, scientific, and spiritual. They are sometimes divergent, vary for different individuals or groups, and are not immutable over time. *See also* significance.

Values-led organizations: Organizations whose values support its vision, shape its culture, and reflect its priorities. Often employees find alignment between their personal values and the organization's values. They are normally in the nonprofit sector and noncommercial settings.

Weather: Short-term changes in the atmosphere in terms of temperature, humidity, precipitation, cloudiness, brightness, visibility, wind, and atmospheric pressure (high or low).

Weather stripping: Materials that fill the spaces between doors and door frames or window sash and window frames.

Yield point: A point in the stress-strain curve of a material that defines the separation between the plastic and elastic regions. *See also* elastic and plastic region.

Young's modulus or elastic modulus: The slope of a material's stress-strain curve in the elastic deformation region, which defines its stiffness or its resistance to being deformed elastically. The higher the modulus, the stiffer the material and the more force needed to deform it.

Zoning: A means of controlling the T and RH for each area, or "zone," in a building rather than having to heat/cool or humidify/dehumidify the whole building to the same settings. Each zone needs to have a dedicated AHU, but they can also be "sub-zoned" through the use of equipment such as variable air volume (VAV) boxes, downstream reheat coils, and downstream humidifiers that are placed in supply air ducts, often near the space served.

About the Authors

Vincent Laudato Beltran is a scientist at the Getty Conservation Institute and active in the GCI's Preventive Conservation research group and Managing Collection Environments (MCE) initiative. His research and teaching efforts include advancement of microfading tester practice, evaluations of packing case performance during transport, and environmental management in hot and humid climates. Vincent was an instructor for the MCE course *Preserving Collections in the Age of Sustainability*, and participated in the 2019 revision of the ASHRAE chapter "A24—Museums, Galleries, Archives, and Libraries." He is a co-author of *Tools for the Analysis of Collection Environments: Lessons Learned and Future Development* (Los Angeles: Getty Conservation Institute, 2022). Vincent holds a BS in general chemistry from the University of California, Los Angeles, and an MS in oceanography (geochemistry) from the University of Hawai'i at Mānoa.

Walt Crimm brings forty years of experience working with cultural institutions, providing expertise that is visionary and focused on sustainable outcomes, intellectually, fiscally, and environmentally. His approach is based on a foundation of thirty years as an architect designing museums around North America and Asia. Over the past decade, Walt has focused on planning and in-depth investigations of strategic utilization of space, recognizing that a programmatic voice linking ideas and content with architectural expertise adds a dimension of understanding that can be achieved with an organization's resources. For Walt, planning is not an abstract exercise. It is a process of engaging stakeholders in approaching experiences through a visitor's perspective driven by institutional leadership and community needs. He is the co-author of *Planning Successful Museum Building Projects* with Martha Morris and L. Carole Wharton (Lanham, MD: AltaMira Press, 2009) and co-founded the Building Museums Symposium, which focuses on supporting informed planning and design for museum professionals.

Dr. Matthew Eckelman is an associate professor of civil and environmental engineering at Northeastern University, and an adjunct associate professor at the Yale School of Public Health. His research laboratory builds data-driven life cycle assessment models and tools for rapid sustainability analysis, with a focus on chemicals and low-carbon materials. He is the CTO of the green engineering firm Sustainability A to Z, and has fifteen years of environmental consulting experience with Fortune 500 companies, industry associations, and public agencies. Based on his collaborative work with conservators, he was awarded the American Institute for Conservation Special Recognition Award for Allied Professionals in 2019. Dr. Eckelman worked previously for the Massachusetts Executive Office of Energy and Environmental Affairs and holds a PhD in chemical and environmental engineering from Yale University.

Jane Henderson, BS, MS, PACR, FIIC, is a professor of conservation and the secretary general of the International Institute for Conservation. Jane was delighted and honored to win the Plowden Medal in 2021. I have, through my career, variously been described as "consistently underperforming," "helpfully provocative," and offering "outstanding leadership." I hope this inspires you to turn to those who lift you up whenever you can. My career has been an odd mixture of continuity and instability. Whenever I haven't understood how or why something is the way it is I have tried to investigate, understand, and explain it. This hasn't always been easy, but it has always been fulfilling. Recently, I have been trying to challenge what I consider to be inherent biases of conservation based on an unquestioning service to the future and a false sense of the possibilities of neutrality.

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

- Sustainable environmental management for museums and collections
- Investigation, monitoring, analysis, and assessment of historic buildings and their envelopes
- Engineered stabilization and relocation of large museum objects

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

Jeremy Linden has been the principal of Linden Preservation Services, Inc., since 2017. He is an active educator and consultant, and works closely with colleagues in libraries, archives, and museums on issues of material preservation, mechanical system performance, energy savings, and sustainability. At the Image Permanence Institute, Jeremy served as a co-instructor for more than thirty workshops and webinars on sustainable preservation funded by the National Endowment for the Humanities. He was also an instructor for the GCI's Managing Collection Environments (MCE) initiative course *Preserving Collections in the Age of Sustainability*, and has recently taught for ASHRAE, the Society of American Archivists, American Institute for Conservation (AIC), American Alliance of Museums (AAM), Northeast Document Conservation Center (NEDCC), Lyrasis, and others. Jeremy is a co-author of recent standards and guidelines from ISO, ASHRAE, and SAA, and is a member of the first Sustainability Task Force for the American Association of State and Local History. Jeremy earned an MLS in information studies and an MA in history from the University of Maryland, and a BA in history from Vassar College.

Michał Łukomski is head of Preventive Conservation research at the Getty Conservation Institute, which assesses the effects of environmental conditions and lighting on museum objects. He received his PhD in physics from Jagiellonian University in Krakow, Poland, in 2003, and completed his postdoctoral fellowship at the University of Windsor in Canada. For the last several years, he has worked on describing quantitatively the response of hygroscopic materials relevant to collections of fine and decorative art—in particular, wood, textiles, animal glue, gesso, and paints—to variations of climate conditions using several scientific methods. His current area of research focuses on the mechanical characterization of historic materials and their response to changes of environmental parameters, as well as monitoring microchanges in art objects using advanced nondestructive techniques.

Bob Norris is an independent consultant focused on business transformation and leadership agility. He has more than forty years of experience in the practice of how to develop and deploy continuous improvement and sustainability in organizations, as well as strategy development, leadership and teamwork, and organizational change management—communication and adoption. Bob has worked as a senior director for PwC leading a consulting practice; a senior leader at Deloitte directing the company's internal consulting group; a senior vice president of business improvement at AIG's Property & Casualty business unit; and the business improvement director for a multinational chemical and pharmaceutical company. Recently, Bob has focused on the cultural arts by delivering leadership workshops for the American Institute for Conservation (AIC), International Institute for Conservation (IIC), APOYOnline, the Getty Conservation Institute, and the Winterthur Museum, Garden & Library, where he has consulted on strategy development as well as integrating leadership concepts into daily work in preventive conservation/facilities management. He has an MBA concentrating in organizational behavior, and a BS in accounting.

Sarah Nunberg is an objects conservator in Brooklyn, New York, treating a range of cultural heritage materials while focusing on preventive care and sustainable environmental management. Sarah works with life cycle assessment (LCA) for sustainable practices in cultural heritage as a principal investigator for a National Endowment for the Humanities grant to create Sustainability Tools in Cultural Heritage (STiCH). Sarah teaches materials properties at Pratt Institute and was awarded the 2021–22 Adele Chatfield-Taylor Rome Prize in historic preservation and conservation for continuing her work with LCA. Sarah received her advanced certificate in conservation and her MA in art history from the Conservation Center of the Institute of Fine Arts, New York University, in 1994 and her MA in archaeology from Yale University in 1990.

Joel Taylor is a senior researcher at the Norwegian Institute for Cultural Heritage Research (NIKU) in Oslo. He was senior project specialist at the Getty Conservation Institute, where he was co-manager of the Managing Collection Environments (MCE) initiative and designed and directed the *Preserving Collections in the Age of Sustainability* course. Prior to that, he was a researcher at NIKU; a researcher, lecturer, and course director at University College London; a senior collections conservator at English Heritage; and a conservator at the National Museums and Galleries of Wales. He is a trained conservator and has a PhD related to preventive conservation.

Cecilia Winter holds a BA in history and a Specialization in museum studies from the University of São Paulo in Brazil, and a BA and MA in painting conservation from the University of Paris 1 Panthéon-Sorbonne. She has worked as a registrar and a conservator in Brazil and France since 2004, focusing on preventive conservation and collection care, documentation, exhibitions, and loans. Before joining the GCI's Managing Collection Environments (MCE) initiative in 2022, she was the head of the collection and conservation department at the Museum of Art of São Paulo, and a preventive conservation instructor in the collection management MBA at Associação Brasileira de Gestão de Cultural and Candido Mendes University in Rio de Janeiro.

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