C2P HANDBOOK: DRAFT VERSION

I. CLIMATE2PRESERV

CLIMATE2PRESERV

Collections · Buildings · Systems

Climate2Preserv (C2P) is a project that aims at developing a protocol that helps cultural institutions explore different energy saving strategies considering their collections, building, systems, and more. The project contributes to the ongoing international efforts on preventive conservation and environmental sustainability.

This document is a collaboration between the Sustainability unit of the Royal Institute for Cultural Heritage (KIK-IRPA, Belgium), the Building Physics and Sustainable Design Unit of the Catholic University of Leuven (Leuven, Belgium), the Building Energy Monitoring and Simulation (BEMS) Unit of the University of Liège (Arlon, Belgium)

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C2P integrates the findings of Resilient Storage. a pilot project focusing on small to mid-size museum depots. C2P helps museums reduce their energy consumption while improving their collection environments. The focus lies on short-term improvements with a relatively low cost. This project was funded by the department of Culture Youth and Media of the Flemish Government, Urban Brussels, and the Federation of Wallonia-Brussels.

Brussel, June 2024

IRPA KIK Royal Institute for Cultural Heritage · KU LEUVEN · LIÈGE université

belspo · ICCROM · Loterie Nationale Loterij

This is a draft version of the Handbook that will be published with corrections and additions as part of the Climate2Preserv (C2P) project.

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TABLE OF CONTENTS

I. Climate2Preserv

INTRODUCTION

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Cultural heritage institutions tasked with collection care have sustainability integrated within their thinking. Implementing long-term strategies that benefit the preservation of movable and immovable heritage for future generations is at the heart of their mission. It should therefore not be surprising that global and local sustainability — be it of a social or ecological nature — is a theme that finds strong support within the sector.

While sustainability is a relatively new (trending) word, sustainable initiatives have always been inherently present in the sector on different levels.

Since the Paris Climate Agreement (2015), ecological sustainability has become a must for cultural heritage institutions. Policy makers have attempted to implement measures, often in the form of either regulations for new builds and refurbishments or subsidies for energy-saving measures and initiatives.

However, many of these policies have a 'one size fits all' approach, often targeting industries and ('newer') residential and commercial buildings. When it comes to energy reduction for cultural heritage institutions, we have to conclude that expertise is lacking. Where expertise does exist, it can be hard to integrate broadly due to the unique nature of many of the buildings concerned.

The preservationist view for which we care for our, often centuries old heritage, has changed as well. In regards to collection care a significant shift occurred after the Second World War. Many collections were temporarily housed elsewhere — hidden, sold, or stolen — and often stored in spaces with very particular climates. Objects hastily stored in caves, mines, bunkers, and larger or smaller often underground spaces often came out surprisingly undamaged. The conclusion was that a stable climate without extremes (in both temperature and relative humidity) had been beneficial for their preservation. This observation was combined with mechanical damage observed after the introduction of central heating in public spaces (roughly a century earlier), which caused indoor air to dry out and led to damage such as cracks in panel paintings.

> *"… (given the limited possibilities) one was forced to experimentally set a certain temperature and relative humidity that was applicable to all works of art, including paintings. We arrived at ± 60% and ± 15°C. … (taking into account) the thermometric and hygrometric conditions in our regions, they should not exceed 70% — the threshold value for mold formation. … (Further practical constraints) led us to keep humidity mostly stable (let's say about 10% above or 10% below the — existing, chosen, average — number)."*
>
> P. Coremans, D. Sc. (1946)

Further research showed the benefits of certain climates in relation to the preservation of specific materials. Additionally, technical advances in climate control made it possible to achieve stable temperature and humidity at a relatively low energy cost. This made many cultural heritage institutions invest in systems to do more than just achieve visitor comfort (mostly achieved by heating). Adding and removing moisture — humidification and dehumidification — became a well-known practice in museums. However, humidification processes are still less well-known by HVAC technicians, and when it comes to determining their impact on energy use, they are often ignored by current analytical systems.

Many of these complex climate control systems were installed during the 1990s (in the European Union). Purpose-built buildings from around that time were often designed to rely entirely on these systems. Historical buildings, on the other hand, have often undergone heavy adaptations to integrate these systems in a relatively invisible way.

After dealing with these systems for over thirty years, it has now become clear that they have a significant impact on many institutional budgets. Heating, Ventilation and Air-Conditioning (HVAC) and other complex climate systems require substantial energy, maintenance, expertise, and space. Furthermore, when combined with older, more historical systems in the museum, achieving optimal control is a challenge. Lastly, annual or more frequent system failures seem to be no exception for many cultural heritage institutions. When striving for narrow indoor climate set-points, this can cause rapid and large fluctuations in both temperature and relative humidity.

Cultural heritage buildings often face the same challenges as public buildings in general: they are not the owner of their building and therefore have to consult with stakeholders to achieve certain goals. It is therefore important that they succeed in efficiently communicating with the building owner, the entity responsible for system maintenance, and the entity that pays the electricity bills (if these are not their own responsibility).

The conclusion is that saving energy is a quadruple challenge for museums caused by their tasks in collection care and their complex buildings, systems, and stakeholder communication. Solving the big 'energy savings puzzle' therefore benefits from an approach that is interdisciplinary and supported by management. Ideally, this challenge is faced by a person representing building and/or systems and one representing collections. They are responsible for informing and involving management and other stakeholders, internal and external, when needed.

Because of these challenges, Climate2Preserv (C2P) is focused on building bridges, creating interdisciplinary understanding, and offering tools and templates to perform specific tasks.

THE CLIMATE2PRESERV PROTOCOL

Author: Annelies Cosaert

The Climate2Preserv (C2P) chapter introduces a practical protocol designed to help cultural heritage institutions reduce energy consumption while maintaining or improving the preservation conditions for their collections. This chapter is your roadmap for navigating the complex challenge of balancing sustainability with collection care, it will:

- Explain the Climate2Preserv concept and boundaries
- Go over the essential steps of an energy savings project following the Climate2Preserv protocol. This can be used in a flexible or modular way to tackle both long or short term projects and/or focus on one specific energy savings strategy.
- Give an introduction to the available materials that can be used to support energy savings projects for cultural heritage institutions.

1. The basis

- T: Temperature
- RH: Relative humidity
- Indoor climate set-points, 'band': the targeted indoor climate for collection preservation
- (Climate control) systems: refer to all systems, passive or active, that can influence the indoor climate.
- HVAC: Heating, ventilation, and air-conditioning (systems)
- Building envelope: refers to the 'skin' of the building. The barrier between indoors and outdoors.
- kWh or MWh: is an energy equal to one kilowatt (kW) sustained for (multiplied by) one hour, commonly used in billing for delivered energy to consumers. 1000 kWh is 1 MWh.

1.1 Concept

Climate2Preserv approaches energy savings in cultural heritage institutions through an integrated methodology that recognizes the interdependence of four key elements: buildings, systems, collections, and energy use. Rather than addressing these components in isolation, the protocol acknowledges that interventions in one area inevitably impact the others, requiring careful consideration and balance.

Climate2Preserv proposes a method or protocol that is constructed around six basic concepts:

- It focuses on reducing global energy consumption, not (solely) on a reduction of CO_2 emissions.
- It starts from an existing context. So, while some aspects of the protocol can certainly also be used to formulate requirements for a new build, it is not its sole aim.

— It focusses on keeping collection risk at the current level unless a reduction of (specific) risk is required.

— It strives at respecting an institutional mission but can give suggestions to change practices with a current big impact on energy consumption.

— It can give preference to maintaining robust and resilient indoor climate systems and practices, even if powered by fossil fuels. This thinking takes into account the energy cost of manufacturing system hardware and its impact on global energy consumption.

— It requires a motivated team with both technical and collections backgrounds and support from management.

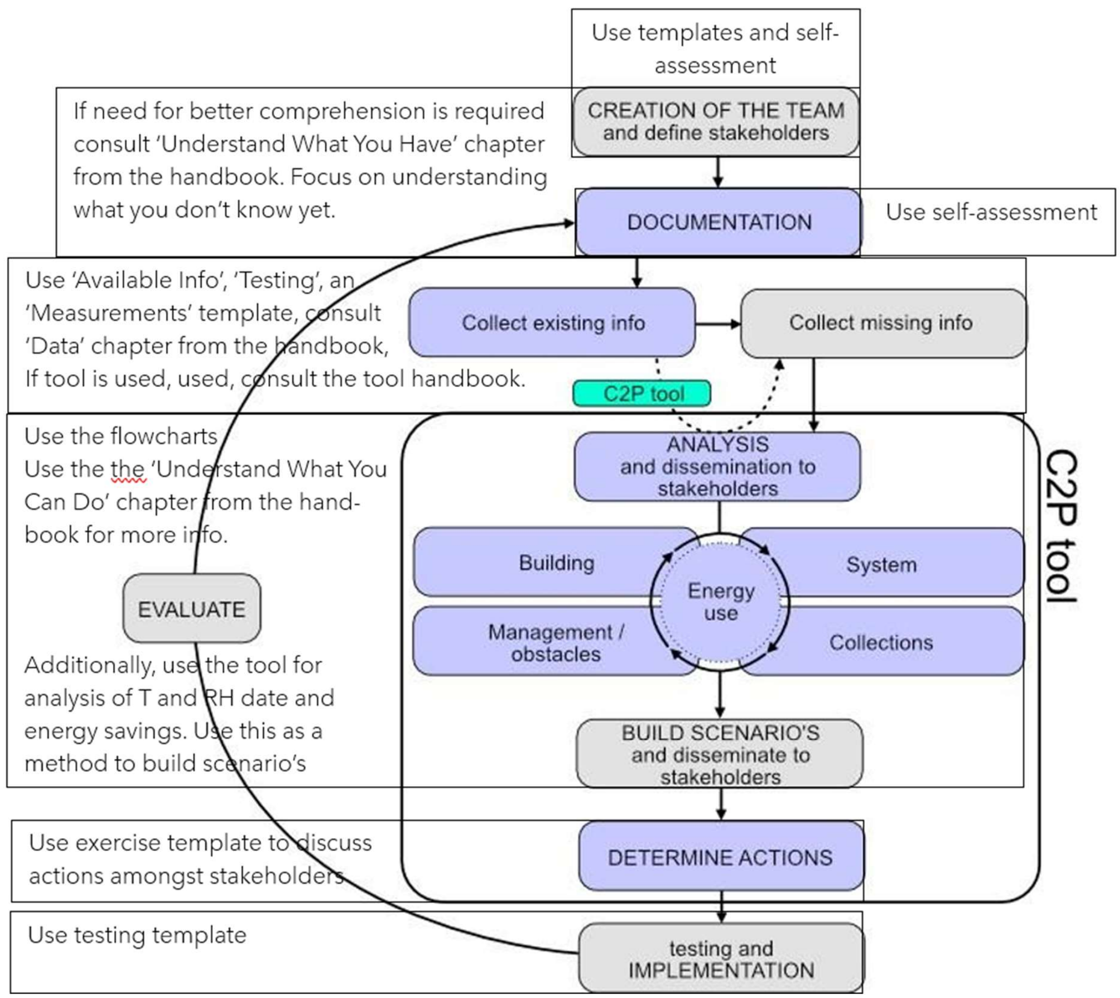

Fig. xxx: correct and improve image. Consider creating an interactive pdf version.

Based on the presentation and project development, Climate2Preserv emerged from practical experience working with Belgian cultural heritage institutions. Through case studies with the Royal Museums of Fine Arts, the Wiertz Museum, and CINEMATEK, the project team identified what heritage professionals know, what they don't know, and where they need help. This grounded approach revealed that while facilities staff understand technical systems and collections staff understand preservation needs, each group lacks sufficient knowledge of the other's domain. Both struggle with data analysis, and often, neither fully grasps how buildings, systems, collections, and energy interact as an integrated whole.

These knowledge gaps translate into six recurring challenges that shape the project's response: stakeholder fragmentation (where building owner, facility manager, energy bill payer, and collections responsible are different entities), interdepartmental communication barriers, organically grown system complexity that's poorly documented, lack of in-house analytical capacity, difficulty communicating with external contractors, and value-based constraints in historic buildings that limit intervention options. Rather than attempting to solve every challenge, C2P honestly identifies which are persistent "pain points" requiring ongoing management (stakeholder complexity, high-end system expertise) versus which can be addressed through knowledge-building and practical tools.

Conceptually, C2P functions as a bridge-building project: between disciplines, between existing knowledge and needed expertise, between current constraints and future possibilities. It scales solutions to match institutional capacity, offers modular tools that can be used independently or as part of the complete protocol, and focuses on what staff can control—maintenance, data collection, incremental testing—while clarifying when external expertise becomes essential. By starting from real institutional challenges rather than idealized solutions, the project creates realistic pathways for reducing energy consumption while maintaining collection care standards.

1.2 Short / long term or modular protocol

Based on your goal, it will be more interesting to follow the short/long version of the protocol or just strive to implement one measure at the time based on opportunity. While either version can be tried at different times, it could be interesting to start with a small scale / short-term project, and scale-up afterwards.

The short version of the protocol will help you identify possible energy saving measures in the short-term. It focuses on adaptations of the climate system or climate settings and changes to the collections level. While it is possible to do limited work on the building envelope, it does not include recommendations on retrofitting options etc.

The long version helps you formulate requirements for building changes and system renovation or renewal. It is important to understand that changes to the building envelope or fabric are the costliest and most challenging, but, when executed well, have the most long-term impact. When considering changes to a building envelope, the envelope requirements are formulated before the climate system requirements. The required capacity of the system is dependent on the quality of the building envelope. It is important to mention that these types of changes often (almost always) require external help. Architects and / or (system) engineers should be consulted.

The modular version is the version in which we envision this handbook might be used most frequently. Museums are most often small to midsize institutions with employees having a series of diverse tasks that requires a varied expertise. Therefore, in reality, we see that becoming more sustainable institution is rarely a complete trajectory and more often a matter of opportunity. Therefore C2P also focused on the creation of tools to facilitate addressing the most opportunistic energy saving strategies.

2. Materials

All materials created for this project, as well as existing tools and methods referred to, are to be considered as a toolbox. While they can be used to complete the protocol, they also have a purpose of their own. Materials were collected or created based on the topics

2.1 The handbook

This handbook gives a theoretical background and guidance to explore the topic of energy savings. It is divided into a theoretical part, a part about data gathering, and an introduction to templates and tools. While it can be used by anyone in the cultural heritage sector, the separate sections have a particular goal. Therefore the recommended way in which to use it is the following:

1. C2P PROTOCOL
   — Understand the protocol and the materials
2. THEORY: BUILDINGS, SYSTEMS, COLLECTIONS and ENERGY
   — Understand what you have
   Read the relevant chapter (your expertise), more importantly read basics about allied fields
   — Understand what you can do
   Discover what you can do within your own field and consider the impact on allied fields. From maintenance to long term measures.
3. DOCUMENTATION AND DATA: COLLECTION AND MEASUREMENT
   — Basic rules for formulating research questions, documentation and data management, data collection, collecting spatial information on floor plans and performing tests
   — Required documentation, measurements and equipment from essential to relevant

The chapters two and three are subdivided in four parts: buildings, systems, collections, and energy. Every one of those chapters is written for project collaborators that work in the other field (e.g., the 'collections' chapter can give the HVAC technician further insight into needs for collections).

While this theoretical part will not turn you into an expert, the goal is not to turn an engineer into a conservator and vice versa, its goal is to better understand the other parties involved.

2.2 The C2P flowchart: 'Define sustainable indoor climate for cultural heritage preservation in an existing building'

The poster 'Define Sustainable Indoor Climate for Cultural Heritage Preservation in an Existing Building' is a flow chart that serves as a guideline to define a indoor climate based on real collection risk in relation to budgetary means, capacity building envelope and more. This poster was created to as the most FAQ: how do I determine new set-points for my institution that don't pose risk to my collections. While this poster focusses on the decision making process, the Climate Energy Assessment for Museums tool focusses on putting numbers to the potential savings.

2.3 The C2P tool: Climate Energy Assessment for Museums (CEAM)

The C2P tool can be used to give an idea about different energy saving options. It can be used to:

- Test the accuracy of the results in relation to the available data and consult on how to improve your predictions.
- Compare your actual energy use to the predicted energy use based on the indoor and outdoor climate.
- It can compare your climate to the ASHRAE Climate classes[1] and predict potential energy savings when compared to other climate classes. It can do this for different functions (heating, ventilation, cooling, humidification) or total energy use, based on the data available.

The C2P tool gives an indication on potential energy savings based on your data. While it can do this for a whole building or for specific rooms, it is important to have a clear overview of which systems use which energy to control which rooms. Other exercises in this handbook can help you with that.

2.4 Templates

Templates are developed to help select and structure information that could be collected for a specific task. They can be considered as data repositories as well. They are based on good practice but are merely examples and can be restructured to be complementary with the way you work internally.

2.5 Other tools and methods

When applicable, C2P refers to existing tools within or in relation to the field of cultural heritage.

3. The protocol

3.1 Create the team and identify stakeholders

The creation of the team is an important first step. This can be both an internal exercise as a very natural teaming up of internal and external stakeholders with similar interests.

However, a team is formed, it is helpful to think about the following things:

- Define your goal, do you want the same things in the short-, mid-, and long-term.
- Depending on the size of the team, identify one or two contact people.

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[1] See 'Chapter II: Theory, Collections, International guidelines and standards' for more information on the ASHRAE climate classes

- Meet regularly to work on specific topics. It can be interesting to create moments where you work in close proximity, focusing on the same topic from two perspectives.
- Learn to know each other's priorities, not only on a project basis, but also for each other's teams / departments in the short-, middle-, and long-term.
- Show respect for each other's knowledge but strive for understanding. Use the same vocabulary.
- Create awareness amongst colleagues about the project.

Information about stakeholders can be logged in a simple STAKEHOLDERS template.

3.2 Documentation

Collect available information

Once your goal is defined and all stakeholders are informed and in agreement, the collection phase can start. During this phase, it is important to collect information about the building, collection, climate systems, and energy use. The SELF-ASSESSMENT and AVAILABLE INFO template can be a guideline for the collection of different types of information.

The following information is considered essential for all versions of the protocol:

- Measurements: indoor temperatures
- Measurements: outdoor temperatures
- Measurements: indoor relative humidity
- Measurements: outdoor relative humidity
- Measurements: energy use and consumption (at least monthly total consumption, ideally hourly consumption of the different systems / functions - heating, ventilation, cooling, humidification)
- Measurements: operating list of climate system components.
- Plans: most recent floor plans (digital and analogue)
- Plans: most recent climate control plans
- Plans: space types of occupancy and collection / non-collection
- Inventory: most recent inventory of the collection composition, types and quantities, storage / display
- Inventory: logs - can be obtained through interviews - of historical events (e.g. system malfunction, calamities…)

It is important that the information that is gathered has an interval of at least 1 hour. For more details, check the data chapter.

Collect missing information

If all stakeholders are consulted and the team feels that essential information is still missing to perform an analysis, missing information can be gathered. To collect missing information, the data chapter can be consulted.

The TESTING template can be consulted for what should be considered before and during the performance of a test.

Be aware that some relevant data might require consultation with an external firm in case measurement equipment or technical expertise are not available internally.

3.3 Analysis

Analysis with the C2P tool

C2P:CEAM – Climate and Energy Assessment for Museums – is a tool that is developed for the project Climate2Preserv (C2P, KIK-IRPA, 2025) by the Catholic University of Leuven (KUL, Zygmunt, 2025). The tool was developed in the Python environment; it consists of six modules providing insights into indoor climate and energy assessment for museums. The software can examine potential energy savings evaluated by AI-based methods, obtained utilizing short-term management strategies evaluated based on indoor and outdoor conditions.

CEAM is a data-driven tool, with a fully functional GUI, working based on the provided input csv files. The minimal required input consists of 3 files including indoor climate data (ICD), outdoor climate data (ECD), and energy demands (ED). The modular structure has the functionalities described below.

Module 0: Data overview part 1. The module is used to systematically evaluate the provided input data and to create the so-called base files used in the further modules (assessments). The required modifications consider typical formatting (i.e., fonts or rows and columns placements), missing assessments, records adjustments, outliers' consideration, data averaging, as well as various parameters (which are used in the following analyses) calculations. This module also provides a key adjustment to the hourly records of the historical energy consumption provided even if the given inputs are with daily or monthly frequencies (the required adjustments are performed based on the evaluated heating and cooling degree days). Moreover, file management (folders and files organization in the working directory) is provided; numerous intermediate files are generated during the simulation, and they are securely managed and saved by the functionalities in this module (users can use them later). Module 0 is essential for the proper assessment by means of CEAM, while the selection of the following modules is optional, based on the needs (scope of the analysis).

Module 1: Data overview part 2. This module provides the graphical overview of the examined data, using the generated base files. The obtained outputs consist of graphs presenting various parameters with their time evolutions grouped for hourly, daily, weekly, and monthly frequencies.

Module 2: Correlation assessment. This module performs the correlation assessment of the included parameters. The correlation examines the relation between indoor and outdoor climates, but also with energy demands.

Module 3: Energy Signature. This module provides the assessment using the Energy Signature method. Based on the obtained outputs a brief but valuable overview of the building energy performance is provided.

Module 4: Climate Classes overview. Module used to examine the indoor climate conditions following the ASHRAE recommendations, particularly the so-called Climate Classes. It provides a valuable assessment of the indoor climate management for the examined building/zone.

Module 5: Energy optimization. Optimization is performed by means of black-box modeling, using the provided historical records to train the optimization algorithms to be capable of predicting energy demands. The potential savings are obtained due to the assumed short-term strategies, adopting pre-defined management of setpoint offsets for temperature and humidity control. The optimization is delivered via scenario analysis, assuming different timing for the offset application. Depending on the examined demand, various models are used using air, dry bulb, wet bulb temperatures, solar radiation, as well as relative and absolute humidities as variables. Based on the performed simulations, the predicted savings vary in the range of 10-50% depending on the examined scenario and selected solution (which follows the available references).

Additionally, a simple text file reporting is generated from each module with the summarized information regarding the performed considerations (including e.g., indicators of accuracy and performance, recorded differences, etc.).

The C2P tool has its own MANUAL. For more details, please consult the tool itself for a more detailed overview.

Analysis using other methods and tools

Besides text, tools, and templates developed for this project, many existing tools can be helpful to perform certain specific analysis. Instead of reinventing the wheel, a list of referred to tools can be consulted. Be aware that these tools are sometimes free, sometimes subject to a subscription and might sometimes be outdated or out of use when consulting this handbook.

3.4 Build and discuss scenario's

With the results of the analysis, it should be possible to propose several options. We propose three scenarios, ranging from less costly or invasive to more costly or invasive. Be realistic and take into account the available budget and staff (even if some idealism can be encouraged).

Describe what the impact of the three scenarios will be on the four components of the analysis: collections, buildings, systems, and energy usage for all proposed changes.

To inform stakeholders, a CONVERSATION EXERCISE (template) might be used. When informing stakeholders, this template might facilitate a healthy discussion and create understanding about conflicting priorities.

The outcome might be to choose components from different scenarios. However, keep in mind that the different components influence each other. Do not combine incompatible changes.

3.5 Determine actions

Based on the protocol followed, it should be feasible to estimate the potential energy savings in greater or lesser detail for several actions or as a whole:

- The short version: potential energy savings when using the C2P tool, or % of savings based on existing situation.
- The long version: in collaboration with an engineering firm complex calculations. When collaborating on results, understand which variables can be changed during projections. Specify what you want to know and create realistic scenario's based on the institutions inner workings. Communicate results back to the team and estimate the impact on the institutions.
- The modular version: can be both exact as well as a gross estimation based on the part of the handbook used for specific purposes.

As spokesperson or person of contact it is important that you are transparent about the impact on the institution and the required investments to implement the changes.

Once a final scenario is chosen, translate the scenario into concrete actions. Create a timeline and inform all stakeholders.

3.6 Implementation

Based on the protocol that was followed, the coordination might be transferred to someone else, internal or external. Either inform all stakeholders or insist on staying informed.

3.7 Evaluation

To evaluate the outcome, the same methods can be used, and the results can be compared to the expected outcome for separate actions, or all actions combined. The result should be a reduction of energy consumption in kWh (or MWh).

CONCLUSION: GET STARTED

C2P aims to helps cultural heritage institutions consume less energy while maintaining or decreasing the risks their collections are exposed to. It addresses the most frequently asked questions by the field and identifies existing tools that can be used to solve specific problems. Tools, methods, and templates were created to bridge some knowledge gaps.

It is important to understand what C2P is:

- Suggested protocol that can be followed from start to finish
- Can be used in a modular way to just tackle one problem at a time
- Focus on maintenance, short and medium term solutions
- Focus on sharing basic concepts / improve communication with allied fields
- Focus on high-end and low-end solutions from simple to complex.

And what it is not:

- Does not try to reinvent the wheel and refers to existing tools where applicable
- Focuses on what you can do yourself (e.g. it will give you information on different options and how-to communication strategies for new builds, it will not make you a building engineer)
- Does not focus on other energy savings besides climate control.

The ensemble of these tools allows institutions to follow the protocol developed for this project. However, using these materials in a modular way to attack certain specific smaller problems that might be quick and impactful is also encouraged.

Let’s get started!

Sources

— De wetenschappelijke bescherming der kunstwerken in oorlogstijd: Europa's ervaring gedurende de jaren van 1939 tot 1945, P. Coremans, D. Sc., Brussel: Centraal Laboratorium Der Belgische Musea, 1946

II. THEORY:
Building envelope, systems, collections and electricity use

UNDERSTAND WHAT YOU HAVE

This chapter will help you understand the current situation that exists within your institution and clarify the energy saving options that are available to you. You should consult this chapter if you need to:

- Better understand your indoor climate determined by your building envelope and climate control systems present, linked to your electricity use.
- Understand the needs of your collection.
- Understand the energy saving options available to your institution, looking at possible minor or major changes: changes to the building envelope, changing, renovating or adjusting your climate control systems, changes in collection management and changing your energy sources on, or off side.

This foundational chapter is designed for cross-disciplinary learning within cultural heritage institutions. If you work primarily with collections, focus on reading the buildings and systems sections. If you work with facilities, prioritize the collections and energy sections. Understanding what your colleagues in other departments face daily, their constraints, possibilities, and decision making processes, is essential for effective collaboration and institutional energy optimization.

The chapter provides basic explanations accessible to any professional, whether you're coordinating with internal teams or external specialists like conservation architects or HVAC engineers. Each section explains fundamental concepts, common terminology, and typical challenges without assuming specialized knowledge. This shared understanding forms the foundation for the integrated approach that C2P requires, where building envelope performance, mechanical systems, and collection care strategies must work together rather than separately.

1. Buildings

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- Q is the rate of heat transfer [W]
- U is the overall heat transfer coefficient [W/m2K]
- A is the examined surface [m2]
- ΔT is the temperature difference [K].

1.1 Introduction: building physics

People spend the majority of their lives indoors. The environmental barrier physically separating indoor and outdoor environments is called a building enclosure or building envelope. It is often referred to as the skin of a building, allowing for indoor climate management despite the impact of the exterior conditions. Thus, the building envelope plays a fundamental role in regulating the indoor climate, providing a comfortable and healthy environment for the occupants.

The building envelope is obviously a critical component of any structure, contributing to the overall durability and sustainability of a building, as well as determining its energy efficiency. Building energy performance depends on the thermal characteristics of its envelope, the efficiency of its systems, and building operation. Yet, controlling the energy consumption of the buildings is effective only with properly designed building envelopes.

On top of that, the building sector is one of the most energy-intensive in Europe, accounting for about 40 % of total final energy use. The building stock has a huge potential to save energy, resulting in lower emissions. All the efforts towards improvement of building energy efficiency begin with building enclosure. Those improvements prevent climate change, as well as increase occupants' comfort and avoid fuel poverty.

This section provides a brief overview of buildings and how they separate and protect occupants from exterior climate factors. The overview is focused on building enclosure, providing heat, air, and moisture (HAM) resistance. This outline allows for a better understanding of the building envelope, mentioning historical buildings and the ones that house cultural heritage objects.

1.2 Building envelope requirements based on outdoor climate

Buildings, or more precisely their envelopes, should provide appropriate protection from the exterior climate conditions. For an easygoing understanding, the requirements for buildings can be simplified with solutions on how to avoid heat / cold, air (wind), and moisture. The demands depend on the local climate in which the building is located. According to American Society for Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) Standard 169, climate regions can be defined based on thermal (nine zones) and moisture (three zones) characteristics. Knowing the climate zone is helpful when considering building envelope performance and its design.

The building envelope mediates the exchange of thermal energy and moisture between the interior and the exterior environments. Thus, the location-specific climate data is used for calculations of loads for systems and envelope design.

Performance requirements of the effective envelope are based on water, air, water vapor, and thermal energy control functions (in particular, how well the building envelope resists a given load), all of which depend on the exterior climate and desired interior conditions. Based on the indoor climate conditions for the collection and the type of climate control present, the envelope requirements can be formulated, taking into account the exterior environment. The necessary envelope performance can be defined as follows:

- all the water loads should be controlled and limited at all costs no matter the required conditions;
- it is recommended to control the thermal flows for all building types, with increased necessity when more narrow indoor climate requirements are applied (rigid climate control, cool storage). Moreover, controlled thermal flows result in lower energy consumption for heating / cooling;
- air leakage and stack effect should be controlled when precision control of indoor climate is required, as well as in a more extreme climate zone. The control is optional for wider, more flexible indoor climate specifications;

— moisture vapor should be considered especially for colder climate types, being moderated or optional for warmer ones.

Finally, it is important to mention that highly efficient buildings must be designed in a way to provide an appropriate indoor climate to preserve collections in a sustainable way. The above-mentioned is possible only with a high-performance building envelope no matter the local climate zone.

1.3 The importance of the building envelope and its components

The building's comprehensive importance can be grouped into functions of:

- support (structural-based);
- control (energy efficiency and sustainability);
- and aesthetics (attractiveness)

The building envelope not only provides resistance from exterior conditions but also ensures the longevity of the building. A well-designed envelope is more durable and requires less modernization throughout its lifetime. Moreover, the design has a meaningful impact on energy consumption. The efficient envelope will reduce the need for managing indoor climate, leading to lower energy bills and a decreased environmental impact. Moreover, the building's carbon footprint can be reduced using eco-friendly materials as components establishing building envelopes. Finally, a suitably designed envelope ensures a comfortable and healthy indoor environment.

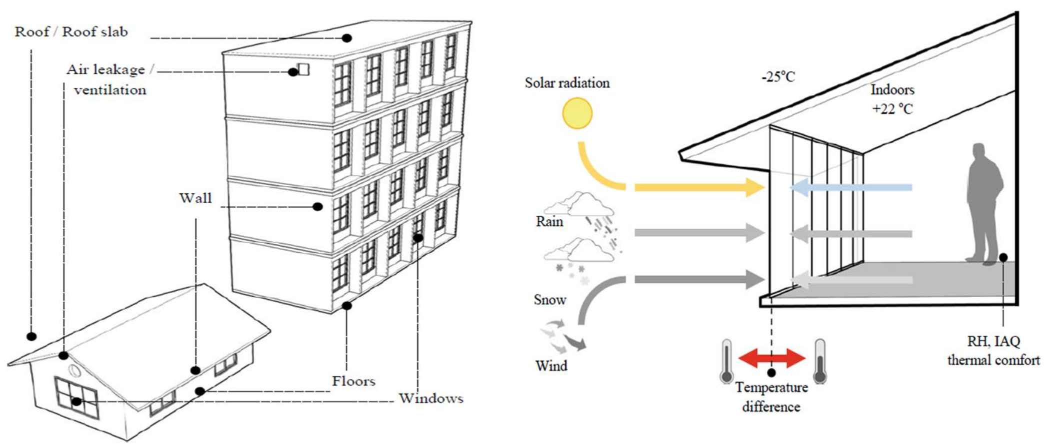

Fig. 1(left): Schematic overview of typical building enclosure components. Fig. (right): Building enclosure as divider between indoor and outdoor environments. (source: Hachem-Vermette, 2020)

The building envelope includes all the components that separate the indoors from the outdoors. Each enclosure component is a three-dimensional, multi-layer, multi-material assembly. Each enclosure component is an assemblage of layers of specified products / materials. Simplifying, building enclosure consists of walls, floor, roof, windows (fenestration), and doors, including underground parts. All the above-mentioned components can be shortly defined as follows:

— wall: the vertical surface surrounding the building provides structural support and insulation. External and partition (internal) walls can be distinguished. A typical assembly consists of exterior and interior finishings, thermal insulation, structural component, and vapor barrier.

- floor: a horizontal assembly typically dividing building volume into stories or being a barrier from the ground or the bottom of a room.
- roof: the uppermost part of the building, designed as a horizontal flat or sloped surface. It's most important purpose (amongst others) Is to protect against precipitation.
- windows: partially transparent components allow natural light to enter the interior (essential for visual comfort). They play an important role in regulating airflow of the building and can be installed in both walls and roofs.
- doors: vertical openings provide access to the building or create connections between different indoor spaces.

All those components work together and should provide a tight, closed physical barrier separating the interior from the exterior, enclosing a structure.

Additionally, the foundation of the building should be mentioned, being the structural component that transmits the loads from the building to the underlying substrate. Despite the structural properties, proper drainage around the foundation as well as a solid waterproofing membrane must be provided.

The visual aspect of the enclosure (its presence) is also important for aspects of urban design and aesthetics.

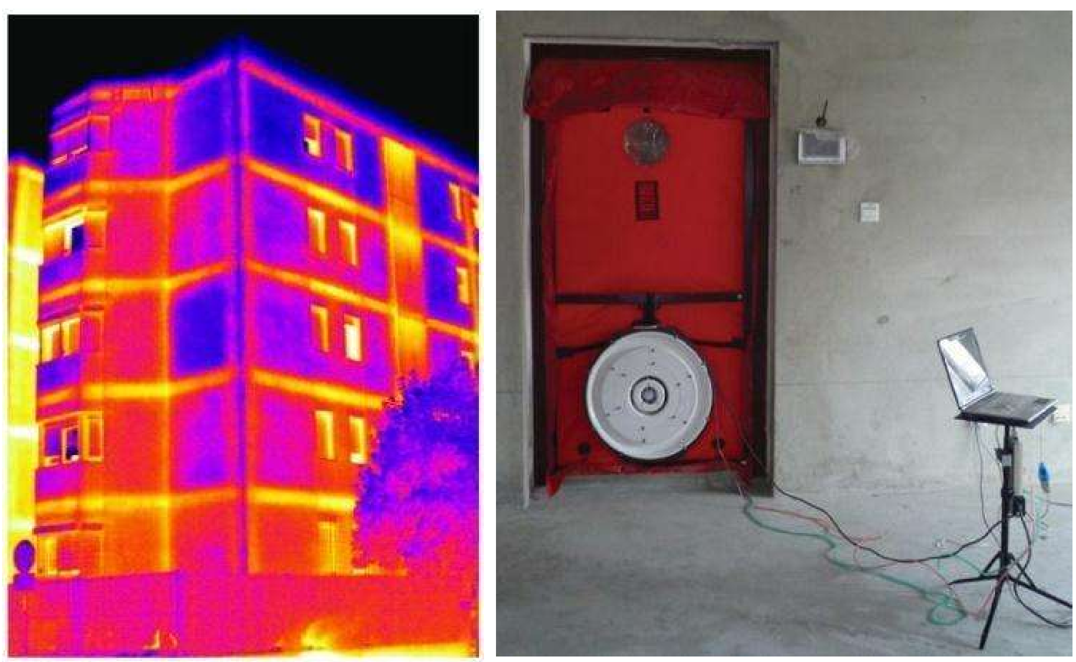

Fig. 2a and 3b: The on-site building envelope assessment: (on left) infrared thermography and (on right) the blower door test (Source: Bienvenido Huertas, 2020 and Yongming and Duanmu, 2016)

Two adjacent internal spaces can also have quite different environmental conditions or design purposes. Thus, the interior separator between those two zones[2] (with significantly different conditions on each side) should be examined similarly to a typical enclosure.

Numerous factors are taken into account in order to design a high-performance building envelope. Firstly, it relates to the construction components of the envelope itself. Building enclosures should be well insulated following the current requirements and minimize the impact of air leakage and thermal bridging.

A thermal bridge is defined as a part of a building enclosure with higher thermal conductivity (heat transfer) than the adjacent areas. Thermal bridges should be minimized not only to reduce energy consumption but also to avoid condensation or frosting, which could lead to mold growth and associated health concerns. The easiest approach to minimize their impact is to include a well-designed insulation layer as part of the building envelope. The impact of some thermal bridges (e.g. projecting elements such as balconies) can be efficiently reduced only if designed correctly. We can effortlessly spot thermal bridges in building envelopes with infrared thermography or examine them using computational tools. The impact of thermal bridges and consequent increased heat loss can be evaluated with simplified (ISO 14683) or detailed (ISO 10211) calculation methods.

Some computation software with different ranges of applications are available: THERM, HTflux, AnTherm (Analysis of Thermal behaviour of Building Construction with Heat and Vapour Bridges), TRISCO, and COMSOL Multiphysics among others.

Buildings are not totally sealed. Infiltration is described as unwanted and uncontrolled ventilation or the uncontrolled flow of outdoor air into the conditioned building space through unintentional openings in the envelope (e.g. cracks or leaks). The reverse phenomenon is called exfiltration (unwanted loss of the conditioned indoor air from the interior).

Besides the overall tightness of the building envelope, infiltration is affected by climate factors, in particular temperature difference (stack effect) and wind velocity (air penetration). An effective counteraction for infiltration is to provide high tightness of the building envelope. Reducing air leakages results in significantly lower heat losses. Still, even well-insulated, airtight buildings must be equipped with sufficient ventilation (natural or mechanical) to provide the required air change. Adequate ventilation is essential in preventing high indoor moisture levels and condensation as well as to provide acceptable indoor air quality (IAQ) for the occupants. Building airtightness can be evaluated onsite with a fan pressurization method (the so-called blower door test), executed following ISO 9972 standard.

An additional parameter related to materials consisting of building enclosures affecting its thermal performance is called thermal mass or thermal capacity. It provides the ability to absorb, store, and release accumulated heat, shaping the thermal behavior of the building. The conceptual overview of thermal mass is shown in fig. 4. During the winter the heat (mostly from direct radiation) is absorbed by building enclosure, stored, and then slowly released (re-radiates) during night hours, decreasing temperature fluctuations indoors (see fig. 5). With a proper building design, allowing to limit solar gains, thermal mass can be

[2] *E.g. thermal zones defined in ISO EN 52016 as internal environment with assumed sufficiently uniform thermal conditions to enable a thermal balance calculation*

effectively used in summer to keep the indoor cool (passive cooling). The mass will absorb the inner warmth during the day, and release it during the night. It allows cool breezes and convection currents to pass more intensively during the night, taking away all the preserved energy (heat).

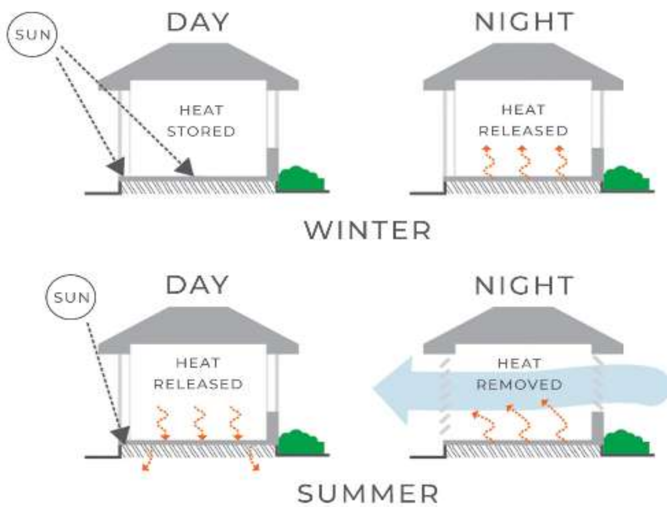

Fig. 3: What is the thermal mass - the conceptual overview. (Source: theconstructor.org, 2021)

The selection of appropriate building thermal mass should be performed during the design stage following the object function. High thermal mass (e.g. brick wall) is recommended for constantly occupied buildings, with uniform indoor climate management, while a light construction (e.g. frame structure) is more appropriate for periodically-occupied buildings. The thermal mass is usually associated with the mass of used materials – typically, the heavier the material is, the higher the thermal mass it has. It is an important element of passive house design, utilized for passive heating and cooling.

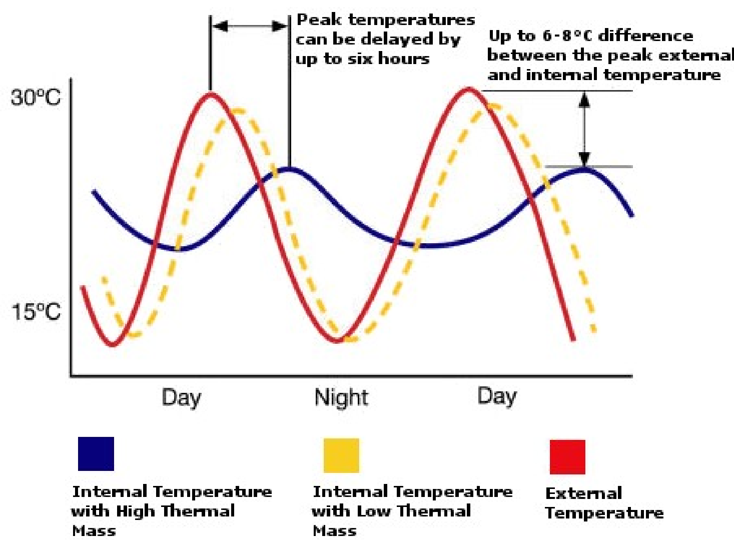

Fig. 4: Indoor temperature with high and low thermal mass (source: University of the West of England (Bristol), 2009)

The building envelope quality, system efficiency, and the occupants' behavior affect the building's performance and the final energy consumption. The above-mentioned characteristics of building enclosures are essential for the proper management of building energy consumption. Buildings that were constructed without the initial design of their enclosures, face a variety of problems related to efficient operation, as well as optimal management. It is possible to overcome all the shortcomings of building enclosures with HVAC systems, yet it is not a sustainable and energy-efficient solution. Thus, no matter how efficiently occupants and building services operate, poor envelopes result in unnecessary energy consumption.

1.4 Regulations requirements and energy efficiency

Typically, each country has its regulations referring to buildings and their energy efficiency; in the EU it is based on EU/2010/31 (*Energy Performance of Buildings*) and EU/2023/1791 (*Energy Efficiency*) directives, implemented individually by each member country. Standard building envelope requirements are related to the minimal level of thermal insulation (to reduce heat transfer), air leakage control, water management (counteraction for water infiltration), structural integrity (provide adequate load support), and fire resistance. Many resources are available to help understand building envelope requirements; some helpful references include:

- International Building Code (IBC);
- ASHRAE Handbook – Fundamentals;
- ASHRAE Standard 90.1 – Energy Standard for Buildings Except for Low-Rise Residential Buildings;
- National Institute of Building Sciences (NIBS), Whole Building Design Guide – Building Envelope Design Guide.

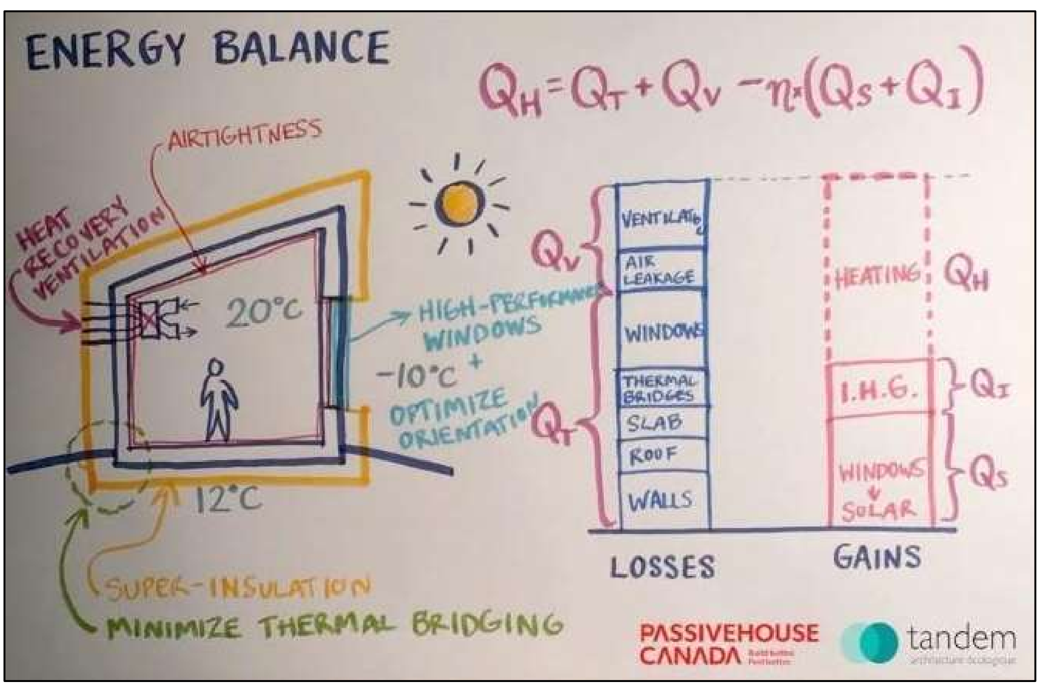

Fig. 5: Illustration about the impact of outdoor climate and building envelope on the energy balance (Source: Passivehouse Canada and Tandem Architecture)

Even for well-designed and maintained buildings some failures can occur. The most common reasons for building envelope failure happen due to a variety of factors, including:

- poor design: for most cases when the envelope was not appropriately designed to withstand the local climate and weather conditions;
- poor installation: incorrect, inefficient, or discontinuous insulation layer might cause various defects (e.g. leaks) in envelope;
- material deterioration: high-quality materials should be used in order to avoid building envelope deterioration due to its exposure to sunlight, moisture, and temperature fluctuations;
- lack of maintenance: lack of regular maintenance leads to envelope flows, which unrepaired will aggregate and ultimately cause significant damage;
- physical damage: it is important to use durable materials, which can withstand extreme weather conditions, as well as acts of vandalism.

Building envelope failure can lead to various problems, including water damage, mold growth, increased energy demand, as well as deterioration of the indoor climate and air quality. Regular inspections and maintenance are essential to ensure the successful long-term performance of the building.

1.5 Building envelope of historical buildings

We should distinguish historical buildings and modify all the common approaches applied to normal buildings. Optimizing the building envelope of historical buildings requires a delicate balance between preserving their architectural integrity and enhancing their performance for modern needs. The standard procedure should follow preservation guidelines, allowing us to understand regulations specific to historical buildings:

- Center of European Normalization (CEN) EN 16883: Conservation of cultural heritage – guidelines for improving the energy performance of historical buildings (2017)
- ASHRAE guideline 34: Energy guideline for historical buildings (2019)

Usually, all the performed modifications are permissible to maintain the building's historical character. The suggested non-invasive strategies are as follows:

- regular inspection with preservation architects, engineers, and specialists to navigate through all the challenges and opportunities of optimization;
- sensitive upgrades and improvements taking into account the original design and materials of the historical building to preserve its authenticity;
- conservation of materials, focusing on the preservation of original resources whenever possible;
- repair and restore existing elements rather than their replacement or replacement using traditional materials and techniques in order to preserve craftmanship;

— implement strategic energy efficiency retrofits with minimal impact on the building's appearance and structure;

— address and counter moisture issues to avoid moisture damage to the historical building and collection;

— adaptive reuse strategies to repurpose historical buildings for the next generation while retaining their character[3];

— document all interventions and changes for future reference, as well as implement monitoring systems to track performance metrics.

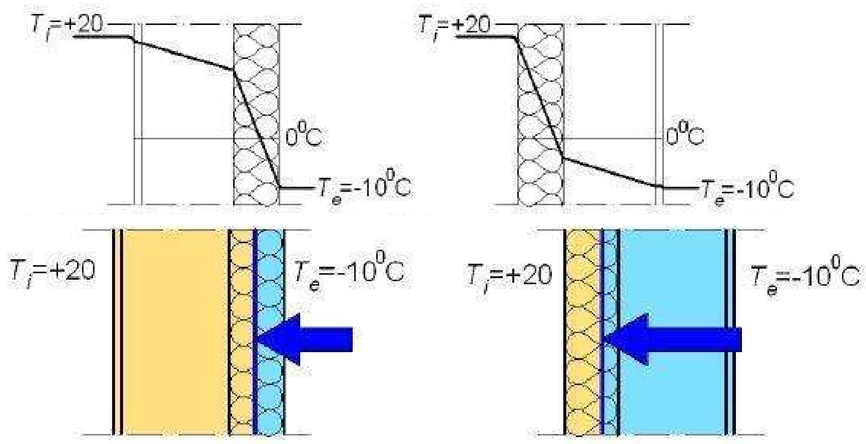

Fig. 6: Temperature distribution within the wall insulated from the exterior (left) and the interior (right). Source: University of the West of England (Bristol), 2009.

By taking a thoughtful and holistic approach to the building envelope optimization of historical buildings, you can preserve their cultural value while enhancing their performance for future generations.

Historical buildings are usually modernized with complex HVAC systems, in an attempt to save the visual integrity of the antique enclosure while obtaining a desired collection environment. Adding thermal insulation from indoors is possible, yet it requires a complex moisture behavior assessment for the modernized component due to the inverse temperature distribution throughout the component section.

1.6 Heat and mass transfer

Heat is transferred because a material will attempt to achieve thermal equilibrium with its surroundings or between adjacent materials. Heat transfer through a building enclosure is ruled by the principles of thermodynamics, through three mechanisms that might operate alone or in combination (e.g. heating or cooling of a building):

[3] *It is a common approach nowadays to e.g. convert historic buildings into commercial or residential buildings*

— conduction[4]: heat transfer through a solid material by molecular interaction (i.e. through materials via physical contact) with the flow from the warm area to the cool area,

— convection: heat transfer through a fluid[5] by the movement of the fluid itself[6] (occurs within air cavities and through the ventilation system),

— radiation: heat transfer by electromagnetic waves through the air, where energy is radiated from one body to another and then partially reflected and absorbed[7] (occurs via heated surfaces and through windows).

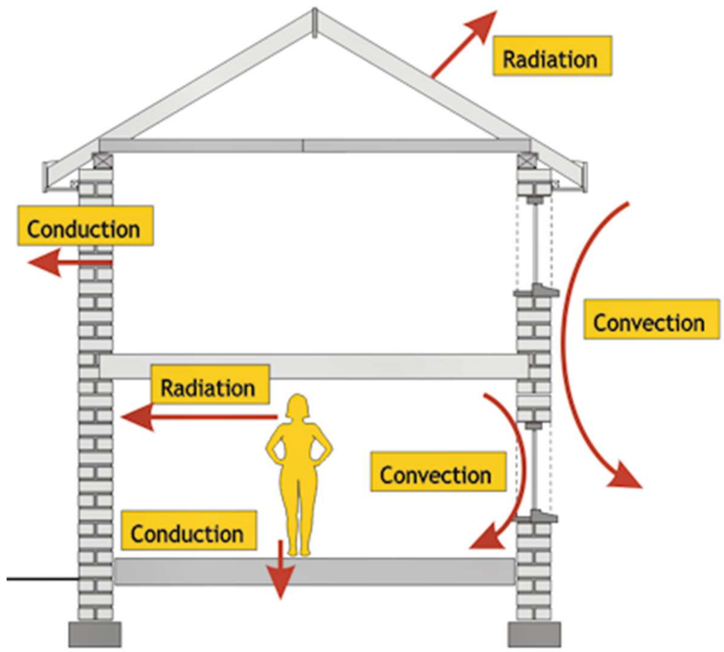

Fig. 7: Heat transfer methods in buildings. (Source: University of the West of England (Bristol), 2009).

The overall heat transfer through a building enclosure can be described using the steady-state heat transfer equation, including all three mechanisms of heat transfer, with its simple form as follows:

$$Q = U \cdot A \cdot \Delta T$$

Where: Q is the rate of heat transfer [W], U is the overall heat transfer coefficient [W/m^{2}K], A is the examined surface [m^2], and ΔT is the temperature difference [K].

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[4] *Expressed with the thermal conductivity λ [W/mK], which is a measure of material ability to conduct heat*

[5] *Fluid considered as air or water*

[6] *Either absorb heat (from a colder surface) or lose heat (to a warmer surface); air movement: warmer rises and cooler sinks*

[7] *The respective amount of reflected/absorbed radiation varies among different materials*

Moisture transfer through building enclosures is a complex phenomenon that involves several coupled mechanisms: diffusion[8], convection[9], and capillary absorption[10]. Moisture transfer is affected by material properties (permeability, vapor resistance, and water absorption capacity among others), temperature and humidity differences, as well as airflow rates (influences the moist movement). Fick's law can be used to describe the diffusion of water vapor through a material due to a vapor pressure difference. Managing moisture transfer through building enclosures requires a holistic approach, considering heat transfer and moisture dynamics (hygrothermal modelling approach) but also the impact of air movement.

Air transfer through a building enclosure affects its performance. We typically referred to air infiltration as a critical aspect of the unpredicted air transfer via enclosure. There is not a single method to estimate the total air transfer in detail through a building enclosure due to the complex nature of air leakage. Typically, we used either the air change per hour or the pressure-driven leakage approaches (both with limitations). In practical applications, the acceptable levels of air leakage for different types of buildings are defined in codes and standards. The proper management of air transfer via building enclosure (thus ensuring appropriate airtightness) is critical to ensure energy-efficient buildings with good indoor air quality and thermal comfort.

It is essential to keep in mind that the above-mentioned are simplified methods. Real-world applications often require a combination of theoretical understanding and practical experience. Thus, calculations are often performed with specialized software to accurately assess heat and mass transfer through building enclosures.

The HAM response of building enclosures is a complex method applied to examine buildings. It combines heat and moisture transfer processes, coupling them with mathematical modelling based on partial differential equations. The HAM model is based on principles of heat conduction expressed by Fourier's law[11], vapor diffusion by Fick's law, and moisture content equation. Today, hygrothermal modelling can be performed using e.g. WUFI or Delphin software. Those software incorporates material properties, boundary conditions[12], and techniques to simulate the HAM response of the building enclosure.

[8] Water vapor moves from areas of high concentration to low concentration through materials

[9] Air movement carries moisture vapor

[10] Liquid water absorption and transport via porous materials

[11] the rate of heat transfer through a material is proportional to the negative gradient in the temperature and to the area, at right angles to that gradient, through which the heat flows

[12] indoor and outdoor (climate) conditions

2. Systems

Author: Dr. Sebastien Thomas – University of Liège

Introduction: systems, generation, distribution, emission and control

A climate control system is the equipment that will maintain your inside conditions at a given setpoint in terms of temperature, humidity, and air quality. This paragraph details some of the mostly used systems to maintain the indoor conditions.

Depending on the outside climate and setpoints, the needs of heating / cooling / humidification / dehumidification can be effectively high or non-existent.

The most popular systems are described, for a same building multiple systems can be present. All systems can be split into three physical parts:

- Generation: equipment producing heat /cold / steam / vapor. (e.g. gas furnace).
- Distribution: set of devices transmitting heat / cold / steam to emission devices.
- Emission : set of devices emitting heat / cold / steam to the climate controlled area.

The fourth part is the control of the system. The system must be controlled to achieve the adequate setpoints within an energy efficient way. This can be achieved from a combination of sensors and actuators that control actions of pumps, valves, fans and controls combined with a computer defining rules, schedules and alarms.

The 'medium' distributing cold and heat can be either water or air. Through water pipes or air ducts the heat/cold is distributed from the place where it is generated to the collection area. In case of air distribution, the ventilation system can be used for quality air control. On the one hand, some filters prevent outside pollutants to enter the collections area. On the other hand, the fresh air flow impacts the air exchange rate for indoor pollutants dilution.

For humidification the 'medium' is generally water steam. Dehumidification is most of the time coupled with cold water production. If generation and emission are common to the same equipment, we do not have any distribution medium. This is particularly the case for direct electrical heating or portable / mobile humidification devices.

2.1 Decision making process: thinking in systems

The HVAC engineer analyzes the situation to build / renew / extend the building HVAC system. The most important design parameters are the indoor climate requirement in terms of air quality, temperature and humidity set points. After the (collection) requirements are defined, the complete system power is chosen according to the gains and losses computed as close as possible to reality.

Gains and losses are driven by the outside climate, the envelope characteristics and the internal gains / losses due to visitors, etc. (the better the envelope, the lower the gains / losses). According to the available place for the HVAC system, the pipes and ducts clutter is drawn as well as the location of emission and production devices. Sometimes, if there is not enough space, the production devices could be installed in a new building extension. Space constraints could lead to inadequate place for production devices (e.g. compressor producing heat placed in a refrigerated area). More generally, for heat / cold distribution, water based system are more compact than air based ones.

2.2 Types of cultural heritage institutions

Collection-managing institutions prioritize sharing and making their collections accessible to the public. Matters such as scenography, education, communication, research, and preservation are important in this regard. Although the building is often essential for the visitor experience and indoor climate is considered important for collection preservation and comfort, systems and building envelopes are primarily seen as means to support museum (or other collection-managing) tasks.

In large institutions, with over 50 full time staff members, large installations and complex HVAC systems are frequently found. These systems typically control both temperature and humidity in the collection-holding spaces. Public collection spaces also require a comfortable temperature year-round (18-20°C). Spaces (or showcases) for loaned pieces must meet special requirements outlined in the 'loan agreement' by the owner of the work (loan provider) and the museum exhibiting it (loan recipient). Most larger institutions have an internal facilities team, working with external companies for some specific tasks (maintenance, programming controls…). These museums often have large depots (more in line with 'archives' described below) where the vast majority (90-98%) of the collection is housed.

In small to medium-sized institutions and religious buildings, HVAC systems are sometimes found. More often, the buildings are only heated, cooled, and mobile humidifiers or dehumidifiers may be used. The heating systems and energy sources can vary greatly. Sometimes there are no systems present or only in some parts of the building. Historic air handling systems and underfloor heating are often encountered, sometimes in combination with central heating. When few systems are present, there can be traditional manual control using a seasonal and daily schedule of opening doors, windows and light blocking materials in order to benefit from the buildings natural heating / cooling capacities. For technical support there is sometimes a (small) internal technical team responsible for maintenance, all other works are done by external companies. These institutions are usually less dependent on strict loan requirements and can be more flexible regarding temperature reduction. Visitors may keep their coats on, and temporary closures (in extreme seasons) are not uncommon.

For archives, depots, and (heritage) libraries, the requirements for public spaces are usually similar to those of small or medium-sized museums. Although the systems present here may also vary, these institutions often have two major advantages: the mass of the collection present, which helps moderate the climate, and the non-public nature of the spaces (if not used as workspace), meaning that the comfort temperature does not need to be maintained.

2.3 Historical museum climate

Museums as we know them today are a relatively young concept. Cultural heritage collections however have existed much longer. Historically they were often stored in buildings with limited climate control that aimed at creating a climate dedicated at human comfort rather than collection care.

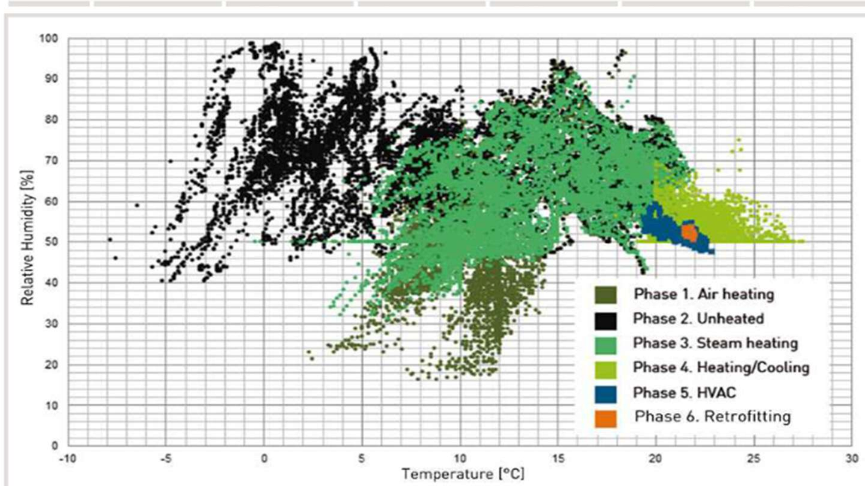
Before the 19th century, in Europe, indoor climate conditions were mainly influenced by the (often massive) building structure itself. Heating (if any) was provided by combustion of wood and / or coal. (Natural) ventilation was established using ducts and chimneys. Moisture control was provided solely by the building envelope through the protection against driving rain and leaks.

During the 19th century, the use of central heating, connected to a boiler using combustion processes, introduced new needs such as mechanical ventilation, linked to pollutants from the combustion processes, and humidification to compensate for the heat drying out the air causing noticeable mechanical damage in artworks.

For one of the first free standing museums, the 'Alte Pinacotek' in Munich (Germany), has studied its climate control history and identified six phases (fig. 9a). From those phases they have simulated the temperature and relative humidity for the Rubens Gallery VII. over the period over a year (fig. 9c). They have translated that data to temperature and relative humidity yearly and seasonal fluctuations (fig. 9b) and compared this to the relative heating demand (fig. 9d).

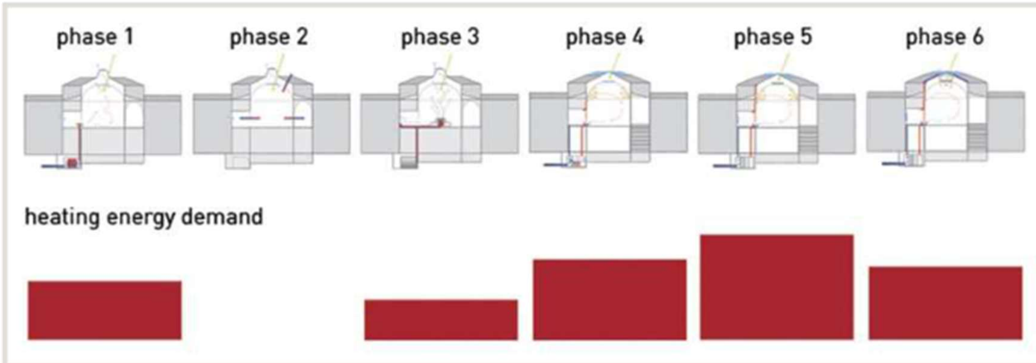
Phase	Period	Short description
1	1836 to 1841	Original building with air-heating planned by Klenze
2	1841 to 1891	Unheated building after deactivation of the air-heating
3	1891 to 1952	Low-pressure steam heating system for heating and humidification
4	1952/57 to 1994	Reconstruction by Döllgast with HVAC for heating and humidification
5	1994/98 to present	Overall refurbishment with installation of a full HVAC system
6	2008/09 to present	Energy-efficient retrofitting of a single gallery room

Phase	Deviation from annual mean		Daily fluctuations winter		Daily fluctuations summer	
	Δ RH [%]	Δ T [K]	Δ RH [%]	Δ T [K]	Δ RH [%]	Δ T [K]
1	< 40	< 9	< 10	< 5	< 5	< 1
2	< 32	< 15	< 7	< 1	< 5	< 1
3	< 26	< 11	< 10	< 2	< 5	< 1
4	< 12	< 5	< 2	< 1	< 5	< 4
5	< 5	< 2	< 2	< 1	< 2	< 1



This is a draft version of the Handbook that will be published with corrections and additions as part of the Climate2Preserv (C2P) project.

Fig. 8a-d: the overview of the different climate control phases of the Alte Pinacotek (a), the consecutive indoor climate achieved (b) based on climate simulations (c) to create an overview of the (relative) heating demand (d). (Source: Eibl and Burmester, 2014, Figures © Melanie Eibl)



These graphs give us an idea about the historical climate these artworks have resided in. Moreover, it clearly shows an evolution towards very narrow setpoint trends, leading to a rise in energy consumption if not combined with a retrofit.

2.4 Types of climate control systems

Systems that control climate can vary largely throughout the world. A climate control system is considered as a secondary control. It is additional to the buffer that is already provided by the building envelope. Systems can be traditional (e.g. a fireplace) or high-tech.

	Central Heating only	Mechanical ventilation without climate control	All-air system	Mixed all-air and local emission devices
Generation	Gas/oil Furnace	No heat/cold generation	Gas/oil furnace (H), Vapour compression chiller (C).	Gas/oil furnace (H), Vapour compression chiller (C).
Distribution	Pump driven water system	Fan driven air system	Fan driven air system	Mixed
Emission	Radiator	/	Air vents	Air vents and fan coil units or activated surface
Control (hardware)*	Pump switch & thermostatic valves	Fan switch & fan variable speed drive	Flaps, pumps, fans, 3-way valves	

*Table 1: most popular systems in Western Europe (for a temperate climate, heating needs are the most important). * in addition to the hardware, some smart control could be existing for each system. From*

simple schedule to complex control based on the weather forecast, many possibilities are available.

The different systems are pictured here below.

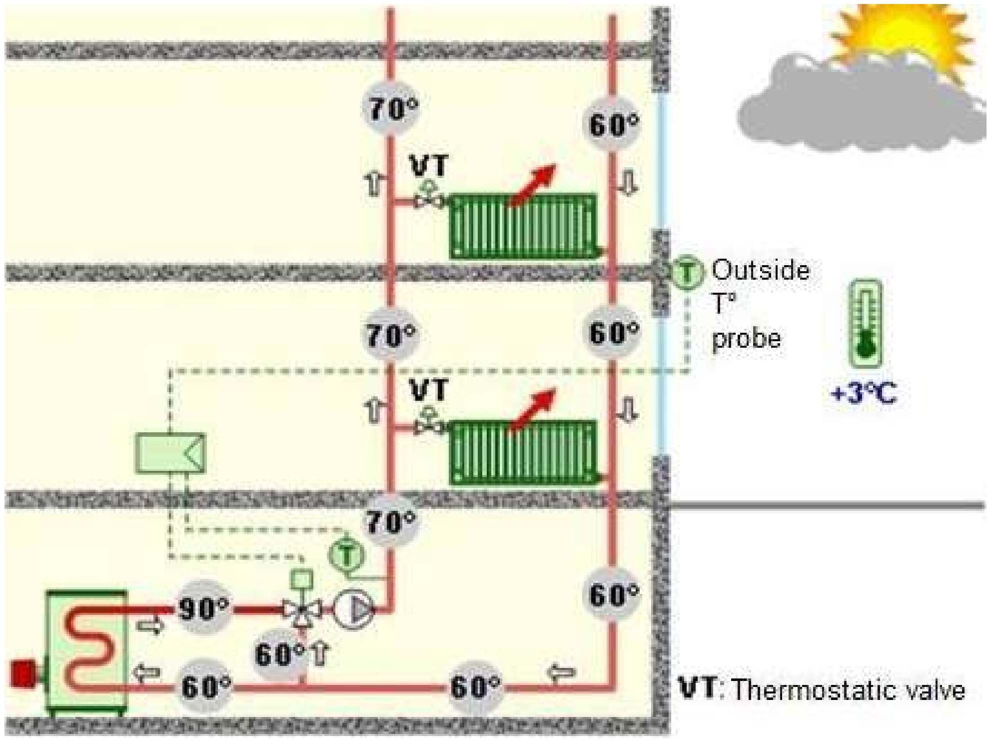


Figure 10: Central heating only. Temperature indoor and / or outdoor are measured by a sensor. This controls the heat production in the furnace which heats up water to a certain set point. The water gets distributed using a pump to one or more emission devices emitting heat.
(Source: Energieplus, 2007)

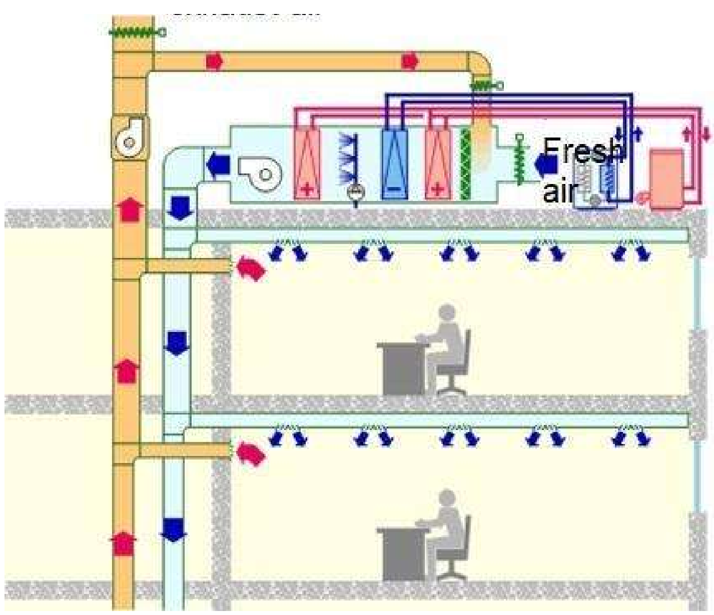


Figure 9: All air system. An air handling unit (AHU) can control several processes (heating, cooling, humidification, ventilation and filtration). Controls (mechanical or computer driven) communicate with sensors (indoor, outdoor,...) and drive the different components. Controlled air is distributed using metal ducts using pulsion and extraction to create air exchange in rooms. Outdoor air can be controlled or recycled.
(Source: Energieplus, 2007)

2.5 System components

The air handling unit (AHU) is the core equipment of an all air or mixed system. Its main components and functions are:

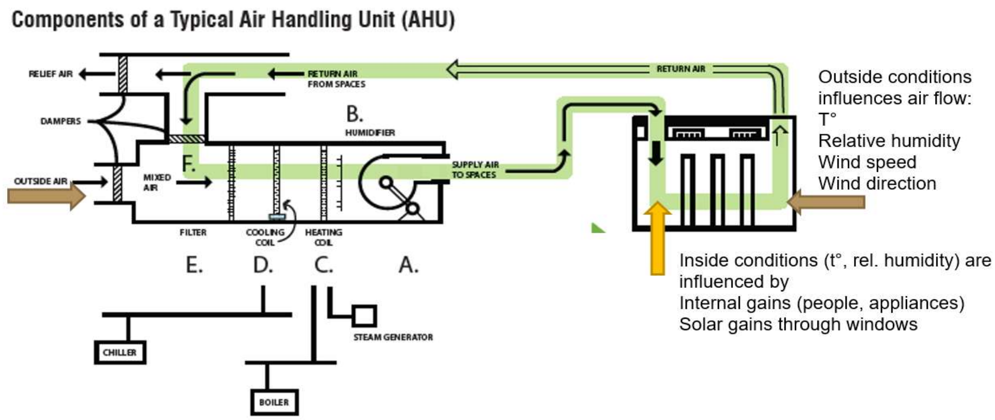


Fig. 11: Components of an air handling unit source AHU components. (Source: Image Permanence Institute, 2014)

- [A] Air Handling Fans move the loop of air to the spaces through supply air ducts and draws it back in through the return air path. Fans may operate at a constant speed or use variable speed drives that adjust the speed based on the volume of air that is exchanged. Fans fight the air pressure losses in the system. Energy used increases with high pressure losses coming from flaps, coils, filters.
- [B] Humidifiers inject water vapor into the supply air, usually as steam which is produced by a peripheral steam generator, if a sensor in the return air stream detects that the space RH is too low.
- [C] Heating Coils are controlled by a thermostat. The stream of air is warmed as it passes over a heating coil before entering the space. A peripheral boiler produces hot water or steam which allows the selected temperature to be achieved. Convectors or radiators may also be used to supply heat.
- [D] Cooling Coils – If a sensor in the space detects that the space is too warm, the stream of air passes through a cold coil before being supplied to the space. The coil is cooled by a flow of cold water supplied by a peripheral Chiller or by the evaporation of a refrigerant provided by a remote compressor / condenser (DX) unit.
- [E] Air Filters remove particulates as all air delivered to spaces passes through one or more filters. Additional filters may be added to remove gaseous components.
- [F] Mixed Air – A portion of the return air from the space is ducted outside through a relief air damper to make room for the introduction of fresh air through the Outside Air Damper. The outside air is blended with the bulk of the return air in the mixed air chamber.

2.6 Use of psychrometric charts

To understand the reason for the presence of the equipment described above, thermodynamic properties of moist air should be introduced.

A graphical tool known as a "psychrometric chart" represents the interrelationships among these thermodynamic properties of moist air. Note that, the psychrometric chart is sometimes shown with opposite axis (X-axis as Humidity ratio, Y-axis as Dry bulb temperature). Both graphs represent the same data.

The three most important properties are:

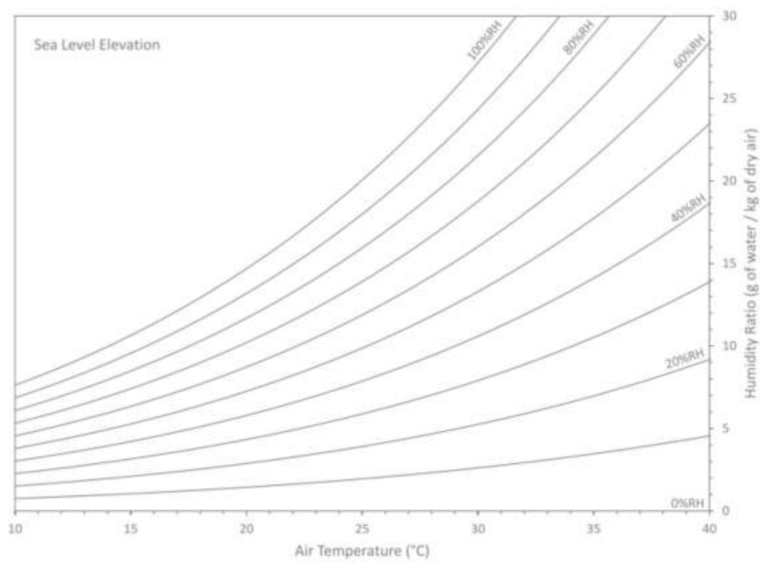


Figure 12: Simplified psychrometric chart for sea level elevation (Credit: Vincent Laudato Beltran for the G. Paul Getty Trust, 2023)

- — 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.
- — Humidity Ratio: this relates the masses of water vapor to dry air, and provides a measure of the total moisture content of the air. This variable appears on the y-axis of the psychrometric chart in units of gram (g) of water per kilogram (kg) of dry air (inside conditions generally contain 10-20 g water per kg dry air).
- — 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.

The graphs help to determine the adequate air treatment to be achieved to reach the temperature and humidity setpoints indoors taking into account the outdoor conditions. A region in the graph is selected as a target for collections or people's comfort conditions.

The air must be handled to attain the "targeted zone"; it is processed with air mixing, heating, cooling, humidification and / or dehumidification. The common air transformations are presented below.

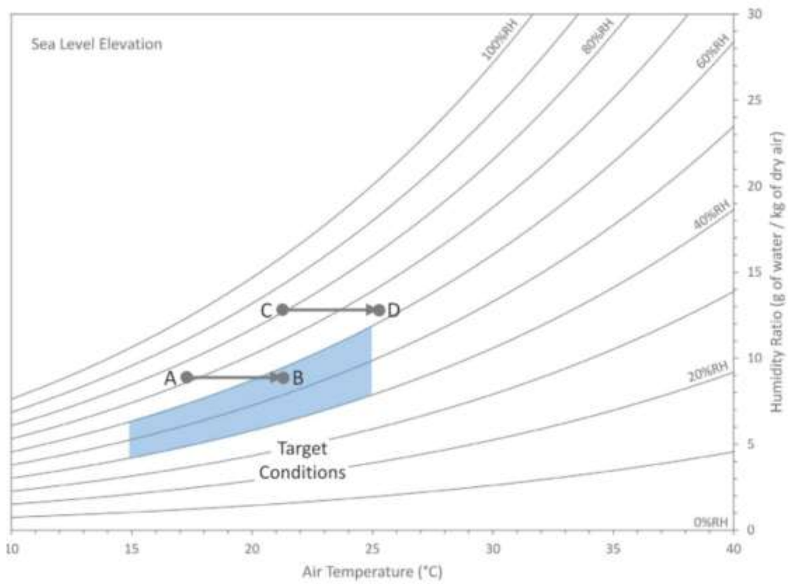


Figure 14: Psychometric chart target, example: implementation of a heating strategy (Credit: Vincent Laudato Beltran for the G. Paul Getty Trust, 2023)

The chart is not solely used for designing HVAC systems but also for displaying the historical measured data (inside and outside) as shown below. This allows us to compare the climate measured to the targeted zone. This tool also helps to determine where any indoor climate abnormalities are.

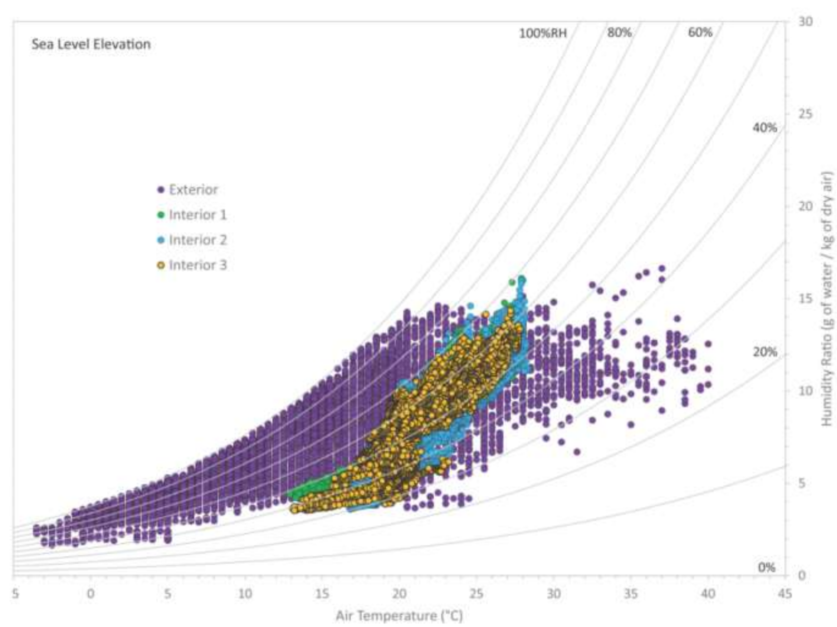


Figure 13: Psychrometric display of historical exterior and interior environmental data (Credit: Vincent Laudato Beltran for the G. Paul Getty Trust, 2023)

2.7 Heating, cooling, humidification, dehumidification and airflow

There are four basic climate control strategies: heating, cooling, humidification and dehumidification. Based on your needs, outdoor climate and building envelope, it might be sufficient to be able to control none, one, multiple or all climate control strategies. To implement these strategies different individual systems (e.g.: central heatingand mobile dehumidifiers) can be combined or all can be integrated within one system (e.g.: HVAC).

Additionally, the recirculated air ratio and the air mass flow play a significant role in relation to energy demand. Recirculating air does not need to be fully conditioned constantly. Also, the airflow for a space that does not require conditioning for human comfort (such as a non-working storage space) is often unnecessarily high. An important note here is that the recirculation of air, as well as reduced ventilation, can cause dust particles and spores to settle more quickly and find a food source for future germination.

Within cultural heritage institutions, multiple separate systems are often in operation, making optimized computer-controlled control sometimes difficult or impossible. Systems can also work against each other. For example, if there is both central heating in a room and humidification occurring simultaneously, using an air handling unit, with sensors located in the supply and/or extract ducts, the humidified air blown in will still further dry out because it is further heated after measurement. This is then corrected by the use of mobile humidifiers. Because the person responsible for climate control maintenance and the curator use different sensors to monitor this, and the systems do not communicate with each other, optimization becomes difficult.

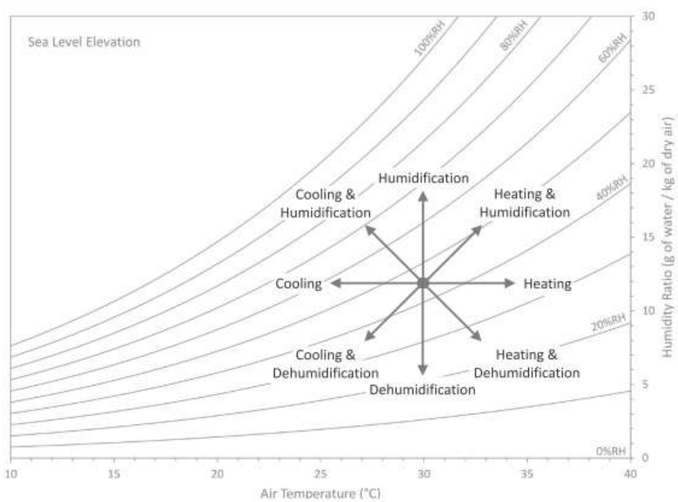


Figure 15: Directions of the basic psychrometric processes. The central circle represents the initial state point. (Credit: Vincent Laudato Beltran for the G. Paul Getty Trust, 2023)

Sensible heating and cooling is defined as the removal or addition of heat to an air mixture, with no effect on the moisture content. Its sole effect is on the increase or decrease of the dry bulb temperature. Practically a coil with hot or cold water obtains this effect, we name it a cooling or heating coil.

On a psychrometric chart, sensible heating and cooling is shown as a horizontal line. It is horizontal because the amount of water vapor in the air is not changed, thus the humidity ratio remains the same. A horizontal movement increases or decreases the dry bulb temperature. As the dry bulb temperature increases with sensible heating, the air's capacity to hold water also increases. The opposite is true with sensible cooling. Sensible heating decreases relative humidity, while sensible cooling increases it.

Latent heat energy is the amount of energy required to produce a phase change, water (liquid) to water (vapor). Latent heating and cooling is defined as the removal or addition of moisture (water vapor) to an air mixture. Latent heating is more commonly known as humidification and latent cooling is known as dehumidification. In an AHU, the humidification can be done in various ways: using centralized steam boiler, decentralized steam boiler, cold water humidification, humidification wheel, etc.

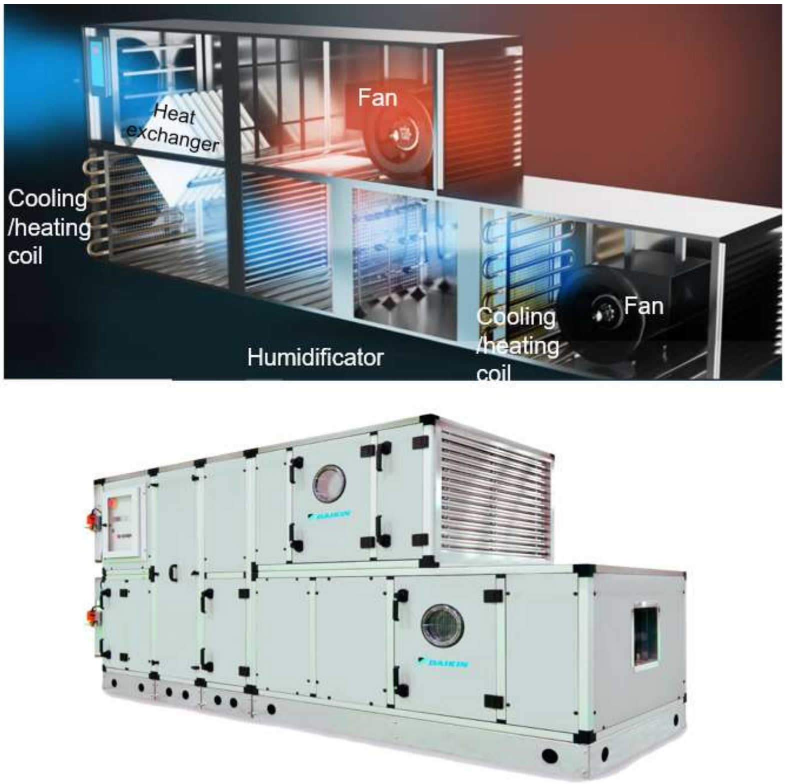


Figure 16: Illustration of an AHU inside and outside (Source: Airtech Solutions)

On the psychrometric chart, humidification with steam is mainly vertical while all other humidification processes are diagonal towards cooling. This means humidification could considerably cool down your air stream.

In an AHU, dehumidification is generally achieved by a cooling coil with cold water (6°C-9°C). Air flow reaches its dew point and a part of the moisture condenses. The psychrometric chart process is diagonal direction cooling. Dehumidification wheel could also dehumidify with desiccant material, in this case the direction in the psychrometric chart is close to vertical.

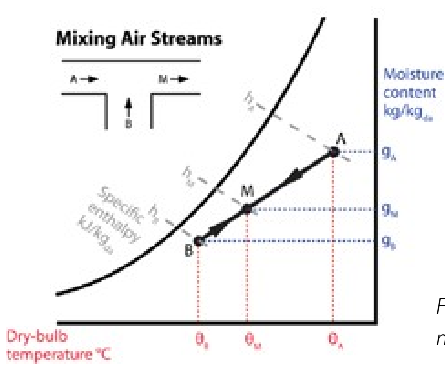


Figure 17: Mixture of two air streams. Flow A and B are mixed, resulting in M. (Source: CIBSE Journal, 2009-10)

A common skill is determining the output conditions of the mixture of two air streams. The important concept to first understand is that the output conditions of the mixed airstream will be most similar to the air stream that has the most volumetric flow rate. The second concept is that the dry bulb and humidity ratios change linearly. For example, if 2000 m3/hr at 20°C dry bulb is mixed with 2000 m3/hr of 30°C dry bulb, then the resulting temperature will be located equally in between 20°C and 30°C. The resulting temperature will be 25°C (dry bulb). The psychrometric chart helps find the air mixing state taking into account temperature and humidity. This is shown on figure 18 where flow A and B are mixed (A greater than B), the resulting mixture is M.

2.8 Considering values and restraints

The value of the building envelope and the experience for the visitor are also crucial for the museum's reputation. The reuse of historical distribution and emission systems is often preferred. Additionally, installing complex air handling systems in combination with a historic building envelope is always a difficult issue. Both the space they take up for generation and the impact of creating distribution channels can have irreversible consequences for the building envelope and/or be very visible.

As there are many stakeholders within the cultural heritage sector and small to medium-sized institutions frequently have no one responsible for the maintenance of (complex) systems, choosing a low-tech, robust, solution combined with less stringent climate requirements is often appropriate. When choosing a system, long-term maintenance costs should definitely be factored in. In addition, it is advisable to provide a procedure that takes into account large fluctuations in both T and RH in case of emergencies (e.g. technical failure or system failure).

SOURCES

TOOLS:

- Dew point calculator: http://www.dpcalc.org/
- Tool: https://comfort.cbe.berkeley.edu/EN

GLOSSARY:

3. Collections

Author: Annelies Cosaert – Royal Institute for Cultural Heritage (KIK-IRPA)

- T = Temperature (°C)
- RH = Relative humidity (%)

3.1. Introduction: collections and risk

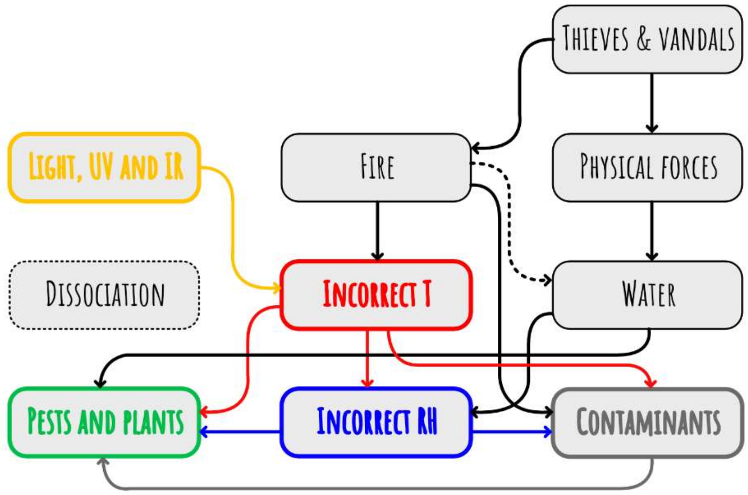
When considering changes in indoor climate it is advisable to analyze all potential risks. The risks that can cause damage to collections are known as 'agents of deterioration'. Often, an unsuitable climate is not the biggest risk a collection is exposed to. It is therefore worth prioritizing reducing other risks first.

The ten agents of deterioration are physical forces, water, fire, thieves and vandals, pests and plants, (ultraviolet, infrared (IR) and natural) light, contaminants, dissociation and incorrect temperature or relative humidity.

There are several popular methods to analyze the risks your collections are exposed to. There is the 'Cultural Property Risk Analysis Model (CPRAM)', the 'ABC Method' and the 'QuickScan' (see figure 20, 'all agents'). Each of these methods have their particular strengths. CPRAM is an all-encompassing and detailed method. The ABC and QuickScan methods are less time consuming to perform.

When changing aspects of the environment, it can be important to consider the impact on other risk factors. The scheme below identifies the most important relation between the different risk factors.

Fig. 18: Different agents of deterioration categories and their primary potential impacts upon other agents. (Based on Taylor, 2012)



The full collection environment also encompasses contaminants or pollutants, light and pests and plants (mold).

When we relate the risks of an unsuitable indoor climate to other agents (as stated by the Cultural Heritage Agency of the Netherlands, 2017), it is important to note that;

— In relation to physical forces, hygroscopic materials can get more brittle at low RH. Polymers can become glassy and less flexible under their glass transition temperature, this increases the risk of mechanical damage (fracture).

— Opening doors to increase ventilation can increase the risk of theft and vandalism.

— The presence of climate control systems that use electricity increases the risk of short-circuits and fires.

— In relation to the presence of water, using humidifiers (mobile or as part of a larger system) increases the risk of leaks. High RH can also lead to condensation on colder surfaces.

— At higher temperatures transport and release of contaminants are accelerated. Temperature differences create airstream patterns that move particles around. At high RH some pollutants become more reactive.

— In relation to light, infrared (IR) radiation is absorbed by surfaces causing a temperature rise and subsequent decrease of RH.

At high RH or T, labels can detach and cause dissociation.

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

Fig. 19: Methods or tools available that help you analyse collection care / damage in relation to exposure to certain agents of deterioration. (Source: Cosaert and Beltran, 2022)

There are several tools and methods available to analyze the links between damage and an exposure to particular agents. It should be noted that analytical methods tend to favor agents that can be measured (e.g. mechanical damage due to bad art handling is therefore not included, even if it occurs frequently).

3.2. Climate and collections: mechanical, chemical and biological damage

It is important to note that mechanical changes are more often considered as damage than natural aging. The first is often a sudden change and the second a slow and constant process.

Mechanical 'damage': such as cracks, delamination, tears, impoundments, deformation, etc. These are largely caused by inappropriate RH in organic objects and by too high temperatures in thermoplastic objects.

Chemical 'damage' or 'aging': are chemical processes like hydrolyses, corrosion and oxidation. They are (with the exception of certain types of oxidation) less perceived as damage and are usually a process of natural aging. For chemically stable objects (such as quality oil paints), this is a slow and barely perceptible process. For unstable objects such as cellulose acetate (photographic film), remarkable changes can occur over a time span of 5-10 years. Chemical processes can be accelerated by present (possibly object-specific) pollutants. The sensitivity of an object to natural aging is usually related to the molecular energy of an element.

Biological 'deterioration': is associated with temperature in the context of mold development (persistently high T and RH). Pollution, in the form of dust particles, is also a good breeding ground for fungi. Biological damage can go undetected for a long time and consequently result in a mold explosion (or serious infestation) under triggering conditions.

The risk of these types of damage can be calculated for certain objects individually (see fig. 20: 'T & RH too high or low'). However, these risks are never considered as cumulative (e.g. if an organic object is subjected to continuous high T and RH, it will have a high risk of both developing mold, deformation and fastened natural aging). While the three individual risks can be limited, a combination of all of them can have a serious destabilizing effect.

3.3. Indoor climate components and set-points

For numbers in relation to set-points and standards, consult 'Standards, guidelines and interpretations'. The text below is simplified and only considered the most frequent set-point settings in relation to the most common damage or natural deterioration. More detailed sources are available (identified by a (*) in the sources).

Indoor climate set points are often defined by:

- An (historical) average T and RH
- 'Long term outer limits' or a long term maximum and minimum T and RH
- Allowed short term, typically 24h, T and RH fluctuations.
- Allowed long term, typically seasonal, T and RH fluctuations

A historical average speaks about the capacity of your building and what your objects in permanent collection or depot are used to. The more your climate is controlled, the more this is also a representation of the influence of your climate control system on your climate. Therefore interpretation is needed. In general we can observe the following impact:

- No climate system: correct representation of the natural capacity of your building envelope
- Heating only: T higher and RH lower in winter
- Cooling only: T lower and RH higher in summer
- Mechanical / natural ventilation: lower chances of mold development
- (De)humidification: RH higher when humidifying, RH lower when dehumidifying then naturally
- HVAC: climate is result of impact of natural building envelope quality + system performance

Long term outer limits are typically set to avoid extremes.

For T this means that:

- it's best to avoid constant high temperatures (increases the risk of mold, speeds up natural deterioration processes and it can melt or evaporated certain materials);
- and freezing (at some low temperatures, objects can become brittle and alternating between T above, below 0°C can have an impact on mechanical properties of objects. Condensation can occur)

For RH this means that:

- it's best to avoid constant high RH (increases the risk of mold and can lead to acidification, corrosion and oxidation);
- and it is recommended to avoid constant low RH (increase the risk of mechanical damage like cracks, shrinkage and delamination, formation of salts and increased embrittlement).

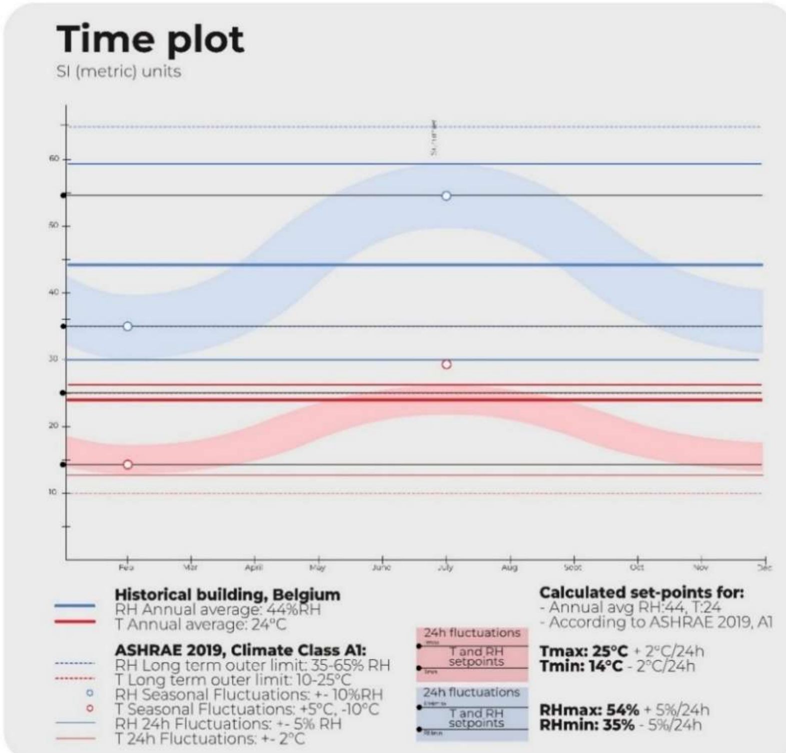
There are some notable exceptions: objects that are permanently frozen, permanently in a dry area, or not exposed to oxygen. They will also preserve well.

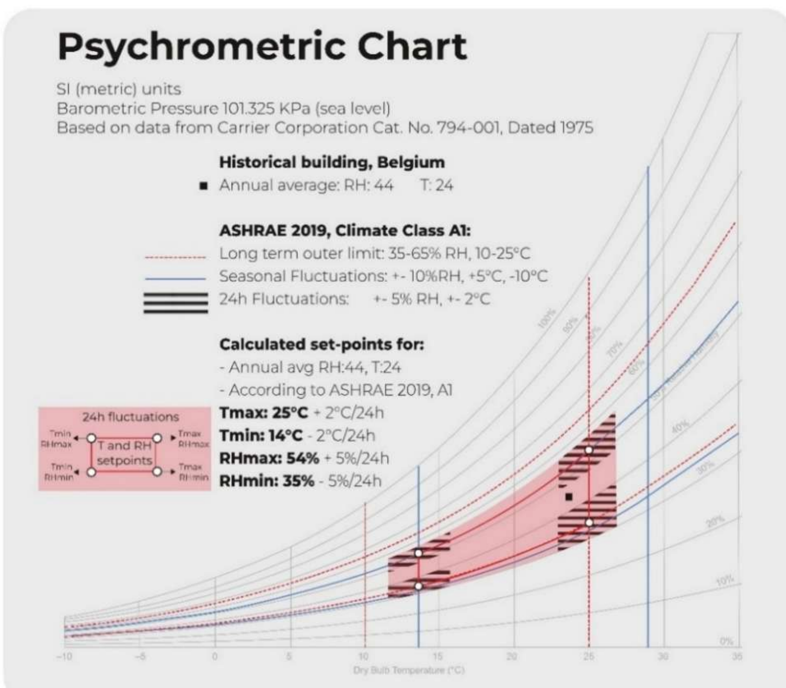
Short term fluctuations are usually defined as 24h fluctuations. However, often a much longer exposure is required to initiate a material response.

- T fluctuations are especially important when it comes to mixed media. Materials will expand and contract in a different way. This can lead to different forms of mechanical damage of which one is detachment and delimitation;
- RH fluctuations relate to the response time of your objects and cause mechanical damage. Every organic object has a certain capacity of holding water. This capacity and subsequence response depends on a whole series of factors such as the material used and the thickness. This can lead to different types of mechanical damage and deformation;
- and both high T as high RH fluctuations can give spores an opportunity to germinate. After that they are capable of growing at lower T and RH.

It is important to note that 'Proofed fluctuation' is a term that is related to fluctuations and climatic extremes. It is observed that objects that go through a consecutive amount of repetitive cycles of RH fluctuations become less sensitive to mechanical damage (as long as

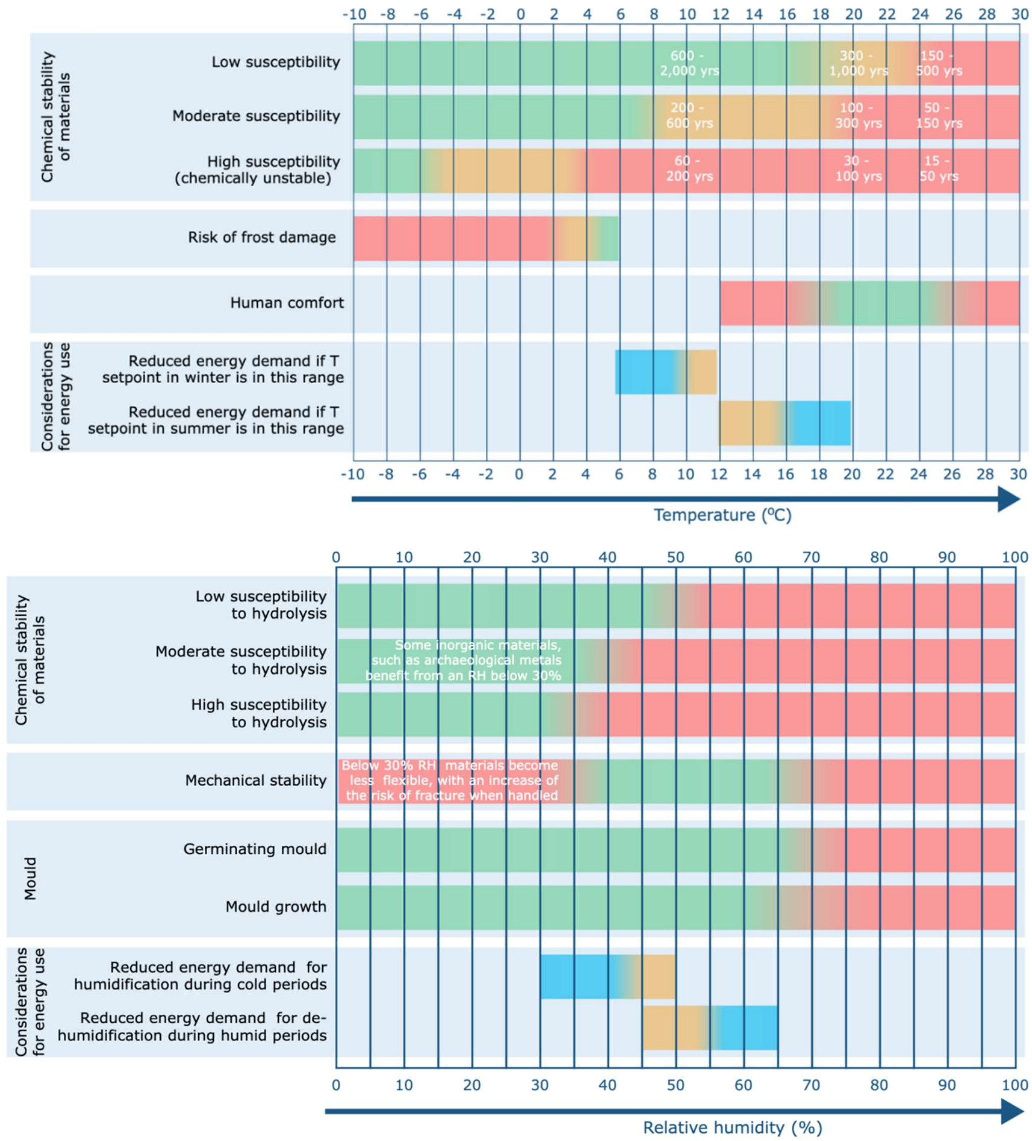
Fig. 20a and 22b: A psychrometric chart and time plot that display a ASHRAE A1 climate (fig. 24) with seasonal fluctuations (a) based on the same annual average. Because the T annual average is high, the seasonal fluctuations surpass the long term outer limit in summer time. It will be difficult to obtain an A1 climate in this building.





This is a draft version of the Handbook that will be published with corrections and additions as part of the Climate2Preserv (C2P) project.

Fig. 21: PAS198:2012 is a guideline that identifies risks for different types of collections and links them to energy use. (Source: Dutch Heritage Agency, 2017)



they have not undergone any structural changes). The mechanical tension that can result in cracks and deformation, has released itself and will therefore not reoccur.

It is very important to take object damage as the basis to implement changes. In other words: if there is no damage, no stricter climate setpoints are needed.

A visualization in the 'PAS 198:2012' guideline visualizes the sensitivity of certain materials to T and RH.

3.4. Types of objects: relation to relative humidity and temperature

Material response is often based on tests on paper, wood, acetate film and metals. This is important to know because, while all objects respond differently to indoor climate, risk is often expressed in relation to these specific objects that represent a 'mixed collection'.

If we look broadly at their response to their environment we can identify large groups:

- Organic objects: these often form the bulk of collections as they comprise all wood (e.g. panel paintings and wooden sculptures), all cellulose based objects (e.g. paper or cellulose acetate film), many textile-based objects (e.g. objects made out of wool, cotton, linen and silk), ethnographic objects and taxidermy (often mixed with non-organic materials), and others like bone, straw, etc. This is a very wide range of objects that can have a very different sensitivity to RH because they all contain water and all are susceptible to hydrolysis.
- Non-organic objects: non organic objects are stone, glass, ceramics and other objects like pearls. They all have a lower sensitivity to water. While metals are non-organic, they are placed into a separate category.
- Metals: because of their specific response to RH, metals are in a different category. At high RH they tend to oxidise and corrode. While oxidation can result in a protective patina, corrosion is clearly considered as damage. Metals prefer a low oxygen, low temperature, low humidity environment.
- Synthetic objects: such as plastic objects, textiles (like polyester, viscose, etc.) and acrylic paintings, are often relatively unstable objects. They tend to profit, like metals, from lower temperatures and a stable RH.
- Other objects: some objects can require highly specific care such as mummies, archeological metals, crizzling glass, nitrate film, specimens on formaldehyde, etc.

3.5. Special climate control considerations in cultural heritage institutions

There are different types of climate control strategies for collections. They are based on collection needs and material response. Climate classes are often defined by standards and guidelines and can simply consist of an upper or lower limit or more specifications (allowed fluctuations etc.).

In practice we see that not all rooms can be conditioned based on the needs of every individual object. Therefore, larger spaces are conditioned based on the needs of mixed (often organic) collections. When public, T in most of these areas is also influenced by the need for human comfort.

However, special collections are often located in spaces with a specific function:

- Cool, cold and frozen (storage): used for objects that are chemically unstable, most notably photographic films and many different types of plastics.
- Climate chambers: can be used for research purposes as well as acclimatization of objects. This can simply be a room where moving objects (coming from another location or a lending institution) can adapt slowly to the institutional climate while

remaining in their crate (taking advantage of the buffering capacity of their crate). They can also have separate climate control systems with flexible controls.

- Quarantine rooms: can be used as temporary housing when an object is a danger to other objects in the room (e.g. an infestation or mold is detected or serious off-gassing is present). They are often combined with climate chambers or treatment rooms (e.g. anoxia). It is very important these rooms are isolated (including ventilation) from other rooms.

- Treatment / conservation labs: while objects are in a process of being restored, they can be at their most fragile, since they are stripped from their protective layers (e.g. varnish of a painting is removed). Furthermore, structural changes might be applied possibly leading to unknown mechanical damage.

- Low oxygen (storage / display cases / treatment chambers): low oxygen environments (or rather nitrogen environments) are seldom used for large scale storage. However, the lack of oxygen has a positive impact on the presence of different organisms and slows down oxidation processes. These environments are more often used for treatments against insects (in bags or separate chambers), called anoxia, or on a small scale to save highly valuable, very sensitive objects (e.g. extremely valuable paper objects or mummies). This said, these types of solutions are very object-based because the presence of nitrogen also has its consequences. Furthermore, on the level of oxygen, these spaces allow for no or a limited human presence.

Use of additional barriers / buffers:

- Use of microclimates (intentional): microclimates are any type of extra envelope, be it packaging, closed frames, display cases, closed storage furniture, etc. These extra layers of 'protection' prove (even if not intentionally controlled) very efficient in reducing RH fluctuations. When relatively airtight, these 'micro environments' can be separately controlled both in passive as mechanical ways.

- Use of packaging: primary (e.g. a box) and secondary packaging (e.g. acid free paper), in particular when dealing with organic materials, act, together with the objects themselves, like a buffer, and can eliminate all short-term fluctuations.

- Impact of collection mass: large quantities of organic materials will function as a buffer for the environment they reside in. For large quantities of cellulose based materials (many archives), the impact of the collection mass can be calculated (fig. 20, moisture calculator).

Loans have been mentioned several times. A loan is an object that another institution gives, temporarily, to another museum, often for an exhibition. Loans can be both short and long term. The conditions for a loan are stipulated in a loan agreement. This agreement contains details on the mode of transport, the duration of the loan, the indoor climate and potential protective measures, etc. On the side of the lender, a facility report is provided in which the conditions and safety measures an institution offers are described. Often loan agreements demand strict climate control. Even when the climate in the lending institution is not that strict. Furthermore, many institutions blame loans for needing a narrow band of climate control. It is therefore important to define a climate that is realistic and not narrower than the institutional climate. The risk of mechanical damage (increasing and decreasing stress and strain in objects) can be estimated (fig. 20, HERIe).

Lastly, it is important to mention the use of movable climate control elements. Many institutions have portable or movable devices to provide extra control to one or several spaces, sometimes on top of existing control elements (which can skew T and RH system measurements). These elements, like small electrical heaters, mobile (de)humidifiers and air-conditioning units, are often low cost and can be used in a flexible way. While they have proved useful, it is important to note that they should be reliable, well maintained and connected to a stable electricity network. Electrical equipment has often been the source of disastrous fires, certainly combined with lack of surveillance and fire prevention.

3.6. Guidelines and interpretations

There are different international and national guidelines for collection care. They should be considered as a basis to determine your institutional guidelines.

The choice of not controlling a climate can always be a valid one, if a collection shows no fast signs of deterioration of damage and / or, if there is an active choice for monitoring to detect problems early on (e.g. regular monitoring of mold). The museum policy should take into account the possibilities the building, climate control and budget (in relation to the cost of technical support and energy) offer.

Some of the most referred to guidelines / texts and their application are defined below (using the ASHRAE guideline as basis):

— ASHRAE Handbook (2019), Chapter 24: Museums, galleries, archives and libraries : is the most referred to text in loan agreements, and more importantly, the climate classes stipulated in this agreement (table 13A). It cannot be freely downloaded. It is written by HVAC engineers in conjunction with international conservation experts, and covers all environmental collection risks. Additionally, it describes the commissioning process if a new system design is required. It is interesting to share this text with architects and engineers, since it is written in a language they understand, and it summarizes specific design needs for cultural heritage institutions.

— Bizot Green Protocol (2014): Bizot is a group of museum directors to some of the world's largest museums. They have formulated 'more relaxed' loan standards in order to allow museums to save energy and be less discriminatory toward museums with particular outdoor environments. While the point of departure might not have been optimal object preservation, this guideline has been widely recognized as acceptable within the museum field. This document is more of a statement rather than a very technical or scientific document.

— International Institute for Conservation of Historic and Artistic Works (IIC) and International Council of Museums – Committee for Conservation (ICOM-CC) environmental guidelines: have formulated a series of remarks on the Bizot Green Protocol (and other national guidelines). These remarks provide some scientific context to the Bizot Protocol. This is a document intended for the conservation community.

Fig. 22: The values for the most referred to international guidelines compared. Notice ASHRAE AA, a much referred to climate class for loans, is not mentioned here since it is considered unnecessarily strict for most heritage objects. This does not take away from the fact that special climates should be considered for those objects that need them.

International guidelines

Existing guidelines can serve as a reference for your institutional climate

	(Annual / hist.) average		Seasonal fluctuations		Long term outer limits		24h Fluctuations	
	T and RH averaged of a representative yeart or a longer period. It's an important starting point for collections that have resided in the same building / climate for a long time. If unknown, an educated guess can be made. Be open to revision after measurements.		Fluctuations **starting from the annual / historic average** allowing for seasonal variations. Seasonal fluctuations will reduce the energy consumption and can relieve stress from mechanical systems. Seasons can be determined regionally (e.g. including monsoon).		Represent the **minimum and maximum values that should not be surpassed** (with a possible exemption of 24h or short term fluctuation). These outer limits are mainly determined to reduce the risk of mechanical response and mold germination		Are related to the **response time of object** or the time an object needs to respond to environmental changes. Lesser daily / hourly / weekly changes will cause lower stress and strain. E.g. unframed paper will respond faster to RH ↓↑ then a wooden sculpture.	
2014 - ICOM-CC & IIC Environmental guid.	Series of remarks endorsing the 'Bizot Green Protocol' (international), AIC (American, national) and AICCM (Australia, national)							
2019 - ASHRAE Climate class A1	T: annual avg.		T: +5°C, -10°C	RH: +10%, -10%	T: 10 - 25°C	RH: 35 - 65%	T: ±2°C	RH: ±5%
2019 - ASHRAE Climate class A2	exhibition rooms: human comfort	RH: annual avg.		RH: no change				RH: ±10°C
2019 - ASHRAE Climate class B			T: +10°C, -20°C	RH: +10%, -10%	T: < 30°C,	RH: 30 - 70%	T: ±5°C	
2019 - ASHRAE Climate class C	T: usually < 25°C	RH: between 25 - 75%			T: < 40°C	RH: > 25 %, < 75%	T: rarely > 30°C	not continually above 65% for x days
2019 - ASHRAE Climate class D		RH: reliably < 75%				< 75%		
2019 - ASHRAE Loans	Loans are not tied to a climate class. They are the result from a negotiation between two parties taking into account their respective climates.							
2014 - Bizot Green Protocol			T: 'stable'	RH: ±10%	T: 16 - 25°C	RH: 45 - 55%	T: 'stable'	RH: ±10%
ISO 18934:2011 Cool storage	T: 12°C (fixed avg.)				T: 8 - 16°C			
ISO 18934:2011 Cold storage	T: 4°C (fixed avg.)				T: 0 - 8°C	RH: 30 - 50%		
ISO 18934:2011 Frozen storage					T: -20 - 0°C			

This is a draft version of the Handbook that will be published with corrections and additions as part of the Climate2Preserv (C2P) project.

- International Organisation for Standardisation (ISO), CEN (European Committee for Standardisation*): these are norms that are formulated by a scientific committee. There are several norms that can be applied to heritage. They define standards but also formulate methods to obtain these standards. These norms also function as quality labels that can be obtained by an institution. However, considering climate control, they are mostly used as informative guidelines.
  * The CEN norms are known in other languages as the British Standards Institution (BSI), Association Française de Normalisation (AFNOR), Deutsches Institut für Normung e.V. (DIN) norms.
- National guidelines: many countries have environmental guidelines for collections based on their outdoor climate, the type of buildings they have and the seasonal variations they encounter.

4. Energy

Author: Dr. Sebastien Thomas – University of Liège
Co-author: Dr. Marcin Zygmunt – Catholic University of Leuven

In SI system
- Energy = E ≡ Joul = N.m
- Power = P ≡ Joul / sec = Watt

In British system
E ≡ Btu, ft.lb
P ≡ Btu / hr , ft.lb / s
hp = 550 ft.lb / s
1 kW = 1.341 hp

Power is energy per time unit:
- 1 W = J/ s
- 1 J = W.s
- 1 kJ = 1 kw.s
- 1 kJ = 1 kWh / 3600

Other energy units:
- 1 kWh = 3600 kJ
- 1 calorie = 4.18 J
- 1-ton equivalent petrol = 1 tep ≈ 11600 kWh
- 1 petrol barel = 0.137 tep ≈ 1600 kWh

4.1. Introduction energy and life cycle analysis

The C2P project's core purpose is energy savings. It must be included in a more global question of environmental impact. These are commonly computed using the equivalent greenhouse gases emissions quantification (carbon dioxide equivalent). Different scopes can be used to evaluate the impact and are defined by the 'greenhouse gas protocol':

The greenhouse gas equivalent approach is probably the most popular one; nevertheless several others indicators exist: soil use, human toxicity, eutrophication, biodiversity, emission of particulate matter, water resources and ozone depletion.

In our case (renewing or refurbishment of an existing collection store/museum), two separated environmental impacts can be evaluated:

- Direct energy use by the building and its HVAC systems (i.e. energy bills of the facility). These are included in 'soil use' and 'human toxicity', energy is converted into equivalent CO2 impact.
- New installed equipment has impact due to its construction phase and end of life. These are included in 'eutrophication'. A deep analysis should be done to evaluate the equivalent CO2 impact of the equipment to be installed. This is sometimes done and can be found in equipment life cycle analysis (or assessment) documentation.

Defining the real needs in terms of indoor climate will greatly affect direct energy use. In this project, direct energy use savings are quantified more than equipment life cycle analysis. Equipment installation and its related installation works is hard to evaluate precisely. In this project, we firstly promote a better use of current equipment according to a smart collection needs evaluation instead of replacement with brand new equipment.

4.2. Energy basics, units and order of magnitude.

Energy refers to "the capacity to carry out transformations". For example, energy is what makes it possible to provide work, produce movement, modify temperature or change the state of matter. In museums, this refers mostly to maintaining temperature, humidity and air quality for collections preservation and eventually for visitors / workers comfort. Other energy uses in museum buildings are lighting, screens, computers and other electronic devices.

Some orders of magnitude:

- 1 J ≈ energy required to raise a 100g apple 1 m
- 1 J ≈ energy required to increase 1°C 1 liter of dry air
- 4.18 kJ ≈ energy required to increase 1 liter of water by 1°C
- 2500 kJ ≈ 0.7 kWh ≈ heat of vaporization of one liter of water
- 10 kWh ≈ 1 liter of fuel oil ≈ 1 m^3 natural gas ≈ 2 kg dry wood
- 1 kWh ≈ the mechanical energy that an athlete can provide in 1 day
- 1 average Belgian home (heating) = 15,000 – 20,000 kWh/year
- 1 new home according to current legislation (in heating) = 5000-10000 kWh/year
- Domestic hot water for a 4-people dwelling = 2800 – 3500 kWh/year
- 1 kW/m^2 ≈ solar radiation power on a well oriented surface in sunny conditions.

4.3. Energy conversions

A series of energy conversion is needed to provide the service (i.e. adequate climate in the building). Different types of energy use can be distinguished. In the figure below, we see different ways to measure energy, depending on the conversion state.

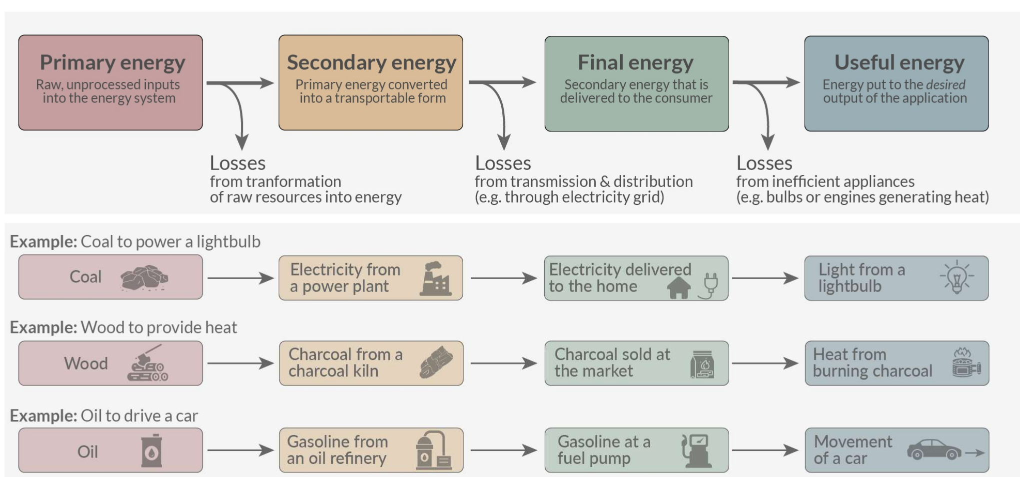


Fig. 23: *Four ways of measuring energy. (Source: Hannah Richie for Our World in Data)*

— **Primary energy**: conversion of secondary energy into energy "withdrawal" from nature. This helps environmental impact computation, it corresponds to the raw inputs.

— **Secondary energy:** conversion from primary energy to a transportable form. This term is rarely employed in energy use of buildings.

— **Final energy or consumption**: energy consumed to provide the energy service. This is energy you pay (electricity or gas, oil, …)

— **Useful energy / Net demand or need:** the energy required to ensure the energy service. For HVAC system it is the energy required to maintain the indoor temperature and humidity setpoints.

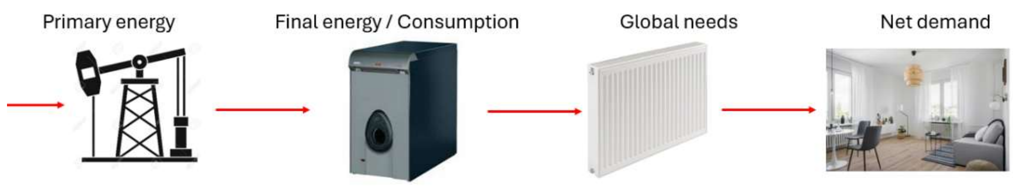


Fig. 24: An example on energy conversion for heating a building.

The losses from final to useful energy include mainly losses of generation, distribution and emission of heat/cold. C2P project focuses on evaluating the **net demand** and **minimizing losses from final to useful energy.**

4.4. Energy carriers: installation cost, energy cost and impact on building envelope

Still focusing on climate control of buildings, in the table below are the most frequent energy conversions linked with the different energy uses (in italic is the most popular in large museums in Western European cities). The energy carrier is finally paid to the energy provider. The list is not exhaustive, energy carriers are electricity, gas, oil, coal, wood pellets, district heating/cooling, etc.

In the text, climate control represents heating and cooling (H&C) of zones as well as humidifiation/dehumidification.

All other equipment linked with H&C have electricity as energy carriers. The pumps, fans, controls, valves are fed with electricity. In some cases, a compressed air network is used to activate some devices (e.g. pneumatic valve). Ultimately, the compressor is driven by electricity.

Energy carrier electricity is often measured in total for a given building, it is not easy to separate the energy dedicated to HVAC systems. For gas use, there is sometimes a domestic hot water production that can also be driven by gas.

Table 2: Most frequent energy conversions linked to different types of energy use.
** water treatment and water pressure management is powered by various devices (pumps, filtering and other ultra violet lamps) all electricity driven.*
*** passive cooling systems do not use chillers to produce cold water / air. They use a cold source (ground, water tank, outside air) to cool down the building. This nevertheless consumes electricity for pumps and fans. Passive cooling systems are largely used to do sensible cooling but no dehumidification (due to the too high cold source temperature).*

ENERGY SERVICE	CLIMATE CONTROL DISTRIBUTION	GENERATOR	ENERGY CARRIER	I	E	S	B
Heating	*Central heating : AHU, radiator heating, surface heating, fan coil units.*	*Furnace*	*Gas*				
			Wood				
			Oil				
			Coal	/	/		
		Heat pump	Electricity				
		Electrical resistance	Electricity				
		District Heating sub station	District Heating		/		
	Direct heating	Wood/pellet stove	Wood				
		Gas stove	Gas				
		Electrical resistance	Electricity				
		Local heat pump	Electricity				
Humidification	*Central heating with AHU*	*Centralised Steam boiler*	*Gas*				
			Wood				
			Oil				
		Decentralized steam boiler	Electric				
		Atomizer	*				
		Humidification wheel	*				
		Air washer	*				
	Direct humidification	Ultrasonic Atomizer	*				
		Vapour generator	Electricity				
Cooling & dehumidification	*Central cooling : AHU, chilled beam, surface cooling, fan coil units.*	*Vapour compression chiller aka "Chiller"*	*Electricity*				
		Ab-adsorption chiller	Gas / District heating				
		District cooling sub station	District Cooling		/		
	Direct cooling	Room air-conditioner	Electricity				
Cooling only	Central cooling : AHU, chilled beam, surface cooling, fan coil units.	Passive cooling system: geothermal heat exchanger, cooling tower	**				
Dehumidification only	Direct dehumidification	Vapour compression chiller	Electricity				

IMPACT	Very low	Low	medium	High	Very high
I = Investment	From very low initial investment cost to very high initial investment cost				
E = Energy	From very low energy consumption to very high energy consumption				
S = Sustainable	From very durable and robust to short lifespan and high maintenance				
B = Building	From a non invasive measure and reversible to irreversible and invasive for the building envelope (and interiors)				
/ = To many variables, non applicable					

4.5. Renewable energy sources

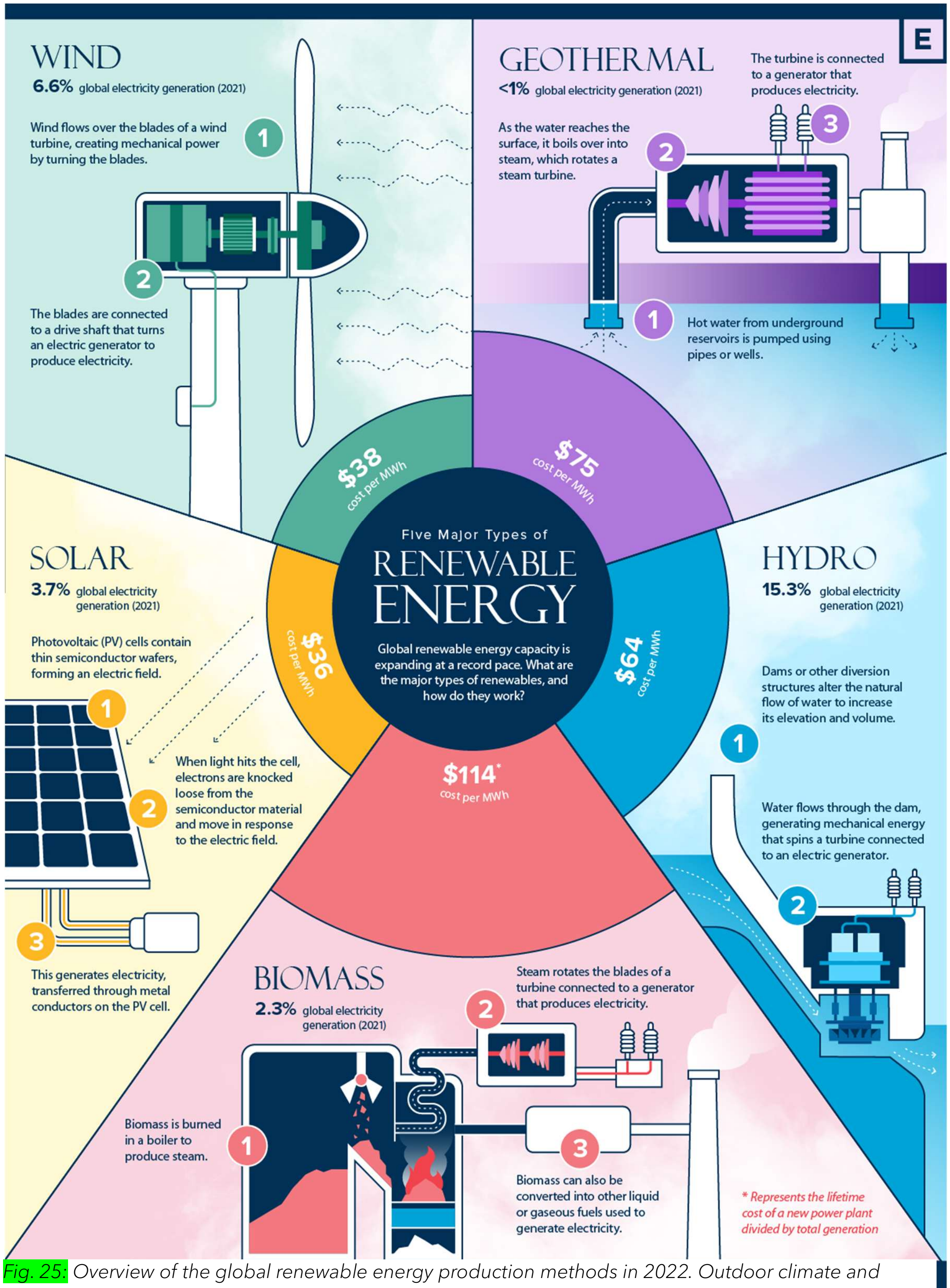


Fig. 25: Overview of the global renewable energy production methods in 2022. Outdoor climate and presence of natural resources have a big impact on the efficiency of the RES. This subject of this table is evolving quickly, both the efficiency of production as the investments in particular production method. (Source: Lazard's Levelled Cost of Energy Analysis 15.0, Ember's Global Electricity Review 2022, U.S. Department of Energy, Our World in Data, IEA)

Traditional energy production can be supported, or sometimes even substituted with renewable energy sources (RES). Conventional fuels (mostly coal and gas) can be successfully replaced with clean sources, with sun and wind leading the way. Green energy can be produced locally, for domestic purposes, as well as commercially, supplying the grid.

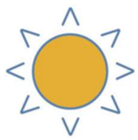
Energy source	Definition	Energy conversion	Usage options	Environmental considerations
Solar 	Radiant light and heat from the sun that is harnessed using a range of technologies	Active and passive heating, solar-thermal engines and photovoltaic (PV)	Heat and electricity production	No operational emissions, questionable disposal phase of PV cells and potential impact on wildlife and vegetation.
Wind 	Use of wind energy to generate useful work	Wind turbines (horizontal or vertical), typically mounted at tall heights on both land and sea	Capturing the kinetic energy created by the wind to produce electricity, according to Betz law[13]	Possible disruption of wildlife habitats, interference with birds, land erosion, and noise. No operational emissions.
Hydropower / Waterpower 	Use of kinetic or potential energy of water to produce power	Water turbines and hydro plants next to dams	Electricity production and mechanical energy	Negative impacts on fish and other wildlife (if constructed artificially), possible inundation of surrounding land and changes in water quality and downstream flows.
Biomass 	Matter from recently living (but now dead) organisms (e.g. wood, agricultural wastes), used for energy production	Thermal, biological and chemical methods, typically burned[14]	Heat, electricity production, and liquid and solid biofuels	Land requirement for biomass growth and the burning generates both emissions and solid wastes.
Geothermal 	Energy generated and stored in the Earth's core	Direct use, heat pumps, and power plants	Heat and electricity production	No emissions. Possible leaks of working fluid, as well as local effects like water use and noise.

Table 3: *Types of renewable energy linked to their different energy conversions, their usage options and environmental considerations.*

Nowadays we experience the renewables boom, with a year-by-year increase by a record margin. In 2023 the newly installed RES were 50% higher than in the previous year. For the

[13] *Betz's law shows that as air flows through a certain area, and as wind speed slows from losing energy to extraction from a turbine, the airflow must distribute to a wider area, resulting in geometry that limits any turbine efficiency to a maximum of 59.3%.*

[14] *Considered renewable because the used fuel (biomass) can be regrown or replenished*

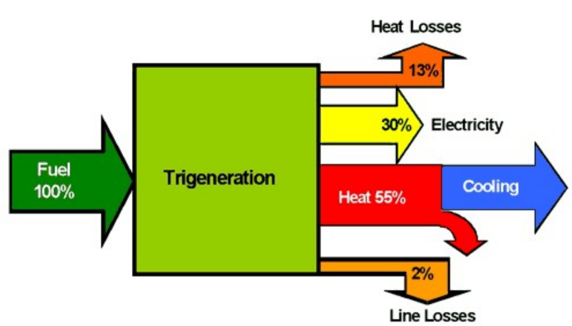
very first time in 2023, the share of renewable electricity production passed the 30% milestone, driven by an increase in solar and wind. Using more energy from renewable sources is crucial as a driver of sustainable development worldwide, following e.g. the 2015 Paris Agreement on Climate Change[15].

Renewable energy is energy generated from renewable, non-fossil-based energy sources which are replenished in a human lifetime. The 5 most traditional types of RES are solar, wind, hydro, biomass, and geothermal; they are discussed in the table below. Ocean energy[16] and hydrogen[17] can be mentioned as well, yet will not be discussed due to the early stage of development and commercialization. RES have significantly more advantages rather than disadvantages. Unfortunately, some RES systems are still more expensive than the traditional ones. Yet, considering the withstanding energy price growth RES should become the undoubtable leader in profitable fuel. Still, the biggest disadvantage of RES is their intermittency and dependency on local climate conditions. Thus, at the current stage of technology development, RES should support the traditional energy sources, considering their full replacement in the future.

4.6. Cogeneration and trigeneration.

Talking about RES, cogeneration and trigeneration should be mentioned, as techniques to produce energy more efficiently. Cogeneration, or combined heat and power (CHP), is a technique allowing the production of heat and electricity simultaneously, powered by just one primary energy source. Thus, this technique guarantees a better energy yield than from two separate traditional production sources, usually with much lower environmental impact. Trigeneration or combined cooling, heat, and power (CCHP), is a superior technique to cogeneration: a process in which some of the heat produced by a cogeneration plant is used to generate a cooling factor, e.g. chilled water for air conditioning or refrigeration. Application of CHP or CCHP should be considered especially for specific commercial and industrial buildings.

Fig. 26: Schematic overview of trigeneration. (Source: Salman Zafar for EcoMENA, 2022)



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[15] *An international treaty on climate change, covering climate change mitigation, adaptation, and finance, accepted by 195 members of the United Nations Framework Convention on Climate Change*

[16] *All forms of renewable energy derived from the sea, in particular from waves, tidals and ocean thermal*

[17] *Mostly the so-called green hydrogen (GH_2), produced by the electrolysis of water, using renewable electricity*

4.7. Energy auditing and performance testing

Typical Energy Audits

Energy audits systematically assess building performance, system efficiency, and consumption patterns to identify improvement opportunities. They range from basic walk-through assessments focusing on obvious inefficiencies to comprehensive detailed audits involving extensive measurements and modeling. Standard audits typically deliver reports with prioritized recommendations, cost estimates, and expected savings, but preparation requires providing building documentation, utility records, and ensuring access to all building systems.

Typical Performance Tests

Performance testing measures actual building and system efficiency through specialized equipment and procedures such as blower door tests for air leakage, thermal imaging for envelope assessment, and HVAC system efficiency testing. These tests provide quantitative data on building performance gaps and verify whether systems operate as designed. The investment in performance testing typically pays off when planning major improvements, diagnosing persistent problems, or when required for regulatory compliance or grant applications.

Historic Buildings Challenge

Standard energy audits often inadequately assess historic buildings because conventional energy models cannot account for traditional construction techniques, material properties, and performance characteristics unique to heritage structures. Historic buildings require modified assessment approaches that consider heritage constraints, traditional material behavior, and regulatory limitations that restrict conventional energy improvements. Successful energy assessment of cultural heritage buildings requires specialists experienced with both energy analysis and historic building conservation principles. Additionally, building audits or assessments rarely consider collection care principles.

CONCLUSION

This section has provided the essential knowledge to assess and understand the four critical components of any cultural heritage institution: buildings, systems, collections, and energy. The foundational understanding presented here enables effective evaluation of current conditions and cross-disciplinary collaboration.

The buildings chapter covered building physics fundamentals, envelope assessment methods, and visual inspection techniques for identifying moisture, thermal, and air leakage issues. It explained how climate requirements drive envelope performance needs and established when professional building diagnostics become necessary.

The systems chapter introduced climate control fundamentals, system types, and psychrometric principles governing environmental management. It detailed system components, their interactions, and the operational constraints different institutional types face in maintaining collection environments.

The collections chapter provided the risk assessment framework essential for environmental decision-making. It explained how different materials respond to climate conditions, methods for evaluating collection vulnerabilities, and approaches for balancing preservation requirements with operational realities.

The energy chapter introduced lifecycle analysis concepts, energy conversion principles, and renewable energy basics. It connected energy decisions to environmental impact and established when specialized energy assessment becomes necessary.

Most importantly, these four components are interconnected. Building envelope performance affects system efficiency and collection environments. System operation influences both energy consumption and preservation conditions. Collection requirements drive system design and building performance needs. Energy choices impact all three domains. This systems thinking prevents unintended consequences and reveals opportunities addressing multiple challenges simultaneously.

Understanding these interconnections enables effective collaboration between team members from different backgrounds. The collections manager can now participate meaningfully in discussions about system limitations and building constraints. The facilities engineer understands why certain collection requirements cannot be compromised. The administrator appreciates how building characteristics affect both energy consumption and preservation outcomes. This shared knowledge base transforms potential conflicts into collaborative problem-solving.

Each domain offers assessment methods that teams can implement independently, from visual building inspections to basic system performance observations to collection risk evaluation. These assessments provide the foundation for identifying priorities and communicating effectively with external specialists.

This understanding equips teams to proceed with systematic data collection and collaborative planning, enabling the identification of institution-specific opportunities for sustainable operation that preserves collections while reducing environmental impact and operational costs.

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UNDERSTANDING WHAT YOU CAN DO

This chapter explores practical intervention options across all domains: buildings, systems, collections, and energy. It emphasizes the connections between them. Reading requires the foundational knowledge from the previous chapter 'understand what you have', though experienced professionals may navigate their specialized sections independently.
The chapter deliberately avoids specific numbers because building envelopes, collection needs, and outdoor climates vary greatly worldwide. What works for a stone building in a temperate climate differs fundamentally from solutions for timber construction in hot, humid conditions. Instead, the focus lies on decision-making frameworks, intervention timelines, and understanding the relationships between different approaches.
Timeline estimates for maintenance and interventions reflect this complexity: while systems often involve standardized manufactured components, buildings and collections depend heavily on original material quality and traditional techniques. The chapter prioritizes optimization and modification strategies over major renovations or new construction, aligning with C2P's emphasis on working with existing resources while minimizing environmental impact through extended building lifespans.

1. Buildings

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1.1 Introduction

The variety of buildings and building techniques worldwide is endless. While some buildings holding collections are relatively new and purpose-built, others have been around for centuries and have stood the test of time, serving as guardians for our collections. New or old, some buildings face greater challenges and some buildings perform their tasks better than others. What all buildings have in common, however, is that they need regular maintenance and that they face new challenges due to climate change.

Regular building envelope maintenance is essential regardless of construction type or climate, though specific practices vary dramatically worldwide. Correct water management - whether through gutters, drainage channels, sloped surfaces, or traditional runoff systems - prevents water penetration that can create humidity problems and structural damage. Roof systems, from ancient stone slabs to modern membranes, require maintenance appropriate to their materials and design to prevent leaks that damage collections and create conditions for potential biological growth. Window and opening maintenance ensures seals, shutters, or traditional coverings remain effective for both security and environmental stability, whether dealing with extreme heat, cold, humidity, or dust infiltration.

Many cultural heritage buildings worldwide rely on passive environmental control systems - from carefully oriented openings in desert architecture to sophisticated ventilation in temperate climates - that require regular maintenance of airflow pathways to function effectively. Clay-based structures may need periodic re-coating, plastering, or repairs, while stone buildings require attention to mortar joints and drainage. Modern glass and steel structures demand different approaches, focusing on mechanical systems and building envelope performance.

1.2 The buildings lifespan and impact on energy consumption

The construction industry is responsible for approximately 39% of global CO2 emissions, including both operational and embodied carbon, making it one of the biggest industries contributing to global warming. In a certain sense, the most sustainable museum is therefore considered to be 'a museum that has not been built'.

Just as any other product, a building has a life expectancy, commonly expressed as a life cycle. There are several ways to analyze this:

- Life cycle assessment (LCA): focuses on the environmental impact over a selected part of a building's lifespan;
- Life cycle cost (LCC): the economic assessment of a building or its part of its assumed lifespan;
- Whole building life cycle analysis (WBLCA): a specific application of the LCA method dedicated to buildings, often guided by additional building-specific standards; Its scope focusses on capturing both embodied and operational carbon impacts; WBLCA assessment is commonly linked with the multicriteria certification rating systems such as BREEAM, LEED, or DGNB.

An LCA or WBLCA can be extended by a LCC since for all building projects, there is a budget involved. However, these are complex analyses, and they are not classically performed for all buildings. Nonetheless, their application can grant insight into different stages in relation to consumption and cost.

A building's lifespan (according to a WBLCA) can be simplified into the following stages:

- Product stage: from the raw materials supply to the manufacturing stage;
- Construction process stage: the building stage, including transport until the building is ready for occupation;
- Use stage: the time the building is used until its torn down. This can include periods of abandonment, renovation, or partial destruction and rebuild due to conflict, budgetary restrictions, change of use, etc.;
- End of life stage: from deconstruction or demolition to disposal of materials.
- In addition, recycling, reuse, energy recovery, and exported energy are taken into account as Beyond the Life-Cycle stage, having a surplus positive impact on the environment.

For cultural heritage institutions, extending building lifespan becomes particularly important as it amortizes the high embodied carbon of construction materials over a longer use period. A Danish study focusing on ‘Lifespan prediction of existing building typologies’ shows a tendency for a declining lifespan based on the construction period, in which the lifespans of newer buildings (no more than thirty years old) are 45% shorter than the average lifespan for all construction periods. Recent research emphasizes that extending

building lifespans to 75-80 years, combined with right-sizing approaches, can reduce carbon emissions by up to two-thirds compared to shorter building lifecycles.
We can assume that if the building and its systems are well-maintained throughout the expected life cycle, then the extended use phase has a meaningful impact on reducing total carbon emissions. The longer the life cycle of a building, the lower the impact of embodied carbon, and the greater the emissions out of the operational phase. We should focus on extending the life expectancies of buildings, simultaneously maintaining them well (with possible renovations).

Since, worldwide, the majority of collection care institutions are housed in historic buildings. European cultural institutions show a high proportion (estimated 80-95%) housed in historic buildings due to extensive conversion of palaces, castles, and historic structures. In contrast, regions with rapid recent development, like China, show more mixed patterns (estimated 50-70%) with many institutions in purpose-built modern facilities alongside significant historic site museums.

Because these types of interventions are based on local standards and are highly climate and material-specific, we will therefore focus on the use phase of a building. Moving forward, we predominantly provide information on buildings that are:

- Already constructed,
- Envisioned to last as long as possible,
- While including possibilities for optimization and modernization, but excluding full building renovations.

It is worth mentioning that, despite regional differences in the interpretation of authenticity, it is essential that, however it is defined, a reflection is made on the impact of any building changes. Please consider impact on the heritage values, building use, fabric, use of traditional techniques, materials, and methods, etc. ### REFER TO GREEN WHEEL AS TOOL ###

1.3 Ongoing efforts: maintenance & minor interventions (1-10 years)

During the use phase, maintenance remains a constant yet obligatory operational cost that varies significantly across cultural heritage building types and purposes. The predictability of these costs depends heavily on building characteristics, system complexity, and institutional capacity. The costs of maintenance and minor interventions are necessary to minimize the total operation cost in the long-term.

Unexpected maintenance or repair

Accidents or failures happen. If calamities occur, it is recommended to respond quickly and fix the fault correctly to avoid additional problems in the future. A common example is water leakage from a leaking pipe/valve: if not fixed perfectly, it might cause leakage in the future.

Annual maintenance

Annual maintenance of building envelopes typically targets the control of liquid water intrusion and the mitigation of hygrothermal loads. In other words, it's about maintaining control of the permeability of the building envelope for water, air, and (in some cases) light. It includes interventions such as the cleaning of gutters, roof drains, drainage systems, and downpipes. Additionally, there are visual inspections of the building envelope for cracks, gaps, or damage, fixing them as they are observed. Early observations of structural problems are extremely important for long-term maintenance as they might be fixed relatively easily while at a later stage, the cost might high.

Short-term (2-10 years)

In the short-term, regular in-depth inspections and more time-consuming maintenance tasks need to be completed. Building assessments are an integral part of the process, as they give an idea of the effectiveness of the ongoing maintenance as well as set priorities for future building envelope optimization. Small inspections, such as a general overview, can be performed by in-house staff, but often require additional expertise. An assessor ideally has expertise working in your local climate and has knowledge of the building materials and techniques required for the proper building assessment. Additionally, the hired experts must understand your mission and the goal of the inspection (if not regulated by local authorities). Mandatory building assessments can be specific to each region/country. These include topics such as fire safety overview, structural condition evaluation, etc.

When short-term maintenance tasks are defined, they can be integrated into a multi-year planning schedule focusing on maintaining the overall water, air, and thermal controls, as well as structural integrity. Typical tasks considered as short-term maintenance include:

- Periodic renewal of protective coatings (whether paint, lime wash, oil treatments, or traditional protective finishes appropriate to local materials);
- Repointing or repair of joint materials (mortar joints in masonry, chinking in log construction, or traditional joint sealants);
- Replacement or repair of various weatherproofing elements (roof tiles, thatch sections, membrane patches, or traditional covering materials);
- Maintenance of structural connections (metal fasteners, wooden joints, traditional lashing systems, or connection hardware);
- Renewal of surface treatments on exposed materials (stone consolidation, adobe replastering, timber preservation treatments, or traditional protective applications);
- Repair or replacement of minor envelope components (window glazing compounds, door weatherstripping, traditional shutters, or protective screens);
- Maintenance of thermal bridge mitigation (insulation repairs, traditional gap-filling materials, or breaks maintenance);
- Upkeep of passive environmental control elements (maintenance of natural ventilation openings, traditional louvers, or climate-responsive building features).

Simple visual inspections: damage indicators

If there is no access to external expertise to assess a building envelope, simple visual inspections can be performed. Symptoms such as mold, salt development, and condensation can be damage indicators. These symptoms can typically be easily identified, also by support staff, as they more often observe the building and surroundings than a planner or coordinator does. Teaching staff to identify these changes and how to follow up with quick interventions is often the easiest way to provide high-quality maintenance. Below, the most common problems regarding building and its structure are linked to probable causes. However, it remains important to know your limitations and except that diagnostics often require further research, certainly if they inform high-impact decisions.

Water control issues

- White crystalline deposits (efflorescence) → indicate moisture movement through materials and/or salt damage, may signal drainage problems or rising damp.
- Dark staining or discoloration → suggests water infiltration from roof leaks, failed flashings, or poor surface drainage.
- Mold growth, dark stains, or discoloration → suggest issue of a combined moisture intrusion with poor ventilation, often indicating envelope failures, can also suggest water infiltration.
- Peeling paint or deteriorating finishes → reveals repeated extended wetting/drying cycles within the given layer (material) or whole component that can be caused by poor design or unexpected water intrusion.
- Visible vegetation on indoor surface → indicates excessive moisture and potential structural water damage.
- Pooled water or damp patches after rain → show inadequate drainage or failed water management systems.

Air control issues

- Noticeable drafts felt anywhere outside the dedicated vents → indicates compromised air barriers and envelope integrity; not uncommon in historic buildings.
- Moving curtains or papers near sealed openings → shows significant air infiltration through envelope gaps, typically through openings edges.
- Different temperatures felt when moving between similar spaces → can have several different reasons, including uncontrolled air exchange affecting thermal performance of different zones.

Envelope performance issues

- Consistently cold or warm spots on interior surfaces → indicate thermal bridging insulation layer failures, or design defects.
- Condensation patterns on windows, walls, or specific elements → reveal thermal performance problems and can be mitigated by lowering indoor humidity, improving air circulation, and increasing surface temperatures.
- Ice formation on building elements → might reveal thermal bridges allowing heat loss in cold climates.
- Frost patterns on interior surfaces → indicate severe thermal bridging and envelope performance failures.
- Cracks in masonry joints or wall surfaces → may indicate foundation settlement, structural overload, or material/layer/component degradation (caused by, e.g., a highly moist environment).
- Spalling, flaking, or crumbling materials → suggest freeze-thaw damage, salt crystallization, or moisture-related deterioration.
- Visible sagging or bulging in structural elements → indicates potential structural distress requiring immediate expert attention.
- Separation at joints between different materials → indicates mismatches in dimensional changes, often related to thermal expansion or moisture-induced deformation.

This low-tech visual approach offers significant advantages: it requires no specialized equipment and, with limited training, can be integrated into daily routines, enables early problem detection before costly damage occurs. Combined with a logbook system, it will build institutional knowledge about building behavior and condition. Most importantly, it empowers existing staff to become active participants in building preservation, creating a continuous monitoring system that catches issues when they are still manageable and inexpensive to address.

1.4 Short-term: building envelope optimization (5-20 years)

When considering the distinction between energy optimization and full renovation in buildings, the fundamental difference lies in the potential scope of actions, where optimization aims to improve the current state, while renovation is typically a deep retrofit, transforming the building or the given elements. No matter the action performed, all the strategies need to consider the current and potential heritage values of the modernized building.

The optimization approach for historic structures emphasizes working with traditional materials and methods whenever possible, following preservation guidelines such as CEN EN 16883 or the EU-EPBD directive for energy performance improvements in historical buildings. The principle centers on enhancing existing building elements through sensitive upgrades that preserve authenticity while improving performance. Materials chosen for these interventions must be durable themselves to justify their application to heritage structures, as frequent re-intervention would compromise both building fabric and collection stability. Due to the high heritage value of the exterior envelopes, modernization of building components (e.g., adding thermal insulation on exterior walls) is frequently performed from the interior; this uncommon method requires a moisture expertise to be performed.

The optimal building envelope can be achieved by enhancing its performance in terms of energy efficiency, structural durability, as well as sustainability factors. The ideal scenario is to implement those actions as early as the design stage. However, in reality, most buildings go through optimization multiple times throughout their use phase, successfully extending the lifetime. Building envelope optimization is challenging, no matter its timing. While reducing energy consumption can be an incentive for building optimization, interventions benefit most from a holistic approach and ideally address multiple goals at the same time. Thus, building enclosure renovation should be performed only with specialized experts providing a long-term perspective after implementing the proposed solutions. The above-mentioned is extremely important for historical buildings and enclosures holding heritage.

Considering different factors in building optimization

The most important factors to be considered to optimize buildings and their envelopes are listed below.

— Design phase: if possible, a building should be comprehensively examined during its design, evaluating different strategies using computational simulations, as well as long-term economic evaluations such as life cycle cost analysis. Building localization and orientation should be considered, as well as building form and shape. All have a significant impact on the overall building performance throughout its lifetime and should be examined in the design phase.

- Sustainable materials: application of materials with low embodied energy and carbon, with high recyclability; this approach fulfills the sustainable development goals for the building sector. The modern building design maximizes the usage of sustainable materials, including recycled materials.
- Thermal insulation: used to minimize heat transfer via enclosure; the applied insulation type (e.g., fiberglass, mineral wool, PIR/PUR foams, natural materials) should be considered based on local requirements, climate, construction, heritage constraints, sustainability, and budget.
- Solar control and passive design strategies: management of solar radiation through building-integrated approaches. Exterior solutions (e.g., blinds/shades on the outside) are significantly more effective than interior ones as they prevent solar energy (i.e., heat) from entering through building envelope (i.e., transparent partition, typically windows). Additionally, specialized reflectance coating, or even including strategic landscaping, can limit the negative impact of solar radiation. Modern solutions include automated louvers, reflective films, and even smart glazing. The strategy involves maximizing beneficial solar gains in cold climates while minimizing overheating in hot climates. Energy-efficiency solutions for windows and other transparent surfaces also include components to reduce heat losses: related to glazing technology (number of glazing, used gas fill, or frame quality) or some easy-to-apply home methods (heavy curtains or roller shutters).
- Foundation and ground interface management: detachment from ground moisture, proper ventilation for wooden structures, vapor barriers, ground drainage improvements, and thermal bridging control at the building-ground interface.
- Natural ventilation optimization: strategic opening placement, stack effect utilization, and cross-ventilation enhancement for passive cooling and air quality management without compromising collection environments.
- System capacity and collection needs: understand the capacity of existing systems and requirements for new systems. Consider the energy demand needed to achieve both appropriate collection environments and human comfort (if required). This factor requires coordination between envelope performance, mechanical systems capabilities, and preservation requirements. ### REFER TO SYSTEMS AND COLLECTIONS SECTION ###

All the above-mentioned strategies allow the owner to make decisions aiming to optimize the building envelope and enhance the overall building performance and sustainability over its lifetime. Appropriate building design and its maintenance allow prediction of expected building energy performance and required maintenance actions over time. However, the remaining unpredictable factors related to occupant behavior and operational variations always have a meaningful impact on the building's performance.

Making strategic choices to find the right energy balance

The key to successful energy optimization in historic buildings lies in establishing a clear decision-making hierarchy (e.g., following CEN EN 16883 guidelines), as follows:

- identify the building's heritage significance and character-defining features that constrain intervention options,
- assess current building performance against collection and comfort needs,
- prioritize interventions based on impact potential, cost-effectiveness, and heritage compatibility.

The goal of energy optimization is to achieve the right energy (i.e., thermal) balance within a building using a lower energy input. Therefore, for temperature, heat losses and heat gains should be balanced by the heat input. In other words, the heating system's job is to compensate for the difference between losses and gains. Energy efficient buildings are characterized by the optimal design maximizing the heat gains usage with the heat losses reduction, aimed to lower the necessary heat input. The analogous logic applies to cooling, as well as humidification.

Fig. x: Exemplary energy balance of a building (– correct source 10 –)

To illustrate a decision-making approach, we mention three examples from different climates. These examples do not showcase the full complexity of a real optimization project, but merely illustrate a train of thought.

- Historic house overheating in a hot climate – former artist residence in Sydney area
  - Heritage assessment: this colonial-era house's character-defining features include large south-facing windows that provide natural lighting and maintain the building's architectural proportions. The constraint is preserving window openings and facade appearance while managing solar heat gain.
  - Performance assessment: current building performance shows excessive solar heat gain through clear glass windows (with Solar Heat Gain Coefficient (SHGC) of 0.81), creating surface temperatures of 36°C compared to 20°C ambient, leading to high cooling loads and collection damage risks from high T overall and significant T and RH fluctuations.
  - Energy balance impact: the building's energy balance is mostly dominated by solar radiation gains that far exceed heat losses, forcing cooling systems to work continuously to compensate for the thermal load.
  - Intervention prioritization: traditional exterior shutters or canvas awnings represent high-impact, heritage-compatible solutions that can reduce the SHGC down to 0.15. This approach prioritizes authenticity (many historic buildings originally had shutters), provides immediate thermal benefit, and remains reversible without altering building fabric.

- Historic stone building in a temperate climate, hygrothermal management – Castle in Belgium
  - Heritage assessment: the thick masonry walls represent the building's primary structural and aesthetic character. The constraint is maintaining the wall's breathability and avoiding moisture trap conditions that could damage historic masonry through freeze-thaw cycles.
  - Performance assessment: stone walls absorb rainwater and release moisture vapor indoors, creating coupled thermal and moisture loads that mechanical systems must counteract. The building's natural hygrothermal behavior conflicts with modern environmental control expectations. The stone walls are also characterized

by a huge thermal mass impacting temperature behavior (stable with slow fluctuations) throughout the day.

   - Energy balance impact: the building experiences both sensible heat losses through thermal bridging in solid masonry and latent cooling loads as absorbed moisture evaporates indoors. Mechanical systems must provide heating energy to compensate for conductive losses while simultaneously removing moisture-driven humidity loads.
   - Intervention prioritization: breathable interior insulation using natural materials works with the building's existing moisture management rather than against it. This approach respects heritage values by preserving exterior appearance, provides thermal improvement while maintaining wall breathability, and uses traditional materials compatible with historic construction methods. These changes might have an impact on the location of certain collection pieces.

- Wooden building in a cold climate, excessive heating demands – Wooden churches in Northern Europe
   - Heritage assessment: the timber frame structure defines the building's character, with exposed structural elements and traditional joinery techniques that must remain visible and unaltered. Constraints include preserving timber frame visibility and avoiding moisture conditions that promote wood decay.
   - Performance assessment: heat loss occurs through uninsulated wall cavities and air infiltration around timber joints, creating high heating demands and thermal bridging through structural elements. The traditional construction was designed for different comfort expectations and fuel availability. Wooden structures typically have a light or moderate thermal mass, affecting more dynamic temperature behavior (unsteady with vibrant fluctuations) throughout the day.
   - Energy balance impact: the building's energy balance shows heat losses through conduction via uninsulated timber frame cavities and convection through air infiltration at joints and connections. Heating systems must compensate for both continuous conductive losses and variable infiltration losses that increase with wind pressure differentials.
   - Intervention prioritization: interior cavity insulation using natural materials like sheep's wool or cellulose, combined with selective air sealing, provides thermal improvement while respecting structural integrity. This approach maintains timber frame visibility, uses breathable materials that prevent moisture accumulation, and can be implemented without altering character-defining structural elements.

This approach requires assembling the right expertise: preservation architects familiar with your climate and building materials, collection managers who understand environmental needs, and building physics specialists experienced with historic structures. Document the decision rationale to ensure transparent choices and inform future maintenance cycles.

1.5 Long-term: major renovations, adaptive reuse, and new builds (20+ years)

Sometimes building optimization is no longer profitable in the long perspective without considering a major renovation that becomes necessary. These interventions approach the complexity and impact of new construction and require specialized expertise and deeper investigation beyond the scope of this handbook. Large-scale envelope interventions typically occur at predictable intervals: weatherproofing and minor envelope improvements at 20 to 30 years, insulation renewal and window replacement at 30 to 50 years, depending on construction quality and climate exposure, and major structural envelope work with comprehensive modernization at 50 to 100 years. It is worth mentioning that structural evaluation of the construction should be performed periodically, e.g., every 5 years. Rather than providing detailed technical guidance for these complex projects, this section focuses on understanding the renovation process and effectively communicating with the external expert teams these projects require.

Renovation planning and project framework coordination

Building renovation should effectively improve energy efficiency through proper sequencing of modernizations to maximize both energy efficiency and financial benefits. The process begins with an energy assessment of the building (stage A) to plan appropriate interventions. Building envelope improvements should first (stage B), providing well-insulated envelopes as the foundation for all subsequent work. The next step (stage C) involves replacing worn-out systems with modern, efficient ones, appropriate for the local climate conditions and lower demands. Traditional installations can be supported or fully substituted by renewable energy systems (stage D). Finally, Building Management Systems (BMS) for advanced building demand and indoor climate operations can further reduce energy consumption (stage E). Some further energy optimizations (e.g., building management following dynamic energy pricing) should also be considered as a part of stage E.

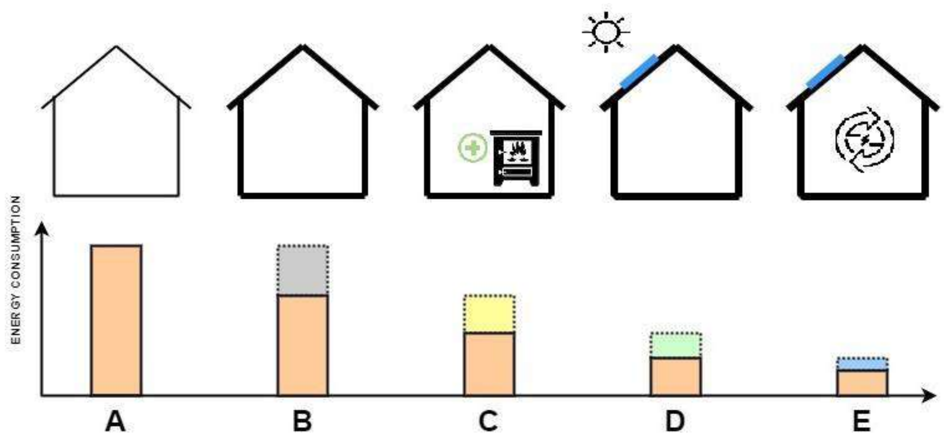

Fig. x: Step-by-step schema on how to improve building' energy efficiency (own study).

Project development requires a clear definition of scope for major envelope work, establishing performance targets that balance energy efficiency with conservation requirements, understanding interaction effects between building changes and all building systems, and developing budget frameworks that consider both capital and operational cost implications over the building's extended lifespan.

Balancing heritage, performance, and sustainability with adaptive use

All building modernizations must maintain indoor climate quality for both occupants and collections housed at the required level. Space transformation opportunities often arise during major renovations, including conversion of previously unconditioned spaces like basements, attics, and annexes for collection use. Such adaptive reuse projects require careful management of envelope performance requirements while integrating these spaces appropriately with existing building systems, always respecting heritage constraints that define the building's cultural significance. Based on budget restraints, sometimes a type of reuse will stay fundamentally unsuited (e.g., basements in areas prone to flooding). Deep building retrofit also provides the opportunity to improve the room layout more effectively, considering lower energy demands or better indoor conditioning.

This level of intervention requires coordination between preservation architects familiar with heritage buildings, building physics specialists experienced with historic construction, mechanical engineers capable of integrating modern systems sensitively, and collection managers who understand environmental requirements. Success depends on assembling this expertise early in the planning process to ensure integrated solutions that serve the building's long-term sustainability goals.

1.6 Professional communication: collaboration with specialists

Building construction or renovation is an action following a pre-defined concept, which involves assembling the specialists involved. Depending on the considered scope, the number of various specialists is different. This section focusses on communication between different parties, be it internal or external. If you want to know more about the documentation and data that is typically provided, please consult the Data chapter ### REFER TO DATA CHAPTER, BUILDING SECTION ###. All different parties should be aware of their tasks, responsibilities, and timelines.

Define your needs

The needs and expected results of building modernization should be considered and/or (if possible) defined. The exemplary goal might be to modernize the building enclosure in order to eliminate water leakage and unwanted air infiltration, as well as to lower energy consumption. Besides needs or goals, requirements can be listed. For building housing heritage, it is often an obligation to provide special treatment of heritage, e.g., façade. If collections are present, collections staff need to be involved in most planning stages since these works often create different or higher collection risks. For larger projects, collection often need to be moved out entirely and stored off-site, which can be a very expensive operation.

Contact the required experts

Based on the needs, the institution should reach out to the expert(s) in the field. It can be a consulting company that has its own experts or individual personnel for each field. It is recommended to involve at least one person with experience in historic structures (if present), as well as experts in building physics and HVAC systems (if the size of the project and modifications require this). Considering building housing heritage, it is also recommended to include external heritage conservation experts or representatives of the heritage authority, in addition to the in-house conservators (staff of the examined building). The combination of the above-mentioned should be enough for most projects regarding building optimization or modernization. These experts should know if some other professional is needed for a specific task.

On-site inspection

Once the research team is set, the on-site visit should be organized to pre-evaluate the current state of the building. During that visit, the main focus is on information exchange(e.g., we have a problem with water leakage that is exaggerated after rainfall). Additionally, it is a way to share information that is not available in the form of project documentation (e.g., these walls were added after the original construction was finished). All possible information can be valuable, even if some might not be important for the assessment. Finally, experts might require some additional information that can be provided in the form of simple answers or additional documentation.

Documentation and data overview

After the on-site viewing, the overview of the available building documentation is scheduled. It is rare to have a complete overview, especially for historical buildings. Thus, some information is given by facility staff, and some parameters are assumed. In some cases, additional tests and/or measurements are requested to receive concrete information on a given aspect (e.g., sample collection out of the wall for lab tests). If testing has implication on the historic building fabric and/or collections, it should be discussed if and to what extent these types of actions are allowed. Personnel and/or visitors should be informed about visible or impactful testing.

Analysis

If all the available documentation is collected, the required and authorized tests and analysis will be performed. These can be either lab tests, e.g., guarded hot box test (to determine thermal transmittance of a given material), environmental chamber test (thermal and moisture assessment for full-scape building component), or moisture transport sorption (drying behavior), or a computational assessments. Computational analysis is more flexible, allowing for examination of a wide range of parametric simulations. For historical buildings, with numerous unknown variables regarding, e.g., their structural composition, assessments should be run with the possible range of outcomes. Results typically range from the most pessimistic and the most optimistic numbers (the expected outcome typically lies somewhere in between). For example, if there is no information on wall thickness, and it cannot be measured, the moisture behavior simulation should be run considering various wall thicknesses.

Decision-making and planning

The critical step is determining whether to proceed with actual modernization. The analysis must be realistic — sometimes, improving the current state is not feasible, or available solutions are not cost-effective. However, if the outcomes justify proceeding, modernization planning should begin. This planning must consider operational constraints such as time availability and necessary adjustments to building operations. In some cases, a complete facility shutdown may be required during implementation. The composition of the modernization team — determining who should be involved and their respective roles — must also be established at this stage.

On-site modernization

On-site modernization should follow the established planning and timeline. Typically, the modernization is led by the renovation team (i.e., the contractor), staying in close contact with the involved experts. Periodical meetings, including the renovation team representative, internal and external experts, and facility staff, are organized. Some adjustments may be made that are thoroughly discussed with all the parties involved.

Acceptance of work - commissioning

Upon completion of modernization work, formal acceptance procedures must be conducted. Facility staff — specifically those responsible for the modernized building — are responsible for accepting the completed work. This process should include an on-site inspection with representatives from both the renovation team and the experts who proposed the solution. A formal acceptance protocol should be documented and signed by all parties. All modernizations, particularly long-term projects, should include warranties from the renovation team or equipment manufacturers (for example, when new heating system is installed). This ensures accountability and provides recourse if issues arise during the initial operational period. The acceptance process should also incorporate any museum-specific requirements or operational considerations that were identified during the planning phase.

Final reporting

Experts should conclude the modernization with a final statement, typically a report. Despite all the analyses made and their outcomes, the modernization process should also be documented, highlighting all the important aspects and changes made during the process. It should include some recommendations for the future (e.g., how to preserve and maintain the building after modernization). The content of the report is case-sensitive. The final report should be signed by all the parties involved in the modernization process.

Long-term evaluation and management

The facility staff should be provided with information on how they should review the performed changes in the following years. Some important evaluations will be made by experts (e.g., stove maintenance), and in some cases, guidelines from experts might be valuable. Yet, all the actions after accepting the final report are typically outside of the scope of the agreement. It is therefore important to agree on possible cooperation after modernization ends, and to include that statement in the final report. For collection teams, often in collaboration with facilities, it is important to verify if the environmental (and other practical needs) are met on the basis of (at least) a full year of measurements.

1.7 Cross-domain considerations: how building changes affect systems, collections, and energy use

Impact on systems and energy

Building changes affect system operation and thus indoor climate conditions at multiple levels. At the room level, envelope modifications impact the heating and cooling energy balance. Better thermal insulation in cold climates combined with reduced infiltration implies lower heating energy for maintaining desired indoor conditions, fundamentally altering the building's energy profile.

Some systems with poor control are detrimental to indoor climate following building changes. Despite adequate system capacity, which is typically reduced after envelope improvements, controls must be adapted to the new building situation. The most important systems control improvements include:

- ON/OFF control adjustments for heating, ventilation and cooling,
- hot and cold water distribution temperature modifications known as "heating curves" that should be adjusted to new envelope characteristics, and ventilation mass flow,
- humidity setpoints that require adjustment according to the new envelope air permeability performance.

For long-term building modifications, heating and cooling systems are often renewed simultaneously. This approach ensures systems are designed adequately for current building and climate requirements rather than fighting outdated parameters. The intended results of improving overall building condition and minimizing the probability of shortcomings should lower the overall energy demand. This lowered demand allows the use of smaller elements in HVAC systems - if heating demand decreases, smaller capacity heating stoves or heat pumps can be installed, with the same principle applying to air conditioning systems.

Building improvements often coincide with infrastructure upgrades, creating strategic opportunities to consider changing energy usage patterns and alternative energy resources. When new wings are constructed next to protected buildings, for example, roof areas beneficial for solar panels become available. Major renovations also provide access for installing potential renewable energy infrastructure that would be impractical during normal operations, while the reduced energy demand from envelope improvements makes renewable systems more cost-effective and feasible for meeting total building needs.

Impact on collections

Be aware that the collections these buildings house often have a combined historical and monetary value that far exceeds the value of the building that houses them. While institutions are often perceived as overprotective their collection is often ultimately the right of existence of a certain collection care institutions. It is therefore not surprising that collection safety is a priority and should be considered during all building projects, small and large. While for larger projects, it is unavoidable to move all objects to an external or internal storage space, for some smaller, objects can stay and place while implementing certain measures. Be aware that some objects cannot be moved, or moving them is extremely expensive. Reasons are often their weight, size, fragility, and/or site-specificity.

Construction activities generate dust, vibration, and environmental disruption that require enhanced protection measures for collections remaining in place. Dust barriers must be established using materials that won't directly contact objects, while sensitive items need vibration isolation measures. Enhanced security monitoring becomes essential throughout work periods, and environmental controls require continuous operation with possible temporary adjustments to accommodate construction schedules.

Major building modifications demand complete collection relocation due to extensive work, system shutdowns, and elevated construction risks. This complex logistics challenge requires careful staff coordination, with clear roles for contractor communication, collection safety management, and conservator oversight of handling protocols. Route planning must identify obstacles and hazard points, while documentation systems track object locations throughout the entire process, creating opportunities for registration verification and inventory updates.

Building envelope changes alter the relationship between indoor and outdoor conditions, potentially creating new environmental patterns that collections must adapt to gradually. During construction, temporary environmental disruptions from dust, altered airflow patterns, and system modifications require careful monitoring to prevent sudden fluctuations that could damage sensitive materials. Post-construction environmental stability often improves but may require adjustment periods as new building performance characteristics establish equilibrium.

Major renovations provide unique opportunities to implement comprehensive environmental improvements that would be impractical during normal operations. This timing allows for strategic rezoning of collection spaces based on material needs, installation of microclimate solutions, and implementation of sustainable setpoint strategies developed through the renovation planning process. The disruption period becomes an opportunity to address long-standing environmental challenges and optimize collection care practices.

Large-scale collection movements during renovation significantly alter the hygrothermal environment of both source and destination spaces. Removing substantial quantities of hygroscopic materials from storage areas eliminates their natural buffering capacity, potentially creating less stable humidity conditions that require system adjustments. Similarly, temporary storage facilities experience increased humidity loads from incoming collections, requiring careful monitoring and possible environmental system modifications to maintain stable conditions for relocated materials.

2. Systems

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2.1 Introduction

The task of a facility manager is to maintain both the building and building systems. The tasks that need to be performed and technical knowledge required from this profile can vary widely based on the building(s) involved. Sometimes the facility manager coordinates and performs all tasks from cleaning gutter to installing a heater while on other sites it is a complex management task dealing with multiple external contractors as well as multiple sites and systems.

While facility managers oversee multiple building systems including lighting, security, and waste management, this handbook concentrates on climate control systems due to their typically high energy consumption and direct impact on collection preservation. Lighting energy efficiency has become relatively straightforward with LED technology adoption, offering clear energy savings with minimal collection risk when properly implemented. Waste management strategies, while important for sustainability, are highly location-specific regarding local recycling infrastructure and regulations, making general guidance less practical than institution-specific assessment. Additionally, both artificial lighting and waste management have a low impact on collection environments unless mentioned otherwise in the collections chapter.

The variety of climate control systems is large, but still more limited than collections and/or building envelope types. Most systems consist of industrially constructed parts that have some type of life span. From filters to cast iron radiators, these lifespans can vary widely and will determine the needs for maintenance, optimization, and replacement of parts and/or entire systems. The types of systems used vary per time and place and are trend sensitive. While complete HVAC control for office buildings in the US is standard, many buildings in Europe still have traditional central heating systems. In hot climates, where cooling is more important, the focus can go from natural cooling using natural ventilation, over integrated systems, to simple window units.

This chapter tries to present options for energy reduction that can be applied to all climate systems, no matter the energy source and equipment used.

2.2 Ongoing efforts: maintenance and verification

System maintenance is crucial for energy efficiency and adequate climate control, whether dealing with complex HVAC systems, simple radiators, or basic ventilation. Maintenance intervals vary significantly based on system complexity, local expertise availability, and institutional capacity.

Annual maintenance tasks

As with building envelopes, good maintenance of systems is the most efficient way to save energy. A good working system, not obstructed, well balanced and correctly calibrated, will make sure there is a minimal energy loss. Some examples of annual maintenance tasks are:

- Visual inspection and cleaning: check accessible system components for obvious wear, blockages, or damage. Clean accessible heat transfer surfaces (radiators, accessible coils, vents)
- Bleeding radiators: remove trapped air from radiator systems to ensure even heat distribution and efficient operation
- Leak detection: check for water leaks around pipes, radiators, valves, and connections. Look for staining, corrosion, or moisture around system components
- Pipe insulation: insulate all accessible heating and cooling pipes to reduce energy losses
- System balancing: for central heating systems, ensure proper water distribution through balancing valves - a well-balanced system can deliver up to 30% more heat
- Airflow verification: for ventilation, ensure vents and grilles are unobstructed and air can move freely through spaces
- Control verification and calibration: make sure measurements are in line with the factual temperature, humidity, air volume, etc.
- Filter maintenance: replace or clean filters in any air-handling systems - dirty filters increase energy consumption significantly and lose their filtering capacity due to saturation.
- Humidification system control: humidification systems are highly maintenance sensitive whatever their type (steam, evaporative, spray…). Air quality by means of bacteria development and energy/water use are strongly linked to the adequate follow up of operation and maintenance instructions.

Typically, system maintenance is provided either in-house, by a facility manager or a technician. For more complex facilities with HVAC systems, a specialized technician or engineer can be deployed by an external maintenance contract. This contract stipulates the required quality of the indoor environment, the series of maintenance tasks, reporting duties, requirements for physical representation on site and required proposition for energy optimization.

Short-term maintenance (1-3 years)

These are more specialized tasks that typically require some more technical knowledge or expertise. When there is no in-house knowledge, consider external expertise. This can go from your local electrician or plumber to a specialized engineering firm. If you don’t know where to start

- Component replacement: Filters, sensors, minor parts in heating, cooling, or ventilation systems.
- Blockage clearing: Check for and remove obstructions in ducts, pipes, drains, or ventilation pathways
- Deep cleaning: Accessible areas of heat exchangers, radiators, distribution components
- Valve operation checks: Ensure manual and automatic valves open and close properly

- System commissioning review: After years of use, systems can become seriously misadjusted - professional review of control settings
- Equipment age assessment: Consider replacement of heat production equipment older than 15 years, particularly when switching to non-fossil fuels
- Performance verification: Test whether systems achieve design specifications efficiently
- Electrical inspection: Check connections, panels, and control wiring for safety and efficiency
- System controls : Proper control relies on a series of sensors and actuators. They can be subject to significant fluctuations (temperature, pressure…). A verification of sensor and actuator ensures a more energy efficient and precise indoor climate.

Finding qualified technicians familiar with your specific system type and obtaining replacement parts can be challenging, particularly for older or specialized equipment. Custom-made components are often expensive and have long delivery times.

To mitigate these challenges, keeping a small stock of commonly needed items such as filters, sensors, belts, and basic valves based on manufacturer recommendations helps. This avoids delays during repairs. Establishing ongoing relationships with reliable technicians before emergencies occur proves valuable as well, particularly those with experience in cultural heritage buildings who understand the specific constraints and requirements of historic systems. Additionally, if possible, when replacing components, favoring commonly available, commercially standard parts over custom solutions ensures future availability and reduces costs. While custom solutions may seem ideal for historic buildings, standardized components often provide better long-term value through easier maintenance and replacement.

Maintaining detailed records of system specifications, part numbers, and supplier contacts speeds up emergency repairs when time is limited. Documentation becomes especially important when original installers are no longer available or when systems have been modified over time.

Timing maintenance activities appropriately prevent unnecessary complications. Scheduling major maintenance well before weekends or holiday periods ensures response capability remains available, and confirming qualified support during transition periods reduces risks of extended downtime.

These preparation strategies become increasingly important for institutions in remote locations or those with specialized historic systems where replacement parts and knowledgeable technicians may be scarce.

Common energy waste patterns

Regular maintenance often reveals energy inefficiencies that are easily addressed:

- Air in heating systems: Trapped air in radiators or pipes reduces heat transfer efficiency and can cause uneven heating, leading to higher energy consumption.
- Leaks and poor sealing: Water leaks in heating systems should be repaired quickly. Installing water meters on HVAC system refill helps detect long-term leakage. Air leaks in ductwork or poor sealing around pipes and components waste energy.

— Blocked airflow: Obstructed vents, dirty filters (which should be changed 1-2 times yearly), or blocked air pathways force systems to work harder, consuming more energy for the same result.
— Poor humidity control: Humidity sensors may drift over time - verify proper sensor positioning and calibration, and cross-check measurements with other available sensors in collection areas.
— Humidification inefficiencies: Poor control of steam pressure can result in excessive water being steamed unnecessarily. Adequate control of condensate return systems prevents excessive steam production compared to actual humidification needs.
— Distribution inefficiencies: Heat loss through uninsulated pipes, poor system balancing, or systems fighting each other (heating and cooling simultaneously) create unnecessary energy consumption.

2.3 Short term: minor interventions introduction (5-20 years)

Energy savings through short-term interventions can be obtained through testing and smarter programming. Simply use your systems in line with your actual needs rather than operating them based on extreme occupancy or outdoor weather conditions. Additional savings can be gained by adjusting behaviors and habits, which is important when changing setpoints in public spaces where people remain relatively stationary. Strategic use of movable control elements, such as portable humidifiers or dehumidifiers, can provide targeted climate control without running building-wide systems. During regular maintenance schedules, replacing high energy-consuming system components can also result in notable reductions. Finally, testing what temporary system shutdowns do to indoor climate and energy consumption allows you to identify specific times when systems can remain unused, which directly reduces energy consumption.

As with collection-based changes, these can be done at any time. However, it is not advised to implement all changes at the same time. When testing it is important to understand which climatic response is caused by which adjustment.

2.4 Short-term: operational improvements, smarter programming (5-20 years)

Not all climate systems offer the same level of programmable control, and understanding what your system can and cannot do determines which energy-saving strategies are possible. The key is identifying what level of control your system provides and implementing appropriate strategies within those capabilities.

Simple systems like basic thermostats and radiator valves allow you to implement manual seasonal adjustments, day/night temperature differences, and basic scheduling through timers or staff training. Sophisticated systems like building management systems (BMS) go further and include features such as multi-zone control, occupancy sensors, CO2 concentration monitoring, and data logging which allow you to automatically optimize operations based on real-time conditions and coordinate multiple system components.

The options below are in order of simplicity. While the first options are feasible with any climate control system, the last ones can only be programmed in advanced systems.

Manual scheduling options and simple thermostat settings

The simplest option is manual scheduling. This requires staff to adjust basic controls according to a schedule ideally based on occupancy, weather and seasons. This is, for example, turning the radiators off at closing time or turn of the heating system during summer. Basic scheduling is possible through timers or lockable valve caps to prevent unauthorized radiator adjustments.

An example of a simple programmable system is a thermostat. Most thermostats these days allow for scheduled programming often per day and per hour. This allows you to translate the mechanical scheduling to an automated one. The time-based programming allows for the implementation of setback strategies when the building is unoccupied. When multiple circuits (with different controls) are present in the building, zone based strategies based on occupancy and collections requirements can be applied.

Temporary system shutdowns

Temporary shutdowns represent one of the most direct energy-saving strategies - the greatest potential energy savings come from non-running equipment at all. This approach works particularly well in collection storage areas where human occupancy is minimal, and in institutions with seasonal operating patterns or predictable closure periods.

Complete shutdowns aren't always beneficial. Additionally, buildings with collections sensitive to rapid environmental changes may experience more damage from the fluctuations caused by shutdown cycles than from continuous operation. The viability depends on how well the building envelope can maintain conditions without mechanical intervention (or without damage risk to collection).

For suitable buildings, night-time and weekend shutdowns or setback during unoccupied hours can provide substantial energy savings.

Extended shutdown periods during seasonal closures can be particularly effective, especially for institutions in temperate climates during mild weather periods. These longer shutdowns allow for more substantial energy savings and provide opportunities for maintenance activities. However, during extreme weather periods such as monsoon seasons or severe winter conditions, maintaining some level of climate control may be more beneficial than attempting shutdowns.

When full shutdowns aren't feasible, setback strategies offer a compromise approach. This might involve temporarily relaxing temperature controls (the "winter sleep" approach in heating-dominated climates), allowing wider humidity ranges, or reducing ventilation rates during unoccupied periods. The specific parameter to adjust depends on your climate, system type, and which represents the largest energy load.

Allowing natural drift

Some system programming will allow you to program an upper and lower limit in temperature and relative humidity instead of one particular set point. E.g. when a RH set point is 55% a system will constantly humidify and consequently dehumidify to keep the RH stable. While if there is a range from 45% to 65% a system will only start working when it goes over the 65% or under the 45% mark and allows for a natural drift of humidity in between these numbers. This allows for significant savings, certainly in combination with seasonal settings. Gradual fluctuations often more closely resemble the historic climate of artworks and can be of less harm then rapid continuous fluctuations.

Upper and lower limit in temperature or humidity is known as deadband. A too narrow dead band implies energy destruction most of the time. Heating/humidify and cooling/dehumidify at the same time is an energy waste. (see paragraph energy destruction)

When controlling heating, cooling, ventilation and humidity allowing for a natural drift is easier said than done. Since temperature and humidity are linked, priority needs to be given to one of the two in programming. Based on outdoor weather and season and your goal (collection, comfort or energy savings), this can be either temperature or humidity. The key is understanding which parameter is more critical for your collection and setting the system hierarchy accordingly. To better understand set-points for collections, consult the respective collection chapters ### REFER TO COLLECTION, 3.5 AND POSTER ###

One example of a system that gives priority to humidity is conservation heating. This can be an energy efficient way to maintain a safe collection environment. This means heating goes up in winter to lower humidity. This system is relatively common in historic buildings in Northern Europe, but often does not reach comfort temperature during the coldest winter months.

Variable airflow settings

In many larger museums, the heating and cooling is provided by air only (all air system). The ability to vary airflow depends on your fan equipment.

Most climate systems have a certain percentage of fresh air intake, a mixture of fresh outdoor air and recirculated indoor air. Many systems are designed to bring in much more fresh air than actually needed, which requires significantly more energy to heat, cool, or dehumidify. The percentage of fresh versus recirculated air can often be adjusted, even on relatively simple systems through manual dampers or basic controls. Instead of bringing in 100% fresh outdoor air, systems can recirculate a portion of already-conditioned indoor air.

Complete air recycling permanently is possible but not desirable because people produce CO2 that must be diluted with fresh air, and recirculating air can concentrate volatile organic compounds (VOCs), dust, and biological contaminants around collections. While advanced filtration systems can remove many contaminants, these are expensive and energy-intensive themselves. Storage areas and spaces with minimal occupancy can typically operate with much lower fresh air percentages than public galleries or lecture rooms.

For example, reducing fresh air intake from 100% to 70% means 30% of the air is already approximately at the desired temperature and humidity, requiring much less energy to condition. This is particularly useful during extreme weather when the difference between outdoor and indoor conditions is greatest, while still maintaining necessary air quality and collection protection requirements.

Additionally, when outdoor conditions are favorable (e.g., when outside air is cooler and drier than indoor air), systems can take advantage of "free cooling" or “free dehumidification” through economizer modes. This involves temporarily increasing fresh air intake to 100% when outdoor air can help achieve desired indoor conditions without mechanical heating or cooling. For example, during cool evenings or mild spring/fall days, bringing in more outdoor air can reduce indoor temperatures naturally, eliminating the need for mechanical cooling. Some systems can automatically switch to economizer mode when outdoor conditions are suitable, while others require manual adjustment. This strategy works particularly well during shoulder seasons when outdoor temperatures fall within or near your desired indoor range. While programmable, it is also possible to allow for natural nighttime ventilation under the same conditions. However, for museums, this often poses security risks and a higher risk of pests entering the building.

Most modern air handling units include variable speed drives that allow fan speeds to be adjusted (typically operating between 30-60 Hz frequency). Older systems may have two-speed motors offering limited flexibility. Even single-speed motors can often be retrofitted with variable speed drives without replacing the motor itself, providing more control over airflow and energy consumption. The flow magnitude has a big impact on global energy needs. Implementing a lower flow means:

- Lower energy use for heating and cooling at a given setpoint.
- Lower electricity for fan use
- Lower humidification needs

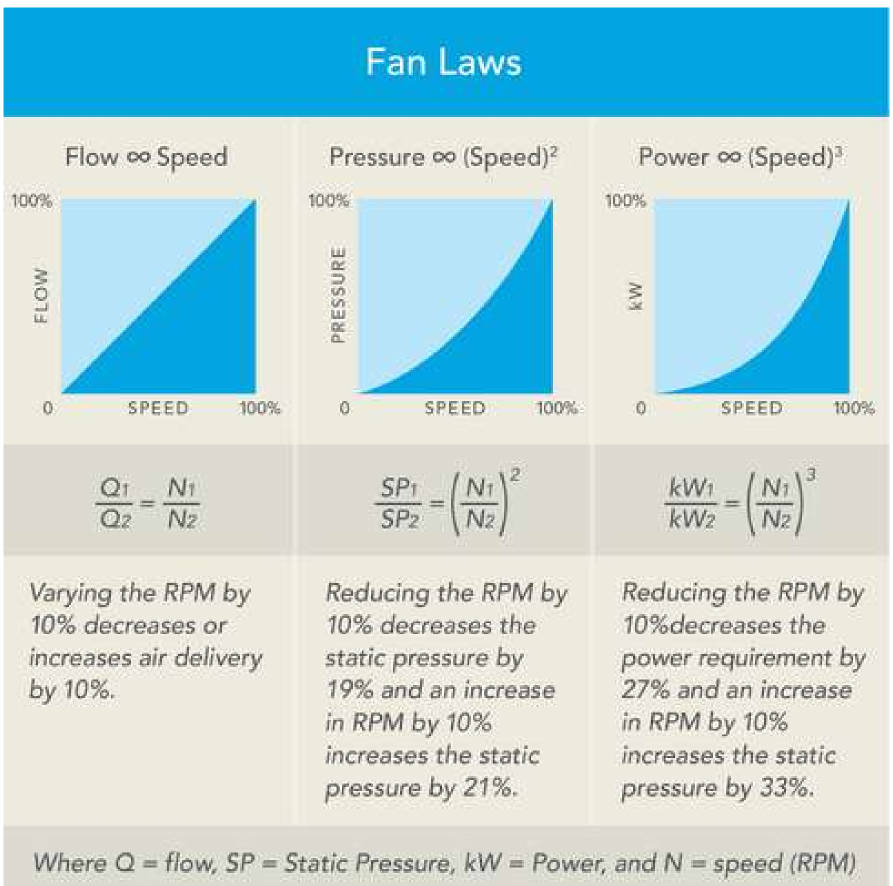


Fig. x.: fan law where RPM is Rotation Per Minute (source: Upsite)

Climate systems are typically designed to handle the most challenging weather conditions - the hottest summer days or coldest winter days. This means they're programmed to move enough air to bridge large temperature and humidity differences between outdoors and indoors. However, during mild weather, you can often achieve the same indoor conditions using much less airflow. The key is matching your system's operation to actual conditions. In order to better understand your options, it's recommended to perform tests:

- Reduce airflow during mild outdoor conditions when heating and cooling demands are lower
- Turn down or temporarily shut off systems during nights, when buildings are unoccupied or in rooms with lower occupancy. ### SEE TEMPORARY SYSTEM SHUT DOWNS ###

It is important to monitor how environments respond to these changes and pay attention to collection safety while performing these tests. ### REFER TO TESTING TEMPLATE ###

For example, a 10% decrease of flow seems to have no important impact on indoor conditions (aside of the extreme outside conditions). The fan law figured above shows the results of a 10% lower fan speed on electricity use. In total the savings can be listed as follows: Decrease ventilation speed by 10%, decreases flow by 10% and results in a reduction of up to 27% less electricity fans. In addition, the energy used for the heating / cooling and (de) humidification of the flow decreases. This decrease is of the same order of magnitude as the decrease in flow (10 %)

In other museums where ventilation is not the only way to heat or cool indoors, energy savings while decreasing ventilation flow are always encountered. In these cases, ventilation mass flow is generally designed for air quality purposes (based on number of people inside the area). It is important to adjust both the fan speed of supply and return fans to avoid an over/under pressure inside the building unless desired.

Based on the use of different spaces a typical number of air exchanges is required per hour. Low occupancy spaces such as storage with no working area require a much lower ventilation rate than visitor rooms or rooms where events or lectures regularly take place. If your systems are installed to control rooms with similar functions (e.g. all rooms are storage rooms), a lower ventilation rate could be considered. While this can be implemented based on theoretical numbers it can also be automated using CO2 level-based control.

The European standard EN16798-1 2019 proposes references values both for mass flow and CO2 level. For an air quality classification 2 (from 1 – high quality to 4 – low quality), the volume flow is defined per person: 25 m^3/hr (source EN16798-1 2019 table B.6). If we have CO2-based control, the maximum CO2 concentration inside is 800 ppm above outside level (around 420 ppm). This is for an air quality classification 2 (source EN16798-1 2019 table B.9). The pollutants inside the building could also be taken into account to increase the ventilation flow. This is very dependent on materials and collections inside. The European standard gives only some reference values with 3 levels of pollutants inside.

Since COVID-19, many museums are required to monitor CO2 levels in visitor areas to ensure adequate ventilation. CO2 sensors provide real-time feedback on air quality and occupancy levels, since people produce CO2 when breathing. When these sensors are connected to the climate control system rather than just providing standalone monitoring, they enable automatic adjustment of fresh air intake based on actual occupancy rather than assumed maximum occupancy. This demand-controlled ventilation means the system only brings in as much fresh outdoor air as needed to maintain healthy CO2 levels, typically below 1000-1200 ppm depending on local regulations.

The energy savings from CO2-based control can be substantial, particularly in spaces with highly variable occupancy. Event and lecture halls that are designed for maximum capacity but often operate with much smaller audiences represent a major opportunity. Galleries or rooms that are used for occasional events experience dramatic occupancy variations between quiet weekdays and busy periods like free museum days, exhibition openings or weekend crowds.

Avoid energy destruction

Energy destruction signifies heating and cooling are done simultaneously, involving energy waste. The energy destruction directly affects the total energy use. This is particularly the case in air handling units where heating and cooling coils are present and operated at the same time, as represented by the figure below. To verify, checking the temperature and humidity measurements at the orange points is useful. They permit analysis of air energy content throughout the air handling unit. Successively heating and cooling the same flow could be an energy destruction.

An example of energy destruction is presented in the figure below. It emphasizes a summer period where the heat gains are high. The humidity management enables heating and cooling at the same time. The 5 measurements illustrate the air process in the air handling unit :

1. Return air from conditioned space is hot and humid.
2. Outside air is fresher and dryer than inside air
3. Mixed air (around 50% fresh air) is too hot to pulse, it has to be cooled down
4. Cooling coil cools and dehumidificates the air down to 40%, the cooling setpoint is 22°C
5. Steam humidifier humidifies and reheat slightly the air, the setpoint it 45%

Blue and red lines show respectively cooling and heating process. A smarter control and set point selection could avoid cooling and heating at the same time. Two possibilities are proposed according to this precise example: Take advantage of outside air cooling capacity to cool down the rooms. This means to tolerate a little drift on inside temperature. The humidification and cooling are therefore not useful. Point 2 shows a sufficient humidity and an outside air cold enough.

Let a little drift on humidity setpoint. If outside air is too hot to be used directly, cooling is necessary. The cooling coil dehumidifies to 40%. This could be chosen as a new humidity setpoint. Finaly, the humidification is not anymore mandatory.

Energy destruction occurs generally when there is no or low bandgap between heating and cooling setpoints. There is no quantitative evaluation here. One easy way to check, in addition to the ventilation case explained, is to verify the heating energy consumption in summer and the cooling energy consumption in winter. These two cases emphasized most of the time energy destruction. When energy destruction is discovered, a discussion has to be done to define new control strategies (e.g. enlarge bandwidth between heating and cooling set points).

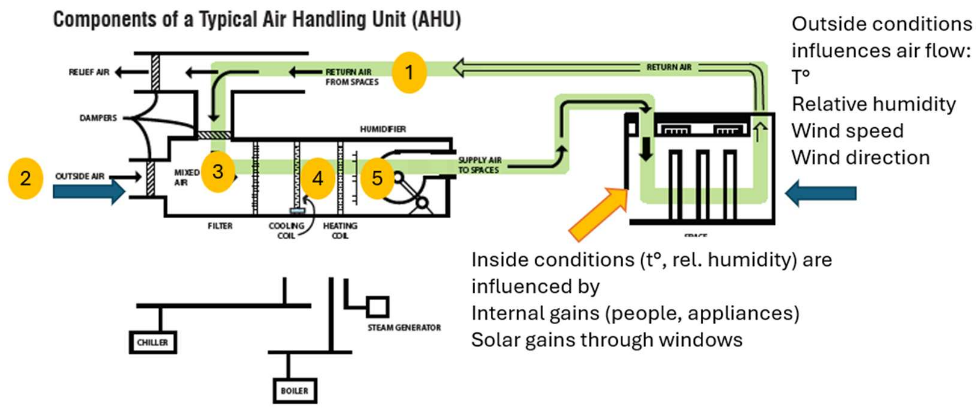


Fig. xxx: *Components of an air handling unit (source AHU components,IPI)*

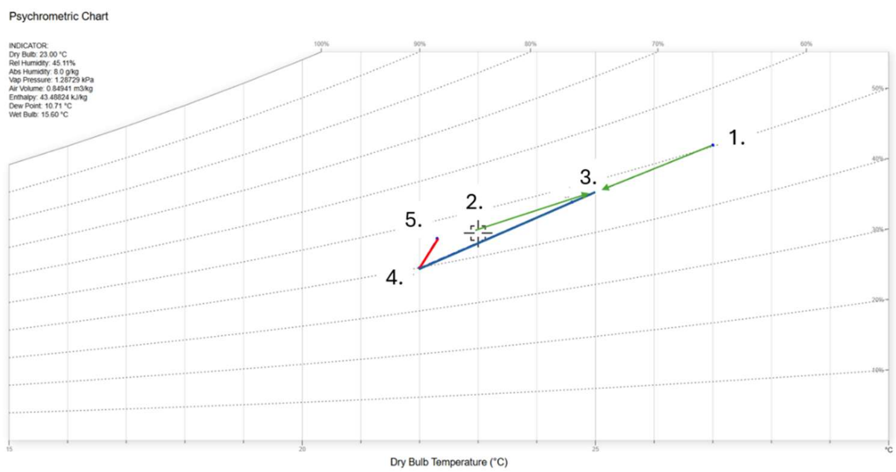


Fig xxx: *energy destruction example on psychrometric chart*

Advanced Systems (Sophisticated BMS’s)

Advanced building management systems represent the automated version of the more manual strategies discussed throughout this section. These systems require additional sensors, specialized programming, and significant upfront investment, making them accessible primarily to larger institutions or those undergoing major renovations. The complexity increases as systems integrate more variables and automation, essentially creating "smart buildings" that perform much of the energy optimization automatically. Some newer systems incorporate predictive algorithms or machine learning elements, though traditional programmed automation remains more common in cultural heritage settings. In order of growing complexity the following options exist:

- Variable frequency drives (VFDs): Automated equipment efficiency that controls motor speeds for both fans and pumps based on actual demand rather than running at constant maximum speeds
- Integrated system coordination: Automatic prevention of energy destruction by ensuring heating, cooling, and ventilation systems work together rather than fighting each other through conflicting operations

— Multi-zone scheduling: Automated time-based programming that implements the manual scheduling and setpoint strategies across different building areas based on use patterns and occupancy schedules
— Real-time demand response: Systems that automatically adjust operations using multiple sensor inputs (CO2 levels, occupancy detection, outdoor conditions, indoor measurements) to optimize all parameters simultaneously based on current conditions
— Data analysis and optimization: Continuous monitoring systems that collect operational data to identify patterns, inefficiencies, and optimization opportunities, with some advanced versions incorporating predictive capabilities for proactive adjustments

These features build upon the foundational strategies already discussed but require substantially more technical infrastructure and expertise to implement and maintain effectively.

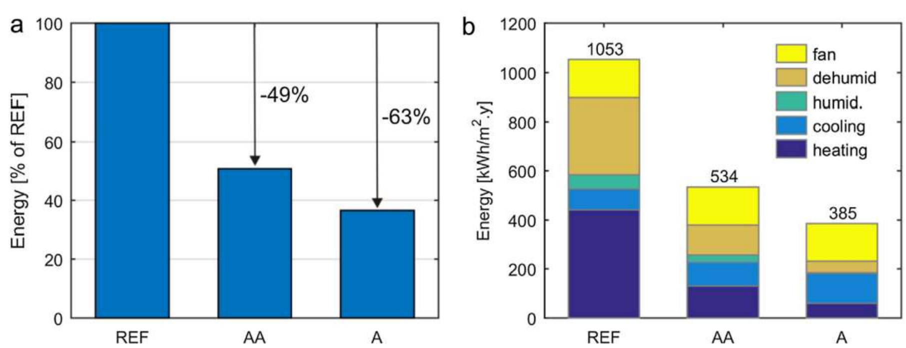
Behavioral adjustments and set-point changes

Less strict temperatures and humidity setpoints allow a huge source of energy savings. Generally a constant temperature and humidity are set all over the year. If the collection accepts variations, it is crucial to implement them in HVAC controls. This requires no equipment costs (if system is designed with automatic controls). The savings are clearly affected by the lowering of "net demand" (see energy conversion figure) .

The savings are dependent on the climate, for Brussels temperate climate (heating needs are dominant) we can assume, for yearly mean setpoint modifications:

— Decrease 1°C = 7% heating energy savings (based on degree days)
— Decrease by 5% relative humidity = 25% humidification energy savings (based on outside humidity content)

A full-scale measurements in museum Hermitage in Amsterdam resulted in a modification of maximum 2°C and 10% RH, and a reduction of energy use by 63%.



T and RH settings of the tested indoor climate strategies.

	Reference	Class AA	Class A
T [°C]	21	20–22*	20–22[a]
RH [%]	50	45–55	40–60

[a] Adjusted to 19–21 °C in winter and 21–23 °C in summer.

Fig. xxx: a) Energy consumption of ASHRAE classes AA and A compared to the Reference strategy (including fan energy). b) Annual energy consumption per square meter specified for heating, cooling, humidification, dehumidification, and fan. source R.P. Kramer et al. 2014

Visitors in museums and cultural institutions are typically dressed for outdoor conditions and often engage in light physical activity through walking and standing, making them more adaptable to temperature variations than people in sedentary office environments. Staff can be encouraged to dress appropriately for seasonal temperature adjustments and incorporate more movement into their daily routines when possible.

Clear communication about environmental sustainability goals helps both visitors and staff understand and accept these changes. Simple measures like providing information about seasonal temperature variations, suggesting appropriate clothing in advance communications, or designing exhibition routes that encourage movement can support successful comfort adjustments. Many cultural institutions find that gradual temperature changes implemented seasonally are well-accepted when visitors and staff understand the environmental and collection preservation benefits.

If you want more information on how to rethink setpoints in a responsible way, you can consult the collection section and poster on determining indoor climate set points for cultural heritage institutions. ### REFER TO COLLECTION SECTION, 3.5 and INDOOR CLIMATE TEMPLATE ###.

Working with movable climate control elements

Movable climate control units provide flexible solutions for bridging extreme weather conditions and making targeted environmental adjustments without running building-wide systems. Portable humidifiers, dehumidifiers, heaters, and air conditioning units can address localized needs or supplement fixed systems during peak demand periods, including climate-controlled display cases that provide precise control for individual objects.

However, coordination between movable units and fixed building systems presents risks. When portable equipment operates in spaces served by central HVAC systems, sensors may receive conflicting signals about room conditions. This can lead to energy destruction, where the central system attempts to compensate for perceived inadequate performance while portable equipment performs most of the actual environmental work, resulting in simultaneous heating and cooling or humidification and dehumidification. Strategic deployment requires understanding sensor locations and control sequences to ensure mobile units supplement rather than fight existing infrastructure.

2.5 Short-term: strategic component replacement (5-20 years)

Technology enhancements have been seen last decades. As an example the figure below shows efficiency increase of electrical motors. The motor is the core component of pumps and fans. Replacing old (> 20 years) pumps has clearly impact on the electrical use and the heat released to the circuit. For cold water circuits, the heat released by pump to the water circuit could be non-negligible.

For example, pump replacement typically reduces electricity use by 60% (e.g. a new Electronic Commutation motor pump compared to a 20-year-old pump). Major pump manufacturers provide online tools and guides to help calculate energy cost reductions when replacing older pumps with newer, more efficient models (Wilo and Grundfos pump manufacturer for example). These resources can help estimate potential savings before making replacement decisions.

For fan motors, similar efficiency gains are possible. New technologies have improved energy performance considerably. In the past, belt-driven systems were common for power transmission from motor to fan. As motor compactness has improved, direct transmission systems are now standard practice. Belt transmission typically loses 3-15% of transmitted power, so eliminating belts provides immediate efficiency gains.

Beyond new technology, aging components clearly affect the energy efficiency of the entire system. For example, older valves may no longer seal properly, causing water leaks or unwanted water flow between different circuits. Similarly, old pipe joints and duct connections can lose their ability to prevent water or air leaks. In heating and cooling systems, these leaks force the system to work harder to maintain the desired conditions.

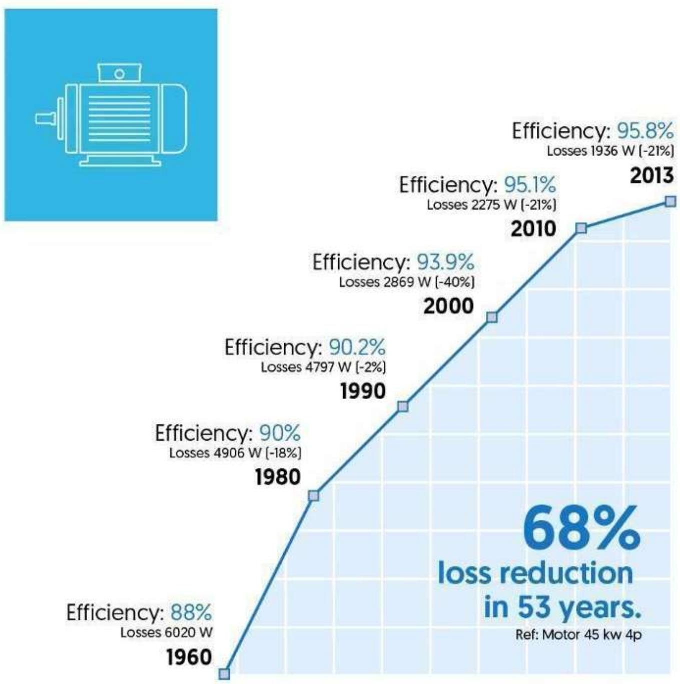


Fig. x.: Electrical motor energy efficiency since 60 years : source Eriks.com

Ventilation system leaks are particularly problematic because they're often invisible - you can't easily see air escaping from ducts hidden in walls or ceilings. To detect these hidden inefficiencies, airflow measurements can be taken at vents throughout the building to check whether the intended amount of air actually reaches each space. When measured airflow is significantly lower than designed airflow, it often indicates leaks somewhere in the system that should be addressed.

2.6 Long-term improvements: retrofitting, replacing systems, and considering system removal (10-20 years)

While the short-term improvements deal with no or low investment focusing mainly on systems, the long-term embraces both envelope improvements and major HVAC renovation. Large interventions in mechanical systems is largely dependent on the complexity of the system. Renewal is recommended every 10-20 years, though this varies based on availability of local technical expertise, institution's maintenance capacity, and system sophistication levels.

For institutions with basic heating systems such as individual radiators, baseboard heating, or standalone units, system replacement becomes more straightforward than complex HVAC retrofitting. These simple systems can often be upgraded to more efficient models without major building modifications or ductwork changes. Similarly, simple cooling systems like window units, portable air conditioners, or individual split systems can be replaced without extensive building work. Mobile climate control elements like portable heaters, dehumidifiers, or air conditioning units represent the simplest replacement category, requiring only electrical connections and no building infrastructure changes.

Simple system replacement

Simple system replacement typically happens on a predictable timeline based on equipment age and maintenance history. Unlike complex integrated systems, individual heating units or mobile equipment can be replaced incrementally as they reach end of life, allowing institutions to spread costs over time rather than requiring large capital investments. The replacement schedule often depends more on availability of maintenance expertise and replacement parts than on building-wide renovation cycles.

Major changes in energy sources, such as transitioning from fossil fuels to renewable energy systems or implementing combined heat and power systems, are addressed in the energy section of this handbook. The following sections focus on more complex integrated systems that require substantial planning, coordination, and often building modifications.

Retrofitting: large scale strategic component replacement

Retrofitting involves replacing inefficient parts while considering the influence of all parts on one another, as well as new technological advances such as heat recovery. Often the focus lies not on replacement of duct work, pipes and emission systems, but on changes in the generation systems or system controls themselves.

Long-term improvements involve investment that can be economically / environmentally justified over a long period (typically larger than 10 years). These long-term improvements should be part of a operational plan to control and maintain the building in the coming years.

Envelope works can include improving thermal insulation, adding solar protection, adding air-tight windows or doors. These interventions lead to lower energy needs for maintaining indoor climate. An adequate new HVAC system can then be designed with lower nominal power, and lower massflows, compared to previous ones. If piping and ducting remain in good condition, the major HVAC refurbishment could be focused on the generation side with, for example, new systems replacing old gas or oil boilers. For air systems, heat recovery could be installed if not present before. For buildings with heating and cooling needs at the same time, coordinated systems can satisfy heating and cooling needs with high energy performance.

For long-term improvement, it is crucial to have a coordinated plan to make the successive relevant investments in the correct time order for minimizing final energy use. Both architects, HVAC engineers and collection specialists must be involved in this planning process.

Heat recovery systems

Heat recovery systems capture waste energy from one part of a building's climate system to benefit another, but typically require substantial modifications to existing ductwork and system configuration. Unlike simple component replacement, heat recovery installations often involve construction work that can disrupt building operations and require temporary collection relocation in affected areas.

The most common approach involves heat recovery ventilation, which transfers heat between incoming fresh air and outgoing exhaust air through a heat exchanger. This reduces the energy needed to condition outdoor air and works particularly well in climates with large temperature differences between indoor and outdoor conditions. Heat recovery works especially well in spaces that generate significant waste heat, such as server rooms, conservation laboratories with equipment, or spaces with high-intensity lighting systems. The excess heat from these areas can be captured and used to warm incoming fresh air for other parts of the building.

Energy recovery ventilation is less common and more sophisticated, going beyond heat transfer to also exchange moisture between airstreams. This proves valuable in humid climates where dehumidification represents major energy consumption, though it requires more complex control systems and maintenance. Water-side heat recovery, which captures heat from cooling systems to provide heating elsewhere in the building, is typically found only in larger institutions with substantial simultaneous heating and cooling needs and requires coordination of complex water distribution systems. Water-side heat recovery proves particularly valuable for institutions with large cold storage areas, such as photographic and film archives that require significant cooling capacity. The waste heat removed from these cold storage spaces can be captured and redirected to heat other areas of the building, such as offices or public galleries.

Heat recovery systems significantly reduce the modularity of room functions since the required ductwork and piping changes create permanent connections between different spaces. The heat recovery effectiveness depends on maintaining specific relationships between heat-generating and heat-receiving areas. This reduced flexibility should be considered carefully in institutions that frequently reconfigure spaces for changing exhibitions or collection needs.

Full system replacement

A full system replacement is usually considered in line with a renovation of the building envelope. The system needs to be dimensioned for the new layout and performance of the envelope. Going further than a retrofit, this can include the placement of new ductwork and emission systems, which has a significant impact on building preservation and collection risk. Furthermore, when institutions depend on systems for adequate climate control, collections need to move within the building or out of the building for temporary storage.

Key system parameters requiring definition during major system changes include:

— Air volume requirements based on space function and occupancy patterns
— Seasonal setpoint strategies that balance collection needs with energy efficiency
— Extreme weather protocols to prevent system failure during challenging conditions
— Occupancy-based controls for variable-use spaces
— Fresh air versus recirculated air ratios for different zones
— Programming capabilities needed for automated operation
— Strategic placement of air inlets and outlets to avoid direct airflow on sensitive collections
— Control sequence design
— Maintenance access requirements
— Integration with existing building management systems

Guaranteeing all these guidelines are aligned with one another requires careful planning during the design phase.

Cultural heritage institutions can find it difficult to translate their needs to system engineers. It is therefore recommended to prepare certain documents in advance and discuss these points internally before speaking to a specialist. Consult both the data chapter and the communications chapter below for more information. ### REFER TO COMMUNICATION CHAPTER 2.8 and DATA CHAPTER SYSTEMS ###

Stop using existing systems

Many collection care facilities have different systems that operate simultaneously. While not the preferred approach, some institutions have discovered system removal opportunities through unplanned circumstances. This often occurs due to years-long waits for replacement parts, traditions of deferred maintenance stemming from funding constraints, or complete lack of capital for major repairs. Some institutions have noticed in the past that when one or multiple systems break down, climate actually stabilizes. This is highly dependent on the outdoor weather, season, systems present and how they compete with one another, but it is not surprising. When a system breaks down, it is often the most complex systems that do so. Rather than focus on the breakdown cause, this often makes institutions reconsider their strategies with the remaining systems present. While this can be a challenge and testing requires close monitoring and adaptation of strategies throughout the year, it frequently results in energy savings in the end.

The chosen strategy is often a combination of available short-term adaptation strategies, such as explained in the respective chapters, combined with close monitoring of both climate and objects.

This raises the question: if not forced, can I consider a full system shut down? This depends on many different factors. However, it is recommended to implement extreme weather setpoints and temporary shutdown testing ### REFER TO TEMPORARY SYSTEM SHUT DOWN ### before systems fail, as this allows controlled experimentation rather than emergency adaptation. Start with simple system temporary shut-downs during specific periods such as shoulder seasons and gradually extend these periods while carefully monitoring. When the results of these (at least two year-long) campaigns are satisfactory, one can consider using systems differently, including getting rid of a system entirely.

2.7 Professional communication: collaboration with specialists

As for Building Chapter, the improvement of System is requiring collaboration between the project stakeholders. The process follows the same steps

Define your needs

At the beginning of your project, the goal. This could be an energy reduction goal or simply a setpoint maintained in some areas.

Contact the required expert

Based on the needs, the institution should reach out to the expert(s) in the field. It can be a consulting company that has its own experts or individual personnel for each field. It is recommended to involve at least one person with experience in historic structures (if present), as well as experts in HVAC systems and building physics (if the modifications require this).

The experts should be aware of the institutional context. In heritage sites, the HVAC equipment does not only reach comfortable conditions for human beings but also conservation conditions for collections. This leads to bandgaps instead of exact values for climate controls.

On-site inspection – documentation and data overview

Once the project team is set, the on-site visit should be organized to pre-evaluate the current state of the systems and required climate. Some document and historical data are important to understand the operation of the HVAC system in the building.

Analysis proposal of renovation specifications

Based on the analysis of the precedent steps, a specification is to be drawn. The specification details the work to achieve. The experts should either write the specification or check them if they are written by an engineering company or public authorities. Specification include the

Selection of companies

Some companies are selected, preferably some craftsman with experience and awareness in heritage buildings.

On-site modernization.

Acceptance of work – commissioning

the larger the project (from maintenance to renovation) the more specialized knowledge is required. This does not always need to be high tech, but can also involve simpler electrical work and plumbing. It can be important to choose a good craftsmen that gets to know the system and gets familiar with it over time.

- Know when to ask information to a specialist (for any timeline) if you cannot answer your own research questions.
- For optimization, renovation and maintenance contracts, describe what a person needs to know and what to consider. What is the regular process? Mention the information that will be asked from you (look at the data chapter) at what stage.

2.8 Cross-domain considerations: how building changes affect systems, collections, and energy use

Impact on buildings and energy

The building and its environmental control systems are mutually dependent: a change in one domain affects the other. Any modification, regardless of scope, influences the building's overall energy needs. Therefore, the envelope, HVAC systems, and energy considerations should always be studied together.

Changes to the building enclosure, particularly during deep modernization, affect not only the total energy demand but also the dynamics of energy use required to maintain desired indoor conditions (especially important for collection preservation). It therefore affects the performance and operation of the technical systems. Typically, following envelope modernization, the HVAC system is also upgraded to further enhance energy efficiency. Greater efficiency translates into reduced energy consumption without compromising the environmental requirements for collections or visitor comfort (case study sensitive).

Modernization of the HVAC system, without corresponding improvements to the envelope, will also impact (yet typically with lesser effect) the building's thermal behavior. Under steady operation with defined climate setpoints, this impact may not be visible. However, when systems operate intermittently, the building's thermal dynamics change, e.g., slower heating-up time in buildings with high thermal mass due to the lower heating power. These effects influence energy consumption and should be evaluated on a case-by-case basis. Consequently, system-level upgrades should be considered only after an initial assessment of the building's characteristics.

Impact on collections

System interventions create direct risks to collections through environmental disruption and indirect risks through workspace requirements. Minor system work generates dust and creates temporary environmental instability similar to building construction, requiring protective measures for nearby collections. However, major system installations or replacements can demand significant space, potentially requiring temporary removal of collections from storage areas or closure of exhibition galleries during work periods.

Larger system modifications may permanently sacrifice collection space to accommodate new equipment, ductwork, or access requirements. This space reallocation requires careful planning to ensure adequate alternative storage and may necessitate collection relocations that create handling risks. The disruption extends beyond the immediate work period, as collections must adapt to new environmental patterns established by modified systems.

Both shutdowns and setbacks require careful attention to the rate and magnitude of environmental changes. Gradual temperature changes (around 5°C per day maximum) help minimize stress on collections. The duration and frequency of fluctuations should be considered. Frequent cycling may cause more damage than steady conditions slightly outside ideal ranges. Furthermore, many materials become more brittle when temperatures drop below 12°C. Avoid moving objects during these periods. While controlled low temperatures can benefit preservation, uncontrolled temperature swings from system cycling can be damaging. In humidity-controlled climates, be particularly cautious about allowing humidity setbacks during periods when condensation risks and temperatures are high.

Shutdowns and setbacks must be carefully planned with collection safety in mind ### REFER TO, INFLUENCE ON COLLECTIONS and TESTING TEMPLATE ###. It should include proper restart timing to ensure conditions stabilize before staff arrive. Data logging alone cannot capture all collection impacts. Visual inspection of objects during and after shutdown periods helps identify any negative responses such as cracking, warping, or other changes that might not appear in temperature and humidity readings. Staff should be trained to observe and document any changes in collection condition, particularly in sensitive materials, as ongoing observation of actual object response is as important as monitoring environmental data.

Poorly maintained or incorrectly programmed systems pose ongoing collection risks that often exceed the temporary disruption of system work. Malfunctioning equipment creates more damaging environmental fluctuations than stable conditions slightly outside ideal parameters. This risk increases significantly in institutions lacking dedicated technical maintenance personnel, where system problems may persist undetected until collection damage occurs.

Complex systems, even those with well-calculated capacities and sophisticated controls, are not miracle solutions. They require substantial ongoing investment in specialized maintenance, staff training, and technical support to function properly. More components mean more potential failure points and higher operational complexity. The most sustainable approach often involves selecting the simplest system that adequately meets collection needs rather than the most technologically advanced option. This principle reduces both operational risks and long-term costs while often providing more reliable collection protection than over-engineered solutions that exceed institutional capacity to maintain effectively.

3. Collections

3.1 Introduction

Collection-based energy strategies can be implemented at any time but vary significantly in their impact and investment requirements. Unlike buildings and systems that follow predictable maintenance cycles, collection interventions are driven by opportunity, institutional priorities, and available resources. The approaches range from immediate, low-cost management changes to major investments that coincide with renovation projects or storage expansion.

The weight of investment, rather than strict timelines, determines when different strategies become feasible. Simple zoning exercises and management policy adjustments require minimal financial investment but can provide significant energy savings when institutional conditions align. Rethinking climate setpoints represents one of the most complex but potentially rewarding collection strategies.

Medium-term interventions typically occur every 5 to 20 years as budgets allow and collection needs evolve. These include updating packaging policies, changing permanent exhibitions, and ordering or retrofitting a large number of display cases. Such projects require careful planning as they often involve temporary collection relocation and specialized protection measures during implementation. Major collection relocations and specialized storage projects represent substantial investments that usually coincide with building renovations or institutional expansions.

This flexible timeline reflects the reality that collection care decisions must balance preservation priorities, available funding, and operational capacity. The key lies in understanding which interventions provide the greatest energy impact for the available investment, allowing institutions to build sustainable practices incrementally while maintaining collection care standards.

Creating a suited museum environment is often a matter of trial and error, as perfect conditions do not exist for all objects individually. Mixed collections require compromise solutions that balance competing preservation needs while considering energy implications.

3.2 Ongoing efforts: housekeeping and risk based collection management

Before implementing any energy-saving strategies, it is essential to recognize that good housekeeping and maintenance form the cornerstone of effective collection care and climate control. Regular observation, dusting, and basic maintenance of both building envelope and interior spaces are fundamental to preservation - and directly impact energy efficiency.

These practices have been described since before a museums existence and have been adapted over time. Contemporary resources that can inform you are: The Nationals Trust Manual of Housekeeping (English), The Monumentwatch Brochures (Dutch), and regional heritage building maintenance protocols that provide structured approaches to preventive care for cultural heritage buildings.

In this chapter, you will learn what the options are from collections and museum management perspectives. Not all proposed options are suited for everyone. It is therefore not recommended to try to implement them all. The options proposed should be in line with the institutional mission, feasible and the result of an interdisciplinary conversation. While a significant amount of your institution can exist out of non-collection spaces where energy saving measures can also be considered, they are not integrated in this chapter since it is collection specific.

Collection risks should be considered. The C2P protocol specifies that risk for a collection should not increase and decrease if needed. It is however impossible to detail all risks for all objects anywhere. A general understanding of collection risk in your specific climate, building and for your specific objects is therefore required. Consult stakeholders who understand your particular materials and institutional context before implementing significant environmental changes.

3.3 Short-term: reversible collection based building envelope strategies (5-20 years)

Strategic Zoning

Zoning is essentially (re)dividing the collections spaces in such a way that facilitate energy saving options. It is an approach that is suitable for any institution. Identifying zones can be considered useful to develop and/or enhance any type of operational management. It requires the collection of data and facts about a given space that allow you to reconsider configuration options. ### REFER TO DATA CHAPTER 3 point 4 ### gives an overview on what minimal collection based data that can be indicated on a floor plan. Different approaches can include:

— Zoning by collection use or access: identify if comfort temperature is required (personnel or visitor space) or is comfort secondary (storage space, no coat removal, special locations and other exceptions). Keep into account places where large group events take place.

— Zoning focusing on material collection composition: understand the impact of climate on materials and techniques used for object creation and/or conservation treatments. Try to divide your collection in material groups (for more information check ### REFER TO DATA CHAPTER 1.1.3.4 ###) that are tolerant to a similar type of climate in order to reduce risks. Focus on the real needs of the collections and take into account proofed fluctuation. If a permanent exhibition is showing no damage in its current climate, implementation of changes might not be required even if, theoretically, it is recommended.

— Zoning by natural indoor climate: Identify the average climate by room in relation to potential risks such as: mold, mechanical or chemical damage ### REFER TO DATA CHAPTER 1.1.3.2 ###. Indicate where certain challenges occur such as high fluctuations, large seasonal fluctuation, overall unsuited climate, etc. Understand that building envelope characteristics such as the amount of windows, materials used, orientation and amount of outdoor vs. indoor walls will determine the impact on your indoor climate.

— Zoning based on climate mitigation possibilities: create zones based on the possibilities of your climate systems present. What factors can you control in that space including heating, cooling, (de)humidification and/or ventilation.

For this approach different strategies can be combined. It can be considered an introductory exercise and will facilitate further specific improvements. It needs to be mentioned that this approach can be in conflict with scenography. It is recommended to include colleagues at the beginning of the discussion.

Physical partitioning and barriers

Zoning can be a tricky exercise, museum spaces are often large and interconnected and systems do not always target rooms of a similar use. This makes climate control more challenging than just turning a switch to a certain set-point. Furthermore, room functions can change and building envelopes might have a very different composition or character. As cultural heritage institutions are often obliged to find additional revenue streams, a modular approach to space usage is often required. The usage of temporary or permanent barriers or partitions might be of help.

- (Semi-)temporary partitioning: Install heavy curtains to separate zones with different climates or types of climate control. All heavy wool felt, linnen or canvas materials can be excellent temperature and humidity buffering materials but can increase pest risks if not properly maintained. Non natural alternatives Think about different types of doors that can be closed or opened based on temporary needs in order to reconfigure certain spaces.
- Air barriers and sealing: Install draft strips at windows and doors which can reduce air infiltration. Seal around utility penetrations and service openings and use vestibules or airlocks at heavily trafficked entrances to minimize environmental disruption. Be aware that historic houses often have a natural air flow that might decrease disposition of mold spores. Reducing this natural ventilation should go hand in hand with monitoring for active mold growth.

Light control and solar heat management

Light control serves dual purposes: protecting collections from photochemical damage while reducing cooling loads from lighting systems and solar heat gain. However, it is important to implement these measures taking into account the architectural value of the space and the experience of the visitor.

- Natural light: If possible, install curtains or reflective roller blinds, especially at single-glazed windows. Light blocking materials outdoors work significantly better than indoors. If historic shutters are present, create a protocol to open and close them based on orientation and outdoor weather patterns. Close them during hot days to prevent unneeded solar heat gain and close them during cold night to prevent heat loss. If roof glazing is present, whiting or 'greenhouse shading' (with a calcium carbonate based product) during summer months is historical and natural way to reduce heat gain. It is sprayed over a glazed surface and naturally rains of over time (by autumn).
- Artificial lighting: it is advized to gradually transition into LED systems who significantly reduce heat loads compared to traditional lighting. In relation to risk, while refitting display cases can be expensive, this can become a priority, certainly when high heat emission lamps are used. Incandescent, halogen and fluorescent light bulbs can make T and RH fluctuate significantly in a small space.

3.4 Short-term: working with microclimates. Adding barriers, from display cases to packaging (5-20 years)

When the annual average relative humidity of a space falls within the 35-65% RH range, limited climate control combined with passive approaches work well. Many collections adapt well to stable conditions within this range. For objects that have specific requirements additional buffering materials can be used. Every additional layer added around the object will act like a buffer. Different types exist ranging from the collection acting like a buffer itself, over packaging materials to display cases or special frames. While C2P promotes passive buffers over active ones, small scale microclimate control systems exist. The particular advantage here is that these can prevent larger scale control.

Collections as their own buffer

Collections themselves can provide environmental stability. Large paper collections, in storage enclosures that are more than half-filled with hygroscopic materials, can naturally buffer humidity fluctuations. This natural buffering effect should be incorporated into system design rather than fought against. This is a normal and beneficial process. The materials are performing their natural function of equilibrating with their environment. The moisture content changes are typically very gradual and small, well within the range that stable collections have experienced throughout their existence. However, one should be aware that while this reduces RH fluctuations in the general environment, the water content of the hygroscopic materials actually increases or decreases as they themselves are the buffering materials. As hygroscopic materials reach a saturation point, as all materials have a minimal and maximal water content, large fluctuations in such a space should immediately be alarming as they are often a sign of a significant building or climate system malfunction.

Display Case Strategies

All display cases, both historical and contemporary, can play a significant role in buffering humidity fluctuations. Display case design is a job in itself where material use, air tightness, design, use and lighting, all play a big role. Additionally, display cases can be part of a museums, often protected, interior design. However, in relation to energy, there are generally three types of display cases.

- Non controlled display cases (low maintenance): the majority of display cases are non-controlled. This means they have no additional passive or active climate control systems. They are just an additional layer to another object creating a buffer between that object and the indoor climate of the room where they are located. Performance of these display cases depend on:
  - How well are they sealed: what is the air exchange rate with their environment
  - Collection materials within cases in relation to the volume of air: the larger the volume of the organic matter vs. air the more stable humidity will be
  - What are the materials used for construction: when they are organic, they can provide an additional buffer.

It is worth mentioning microclimate frames for conservation framing here (often referred to as 'climaframes'). They are small scale display cases for 2 dimensional objects. It is typically made out of glass (acrylic, or polycarbonate) with anti-reflective and UV-filtering properties that is put around the objects itself and subsequently integrated in the original frame.

Alternatively, this is a small display case that is added around the frame. The principle of these small, well sealed cases is that the object-to-air volume ratio is high and thus the object or other display materials present (e.g. a mat or passepartout) act as a buffer for their own environment. It is sometimes possible to work with silica gel here as well. The size of these cases and the fact that they are often chosen as a permanent solution makes choosing high quality and non-polluting materials highly important.

Fig. xxx: Different types of display case constructions

— Humidity buffers based on desiccant materials such as silica gel (medium maintenance): removable humidity buffers (typically silica gel) can provide reliable intervention. Ideally display cases provide a space in which a humidity buffering material can be stored. Typically, this is a type of drawer under the case with a slit or perforation to facilitate air exchange. These materials are naturally moisture regulating and should act faster than e.g. cellulose based object in that same case will. This might require some retrofitting of existing display cases. The performance of this method depends on:
  - 〉 The display case design: the size of the perforations through which the air exchange take place and placement of the desiccant materials.
  - 〉 The chosen desiccant materials: The type of desiccant can be both natural - often very location specific - as synthetic. Typically and by for the most used are silica gel in the form of cassettes, bags or just as pellets or sheets. Some are better to use for typically low RH, others are known for their long-term stability (low maintenance). Commercially available products, used in pharmaceuticals and the food industry, can be used as well although there are other factors to take into account such as dust disposition, handling and off-gassing. Some desiccants can be preconditioned (e.g. wetted if higher RH is required) before they are added to the microclimate. The provider of the desiccant should indicate more information about the required amounts needed for which air volumes to obtain which RH averages over time.
  - 〉 Air volume of the case: for very large display cases the amount of desiccant materials might be very high and unfeasible to integrate or just unpractical to maintain.
  - 〉 Target RH range and outdoor climate conditions: different desiccants work optimally at different humidity ranges. The difference between the RH indoors and the targeted RH in the display case, will determine how much desiccant is needed and when replacement or reconditioning is required. Based on the differences needed and the stability of the indoor climate, this can be anywhere between 1-12 months. Most institutions monitor the RH in order to determine when the product needs to be reconditioned.

Implementation of desiccant-based systems requires careful institutional planning beyond the initial installation. Seasonal conditioning requirements mean that desiccants may need different preparation for winter versus summer conditions, as outdoor climate variations affect the equilibrium moisture content that desiccants can achieve. All desiccants have limits and can become saturated, requiring regular monitoring to determine when reconditioning is needed.

— Active microclimate control systems such as small scale HVAC's (high maintenance): if the climate needs for one particular object (or group of objects) need to be significantly different than the indoor climate (e.g., precious photographs among organic collections), additional active regulation can be an option. Additional heating, ventilation, cooling and (de)humidification can be added separately, or in any combination based on specific needs. Typically, these systems are located underneath a display case with perforations or slits for air circulation and extraction vents. Typically, these systems can also be provided by the display case manufacturer. Additionally, for someone with sufficient technical know-how, there is an option to create simple systems by assembling commercial parts and implementing them after sufficient testing. Performance of these systems depends on:
  - Quality of case sealing and air exchange rate: leaky cases overwhelm small active systems quickly
  - Maintenance schedule and staff technical competency: complex systems require regular professional servicing and troubleshooting capabilities. It is strongly discouraged to implement a large number of these systems if one does not have on-site technical personnel or permanence in the spaces where these systems are located.
  - System capacity relative to case air volume: undersized units cannot maintain stable conditions in large cases
  - Reliability of power supply and backup systems: electrical failures can damage collections rapidly

Be aware that these systems are expensive in large numbers and require high maintenance. Based on the needs, these small machines need electricity (all functions) and/or need to be connected to the water supply (humidification) or drainage system (dehumidification). Often electricity is feasible as the cases can have integrated lighting; however, when humidifying, adding water to and removing it from the system might be a constant task for support staff and difficult during nights or weekends. Additionally, retrofitting older display cases might be difficult. While different sized active microclimate control systems exist, they tend to take up much more space than silica gel cassettes.

Packaging and storage enclosures

The same principles mentioned above also apply to storage enclosures. However, three things are fundamentally different: objects do not (always) need to be visible, the ratio between objects versus air volume is on average much higher, and these spaces do not (always) have to be conditioned for human occupation. While the latter two factors influence set-points determination, discussed below, we will focus on packaging as buffering material.

It is important to note that while increasing the amount of objects per air volume might seem beneficial in storage areas, manipulation and identification must remain feasible. As a standard rule, it is undesirable to move over 3 objects to reach any given object in a storage space.

Fig. xxx: Different primary packaging, secondary etc.

There are specialized publications and recommendations dedicated to choosing suitable packaging for different types of objects. To simplify, here are a few things to consider when it comes to buffering performance and quality:

- Chosen materials for packaging:
  - Material properties: overall, non-synthetic organic materials buffer better than inorganic materials but they are more sensitive to pests and mold. When transparency is required (for regular observations and condition checks with minimal manipulation), plastics, open shelves and glass are better options to consider. The closer any material is to your object (materials in direct contact with objects are referred to as primary packaging; materials not in direct contact with collections are secondary/tertiary packaging, etc.), the more important material inertness is.
  - Quality considerations: ideally packaging materials and furniture chosen are materials with high inertness such as powder-coated, enameled or stainless steel, acid-free boxes, silk paper, inert foams, unbleached and uncolored cotton or linen, and spun-bonded HDPE (high-density polyethylene, better known by its brand name Tyvek), etc. Be aware, however, that these materials can lose their inertness over time. ISO and other quality standards can give you more insight into their material qualities.
  - Materials to avoid: glued and acidic types of wood, certain plastics (such as single-use and early plastics, polyvinyl chloride (PVC), and polyurethane (PU)), acidic paper, and strongly colored fiber, etc. All materials have advantages and disadvantages, but it is not always easy to balance different options. For example: when objects are highly sensitive to both humidity and pests (e.g., taxidermized animals), it might, also due to their size, be more practical to display them on open shelves in order to enable regular inspection and maintain good airflow. The best advice is to stay pragmatic and/or ask colleagues from similar institutions for advice: ask which systems work for them and which do not, and why they have made certain decisions in the past.

- Amount of and thickness of the layers added: every additional layer will stabilize the climate and reduce humidity fluctuations. Sheets to separate one object from another, and/or stacking objects on top of one another (e.g., a collection of maps or drawings), will have a similar effect. Thick layers of hygroscopic materials (e.g., heavy oak closet) will create a better buffer than thin ones.

- Furniture systems and layout: gasketed, closed, and airtight systems will perform better as buffers than open shelves. Mobile storage or high-density storage systems (such as mobile shelving systems, often referred to by the brand name Compactus, or painting storage screens on rails) have a double advantage. They increase the collection-to-air volume ratio and save space. When rooms are conditioned, it is important to place storage elements at least 1m from HVAC supply or extraction vents and/or from any heat-emission elements. If possible, avoid contact between storage furniture and exterior walls. When storage is placed parallel to the airflow, this will enhance air movement around objects and avoid dust deposits. Air circulation between different furniture components can also be important. A 40–60mm gap between different components – whether between different objects (e.g., two sculptures), groups of objects (e.g., a stack of books on a shelf), or building envelope and furniture (isolation from floor, ceiling, and walls) – is beneficial for air flow and prevents creation of unwanted microclimates and dust deposits.

Reusing furniture is always a sustainable choice. If your storage systems work for you, there needs to be a good reason to remove them, such as visible changes in object condition or lack of storage space. In relation to risk, it is important to note that objects themselves can contribute to pollution. Examples include acetate and nitrate photographic films and other magnetic media, furniture, fashion and design made of early and modern plastics and polymers or wood composites that contain glues, rubber objects, objects treated with pesticides etc.. If possible, they should be stored separately or somehow be isolated from the rest of the collection.

Awareness of Unwanted Microclimate Risks

While creating a microclimate can be an ideal solution, it can be a balancing exercise as well. Working towards maximal buffering and control can also increase certain risks. However, this can be countered by good collection management, pragmatic decision making, testing and observation. The balancing exercise is often in relation to:

— Dust deposits and mold - generous airflow vs. air tightness: When a microclimate is airtight it increases its buffering capacity but reduces air circulation, creating conditions where dust accumulates. Furthermore, when objects coming out of a more humid environment are placed in a small closed and dryer environment a part of its water content will evaporate possibly increasing the RH significantly or causing condensation. High humidity (and temperature) combined with dust increases the risk for mold germination significantly.
  Mold development is therefore often found in corners of rooms or inside or behind larger objects that are placed too close to the wall (back of paintings, tapestries and furniture) where airflow is poor. Lastly, condensation on cold surfaces - such as near windows, ductwork, or thermal bridges can create particularly high-risk conditions that can induce mold germination.

— Potential pest risks - hygroscopic organic materials vs. plastics and inorganic materials: while plastics can be a source of pollution, organic packing materials and furniture, besides the collections themselves, can be considered a delicious snack for certain pests. Additionally, objects packed in non-transparent packaging can make it harder to observe the presence of pests (or mold). So when collections are highly sensitive to pests (e.g., taxidermy and ethnographic collections) and they are located in a room where pest control is challenging, it might be more wise to choose for easy observation.

— Mechanical risks and chemical aging:
  〉 Space optimization vs. choosing relatively risk-free storage spaces: while 'full' organic material storages can be a buffer themselves, overfull storages can also causes other risks to increase. One of those being the lack of space for movement and manipulation of objects. Additionally, spaces with a lot of canalization (pipes and ducts to supply air, water and gas) machinery and servers can both cause calamities (e.g. a breaking pipe cause water damage) as well as create unwanted microclimates (e.g. heating pipes and servers causing small heat islands). One way to deal with these risks is not to fill a storage to the rim, stay away from heat or cold sources, leave top and bottom shelves empty and try to avoid placing them underneath canalization and foresee enough space for air circulation (as described in the previous point).

- For active systems, connection to general HVAC system vs. small scale control: direct connection of HVAC supply air to display cases often fails because case moisture and thermal loads that are not in line with the room loads, leading to erratic conditions inside cases. On the contrary, when systems are not connected to the main system, fluctuations and calamities can occur when they are not monitored (e.g. during the night and museum closure). In general, these system require regular interventions and require technical or support staff on site 24/7.
- Daylight and or heat emitting artificial light: be aware of display cases being exposed to direct sunlight or being lit by lamps with a high heat emission during certain moments of the day. These can rapidly increase the temperature inside the display case for several hours, which will also make the RH decrease. Detachments can occur for mixed media objects that have a very different thermal expansion coefficient (e.g. musical instruments). Additionally, this will speed up natural aging and can cause other types of damage such as ghost imaging.
- Working with what you have vs. new materials: Although tightly closed display cases perform better than leaky ones, the risk of accumulation of gaseous pollutants is higher. For this reason, display cases should be manufactured with inert materials such as glass and metal, which do not off-gas harmful contaminants.

The solution in all cases is to measure where problems might occur based on theoretical assumptions or have occurred based on testimony or observations. Simply monitor in both in a representative space in the room and inside the microclimate as well. Often observing your space with a thermal camera can provide more information on heat and cold sources, as well as spaces with lack of air circulation. Testing can be of help as well. Before buying either materials for packaging, new storage furniture and display cases, see if there is a possibility to test one. Review both their performance and the labor intensity for maintenance purposes.

Pay attention to material use in relation to damage. Paint, glues, some wood species and other materials can emit pollutants, certainly when new. Object damage such as for example corrosion can therefore be related to pollutants rather than humidity.

3.5 Short-term: Climate systems, rethinking set-points (5-20 years)

Set-points are thresholds that are defined by numbers in order for any climate system to understand what indoor climate they should achieve. This can go from a thermostat to complex programming in a BMS system. It is important to know that not every system can be programmed in the same way. Sometimes changes need to be made manually and seasonally. Defining these thresholds can help establish a better notion of both when and where you need to pay extra attention to possible collection risk. In short, an institutional (or zone-specific ### SEE ZONING ###) set-point is used here to define a desired climate in relation to collection risk and not in relation to the climate system present.

This part follows the structure of the chart ### 'define sustainable indoor climate for cultural heritage preservation in an existing building' ### and will refer to other sections of the C2P handbook for background information. This roadmap is intended to be an aid for decision-making.

The goal is to rethink certain set-points and create more flexibility, at least by implementing seasonal set-points and exceptional set point (in relation to climate change), and ideally widening them based smart and sustainable collection care mitigation strategies proposed here.

Once a decision is made to adapt certain set-point, ### CEAM ### can be used to calculate how many energy savings can be achieved by changing from your current climate to the newly defined needs.

Once you have established new and hopefully more sustainable climate, you can start communicating about it by, first and foremost to institutional stakeholders, but also by ### resetting alarms ###, if any, adapting your ### loan agreements ### and ### facility reports ###.

For all these tasks, tools, templates and instructions were made that can be used by any institutions. These documents redefine existing practices but integrate sustainable practices. They can be used for this project but can be standalone documents as well.

Reality check

Starting with and performing an intermittent reality check is always beneficial to a project. The most sustainable set-points are those that a museum is able to achieve on the long-term, preferably even when systems temporarily fail and/or calamities occur. This automatically means that outdoor climate, you're building envelope, and your available budget and staff, play a very significant role in putting numbers to a desired indoor climate.

A well-defined sustainable indoor climate has flexibility and promotes resilience while minimizing collection risk when exceptional events occur. A non-sustainable indoor climate is creating a yearlong flatline using active climate control just because you can (e.g. the staff, budget, resources are available). Even if feasible, and certainly beneficial for certain types of collections, this is not in line with the C2P principles that strive for a reduction of energy consumptions.

Identify and understand collection damage and change

A good but challenging exercise is tracking the condition of your objects over time and identify which damage is actually proven to be related to an unsuited indoor climate. As previously highlighted there are three types of damage or change that can occur being mechanical, chemical (or natural aging) and biological ### THEORY 1: 3.2 climate and collection ###. It is important here to make the distinction between historical damage, damage caused by an unknown source and actual climate related damage. Try to relate the damage to your climate data, is the damage observed in line with too high, low or fluctuating T and RH?

Fig. xxx: most prominent types of damage related to unsuited climate.

Define zones and understand your systems and collections

As discussed earlier in this chapter it is valuable to define zones. Based on your research question, different types of strategies can be chosen. It's interesting to combine building, system and collection related information. It is recommended to at least indicate:

- Comfort: collection / non-collection and public or not public spaces have an impact on comfort temperature. If human occupation is no or only a short-term requirement, temperature, ventilation rate and oxygen levels can be lower.
- Collection: moving, permanent or in (long-term) storage. These type of collection have different needs. Permanent collections will determine the general 'institutional' climate. Moving collections might need to go through a slow transition to adapt to another climate. Storages have special advantages such as natural buffering through a large collection mass.
- Collection needs: these two previous will determine what type of (different) climate(s) you define such as:
  - Classic museum climate: are usually some type of translation of international guidelines.
  - Microclimate: A type of buffer for the general indoor environment. Different options are described in ### point 3.3 ###.
  - Climate chambers and quarantine rooms: are for objects on the move that need to adapt to another environment or need to be kept in isolation for inspection or treatment due to being a risk to other objects (e.g. pest or mold present).
  - Specialized climates (cool, cold, frozen, dry or low oxygen): for non-public storage spaces usually containing chemically unstable materials.
- Systems: no control, heating, cooling, (de)humidification and mechanical ventilation

For more information on these choices and their purpose you can consult ### REFER TO: Documentation and Data, 1.4. ### and the more detailed function description of different specialized museum rooms. Furthermore, some of these climates are linked to international guidelines for both public spaces as storage spaces ### REFER TO: Theory I, 3.5 and 3.6. ###.

Understand international guidelines and understand the requirements and impact

International guidelines are only mentioned because they are universally known and referred to and they are translated to specific collection risks. However, any institution is free to create their own internal guidelines based on the institutional context.

The guidelines defined in ### REFER TO: Theory I, 3.6. ### cannot all be realized in any type of environment and with any type of building. It is important here to do a new reality check. There are many factors here that play a role and decision-making is partially based on making educational guesses. However, it is important to understand:

- Outdoor climate: the bigger the gap between your outdoor and indoor climate, the more energy is required to bridge this gap.
- Buildings: If your building is a purpose built and passive structure, minimal control might be possible to obtain a strict classic museum climate.

For an existing building, of no modifications to the building envelope are planned it's those two factors will determine the type of system that is required as well as the energy that will be consumed.

- Climate systems required: if there is a big gap between outdoor and the defined indoor climate and there is a low-quality building envelope, complete control (heating, cooling, (de)humidification) will most likely be required.
- Energy use: the higher the dependence on active climate control, the higher the energy use.

The consequence of these choices have a significant impact again on your general budget and the staff. Complex systems need regular or even permanent specialist control and maintenance.

Determine your set-points and compare to your climate data

To define your indoor climate it is recommended to take your historical annual average, seasonal and short-term fluctuations, and long-term fluctuations into account. However, if preferred simple upper and lower limits can work to. In most cases, due to climate change, exceptional regimes might be required. These 'extreme weather setpoints' are there to avoid calamities such as system failures. They can be set during the hottest, coldest, most humid and driest moments of the year. If a small refresher on the impact of these choices are required one can consult ### THEORY I, SECTION 3.3 ###.

These theoretically defined guidelines now need to be compared to your actual institutional climate. This procedure can be as simple as printing out your yearlong climate timeline and drawing this out on paper. Multiple online tools can be used as well ### THEORY I, SECTION 3.1 ###, however for this specific purpose CEAM is recommended since it also proposes subsequent adjustment and predicts energy savings. The climate data fed to CEAM will be compare to the ASHRAE guidelines as well. For more information on CEAM, consult ### C2P, SECTION 2.3 ###.

Fig. xxx: Add the systematic overview of determining set points (ref. C2P presentation to KMSKB).

Implementation

Once you have found your feasible institutional climate(s), it is important to translate this to system settings. It is advised to implement gradual changes based on collection response. Keep on monitoring (observing) at least the more sensitive objects in the collection for changes. Consider reversibility options for unsuccessful adjustments

Furthermore, it is important to Avoid implementation just before weekends or holidays when response capability is limited and ensure qualified technical support is available during transition periods. Seal external infiltration sources before expanding environmental ranges so you measure and follow the implemented changes rather than external influences (e.g. close doors and windows). If possible, set your alarms in order to detect anomalies ### LINK TO TEMPLATE ###.

If you are sure to have a stable knowledge of your (new) environment, you can adjust your facility reports and loan agreements. As part of the C2P projects templates were made that integrate sustainability into these documents ### LINK TO TEMPLATE ###. More about the importance of honest and evidence-based communication, can be found below ### REF TO POINT 3.6 ###.

3.6 Short-term: management strategies (5-20 years)

While it is a core mission of an institution to share cultural heritage with the public, it is not that uncommon to implement strategies to control visitor flows or implement seasonal closures. While these measures might seem extreme for some, they are not out of the ordinary for others. While some of these strategies are highly efficient to save energy, they need to be in line with a museums mission and vision.

Visitor flow and comfort

High occupancy periods (1-2 m^2/person in galleries) create significant heating, cooling, and humidity loads. It is advised to keep track of your visitor stream and limit the amount of visitors in certain rooms to avoid sudden peaks in high temperature and humidity. Furthermore, when it is raining outdoors, it is advised visitors leave their wet items in cloakrooms to avoid additional contributions to the already higher humidity load. On the contrary, when providing minimal heating in winter and occupancy is limited, it might be advised to keep cloaks on for personal comfort. This is a common practice in spaces with large volumes and limited climate control such as historical castles and religious buildings.

High occupancy can be related to the organization of events. When climate systems are present, it might be interesting to consider pre-conditioning strategies that anticipate the mounting loads and create a buffer before arrival (e.g. do not heat to regular comfort temperature, keep it a bit cooler and let temperature naturally rise as occupancy rises)

For buildings or rooms with very specific functions, it can be advised to keep conditioning to a minimum when there is no occupancy. Here it can be advised to keep ventilation rates end heating to a minimum. However, when heating, it is advised to do it with a difference of around 5°C a day in order to keep responses to short-term fluctuation minimal.

It is possible to let visitor patterns inform HVAC scheduling and capacity planning such as using CO2 sensors to modulate outdoor air intake based on actual occupancy.

Seasonal closures and operational adjustments

Institutions with seasonal operating patterns can achieve significant energy savings by Implementing "winter sleep" temperatures during closure periods. Specifically for institutions with limited climate control in Northern countries this might be an option. While the cold is beneficial for all objects, minimal heating can be advised in some cases in order to avoid too high RH and temperatures that go towards freezing. For southern countries and climates with monsoons, both closures and visitor control can be an option to avoid to increase T and RH even further.

Temporary and seasonal closures can be an opportunity to perform long-term tasks and maintenance.

Guardes, guides, cleaning staff and concierges

Guards, guides, cleaning staff and concierges are essential for museum operations and their expanded role in climate monitoring and energy management requires specific dedication from management to properly inform and train them. Investment in staff education about collection care, environmental monitoring, and energy-conscious practices transforms everyday personnel into active participants in both preservation and sustainability goals.

There are a few measures that can facilitate better climate control and energy saving strategies:

- Staffed areas - enhanced control possibilities: When concierges, guards, or guides are present, constant climate monitoring and immediate alarm response become feasible. Basic training in recognizing climate-related risks (condensation, unusual humidity levels, temperature fluctuations) allows staff to respond quickly to system alerts or observed changes. This human oversight can enable more dynamic climate control systems that might otherwise require continuous automated operation.
- Remote or vulnerable collections - guided access: For collections in remote locations or containing particularly vulnerable objects, eliminating constant comfort conditioning and organizing access only through scheduled guided visits offers several advantages: significant energy savings from reduced heating/cooling demands, better control over environmental disruption from visitor presence, and enhanced security through supervised access. This approach works particularly well for storage areas, historic house collections, or specialized climate-controlled spaces.
- Staff as first observers: Guards and cleaning staff often spend more time in collection spaces than conservators and are frequently the first to notice changes in object condition, unusual odors, pest activity, or environmental anomalies. Their regular presence makes them valuable early warning systems for collection risks, provided they receive basic training in what to observe and report.
- Selective comfort conditioning: While staff comfort remains important for productivity and wellbeing, it's not necessary to maintain full comfort conditions throughout all museum spaces. Strategic heating of staff work areas, security stations, and frequently occupied zones can balance energy efficiency with appropriate working conditions, while allowing less-frequented spaces to operate on minimal climate control. The distinction between mobile staff (guides, cleaning personnel) who generate body heat through movement and stationary staff (guards at security desks, concierges) who require warmer ambient temperatures should inform targeted comfort strategies.

3.7 Long-term: moving collections due to building and system changes (20+ years).

Cultural heritage preservation requires long-term thinking. While we don’t advocate for undynamic collection presentation, the simple principle remains: the less activity around collections, the less energy consumption required. Some collections remain on permanent display for decades without major intervention, representing the most energy-efficient approach.

Collection-driven modifications requiring building changes:

Long-term changes can occur for various reasons, but some are specifically collection-driven. These modifications typically require building envelope or system modifications to facilitate new collection needs, rather than routine building maintenance cycles.

- Collection management needs: growing collections requiring additional storage, rezoning and compartmentalization for different collection types, creation of specialized spaces (quarantine rooms, anoxia treatment chambers, climate-controlled areas)

— Institutional changes: political decisions affecting museum scope or function, mergers or splits between institutions, changes in museum mandate or focus

— Standards and expectations: evolving museum standards for collection care, growing visitor expectations for comfort and accessibility, new security requirements, updated fire safety regulations

— Space optimization: conversion of unused areas (attics, basements, service spaces) for collection use, repurposing between collection and administrative functions, adaptive reuse of additional buildings

— Exhibition needs: new exhibition spaces, renovation of permanent galleries, installation of updated display infrastructure, adaptation of historic rooms for public access

Whatever the reason of a building or system modification, it can be an ideal time to think about (reversible) collection based building envelope strategies ### refer to 3.3 ###, rethinking set-points ### REFER TO 3.5 ### or a new environmental policy, using a combined approach considering all proposed short-term measures.

Planning for minor modifications

When modifications involve limited dust, vibration, and equipment installation, collections may remain in place with appropriate protection measures. This approach requires careful risk assessment and protection strategies.

Keeping objects in place during minor work requires establishing dust barriers using appropriate materials that won't directly contact collection objects, implementing vibration isolation measures for sensitive items, and maintaining enhanced security monitoring throughout the work period. Environmental controls (if present) ideally continue operating, though temporary adjustments may be necessary to accommodate construction schedules.

Fire risk management becomes critical during any construction activity. The risk increases during renovation work, as demonstrated by devastating fires at Notre Dame Cathedral (2019) and the University of Antwerp (2021), where renovation activities triggered large scale fires. Construction introduces ignition sources through welding, electrical work, and heating equipment, while dust accumulation and system disruptions create additional hazards. Fire detection systems, modified emergency procedures, and coordination with local fire departments familiar with collection locations become essential during construction periods.

Planning for major modifications

Major renovations require complete collection relocation due to extensive building work, system shutdowns, and elevated risks from construction activities. This process demands careful planning and coordination across multiple departments and (often) external contractors.

Moving collections out and back in can be a complex logistics challenge. Staff coordination requires establishing clear roles - someone must manage contractor communication, another person handles collection safety and logistics, and ideally a conservator ensures proper handling protocols are followed.

The key is making smart choices for temporary storage facilities. Consider distance from the main building (shorter moves reduce handling risk), accessibility for loading and unloading equipment, security systems that match institutional standards, environmental conditions similar to the original storage, and adequate space for the collections and their manipulation in the form of dedicated work space. Basic risk mitigation includes identifying the most valuable items for priority attention during emergencies and ensuring local emergency responders know where collections are temporarily housed.

The actual move execution requires careful route planning to identify obstacles and hazard points requiring additional personnel, selection of appropriate equipment for different collection types, staff training in proper handling techniques and emergency procedures, and documentation systems to track object locations throughout the entire process. Moving projects also provide opportunities for collection management improvements including basic registration verification, condition assessment documentation, inventory updates, and storage optimization planning.

Budget considerations

Collection moves represent substantial project costs that are frequently underestimated in renovation budgets. Professional moving services, temporary storage facilities, specialized packing materials, additional insurance coverage, and extensive staff time for planning and supervision create expenses.

The complexity and cost of collection moves often influence the scale and timing of building modifications, making collection requirements a primary factor in long-term building optimization decisions rather than an afterthought to building improvements. Institutions must recognize that moving collections is not just an operational necessity during renovation, but a major budget line item that can represent a substantial percentage of total project costs, particularly for large collections or institutions with numerous fragile or oversized objects requiring specialized handling and transport.

3.8 Professional communication: collaboration with specialists

The data chapter ### DATA: 4. COLLECTIONS ### goes into detail about the most essential documents needed for energy saving projects. Some of the most essential ones here are floor plans and T and RH measurements that have been running with an interval of at least 1h over at least 9 months, including the hottest, coldest, dryest and wettest month of the year.
Energy saving projects are not always straightforward. While working with microclimates seems evident, mapping out different zones and determining feasible set-points can be challenging for anyone without any experience. Whether due to a lack of time, prioritizing other tasks over climate control or a lack of in-house support, it can be interesting to gain external expertise.

External expertise

External expertise for collections can be provided by governmental or non-profit organizations and private contractors. These projects often require a close collaboration with institutional staff. Projects often include the following steps:

- A formulation of a demand, research question, or, for more complex matters, a (public) procurement that summarizes all tasks.

— At least one visit on site to better understand the complexity of the project.
— If environmental data is not available yet, T and RH loggers will be installed, most probably for over one year. A schedule of institutional closures, occupation rates and other relevant logbook information can be required.
— It is not uncommon to have a series of (structured or free) interviews that better frame the institutional context.
— An analysis will take place that will compare the collection needs to the existing museum environment. This should separate minor from major risks and help determine priorities.
— Changes or adjustments will be proposed. The institution is usually responsible for the implementation of these changes. Some projects, and this is recommended, include a second analysis after implemented changes in order to further finetune proposed solutions.

Evidence based reporting, transparency and honest communication

For museums, relationships with other similar institutions is essential. Being a relatively small sector, lessons are often learned through communication with colleagues. Additionally, organizing exhibition often involves administrative paperwork that guarantees the safety of visitors and collection (permanent in case of loans). These outward facing documents, most notably loan agreements and facility reports, are often shared freely and contain highly specialized information in relation to indoor climate conditions. Because they are shared widely, it is important to communicate honestly and build trust.

We find that strict climate control (such as 50% RH with a maximum fluctuations of 5% and 21°C with a maximum of 2°C daily fluctuations) is extremely rare in all exhibition rooms of an institution. Misrepresentation of the actual indoor climate in loan agreements and facility reports can have serious consequences such as legal consequences (negligent misrepresentation, coverage by insurance that is not provided, loan recall) and unforeseen damage. Furthermore, big international lenders attach T and RH sensors to the object, a practice only expected to grow in number. Therefore, proving a climate is not what is specified, will not be a complex tasks for the lender and can lead to serious reputational damage for cultural heritage institutions.

Facility Reports

Facility reports often misrepresent the actual environment in different rooms. They can take an optimistic approach through consequently choosing to represent spaces that mimic an ideal situation rather than a realistic one. The intention of a facility report for loan purposes is to show you understand your building, you understand the risks objects are exposed to and know how to mitigate them. These documents should give the lender an idea about all risk levels from the time of arrival of an object to the facility until departure. Evidence-based facility reporting should include:

— Actual achieved environmental conditions, not just target specifications
— Seasonal variation patterns and their correlation with collection stability
— Energy efficiency measures implemented and their preservation implications
— Risk assessment based on actual environmental performance rather than theoretical standards

— An overview of mitigating strategies such as transition rooms, quarantine rooms, microclimate strategies, exceptional outdoor climate mitigation (e.g. operations in time of heatwaves and monsoons) etc.

The C2P handbook includes a template ### TEMPLATE ### that integrates sustainable options. Please use this template to communicate honestly and transparently.

Loan agreements

A loan agreement is an object specific agreement. It takes into account materials and techniques used and the value of an object to the institution. While climate might be a lesser risk for an object compared to e.g. physical damage caused during transport, it can often be a reason for loan refusal. Therefore it is advised to refer to the possibilities specified in the facility report (e.g. mitigation strategies) and apply this to the object itself. Additionally, it can help to focus on focus on response: what can be done if unsuited climate conditions occur? Negotiations are not uncommon and, with a focus on knowledgeable tailor made strategies, almost any loan can be granted even if initially deemed unrealistic.

The ### THEORY 1: 3.2 climate and collection ### first theory chapter and additional reputable sources will help you specify the real needs of a specific objects.

The C2P handbook includes a template ### TEMPLATE ### that integrates sustainable loan options. Please use this template to communicate honestly and transparently both as lender as well as borrower. Do not ask for climate specification that are unobtainable for your own institution. This is both unneeded as well as potentially damaging.

3.9 Cross-domain considerations: how building changes affect buildings, systems, and energy use

Impact on buildings

All actions related to collection management can indirectly affect the building itself. Each building has a predefined floor plan that determines its zoning scheme; thus, moving, temporarily storing, or conserving parts of a collection can influence this system and, consequently, the building’s performance (or perhaps energy use as well). Such interventions may alter local microclimatic conditions, while corresponding setpoints or control adjustments can further affect the behavior of the building and its components. Therefore, any action concerning the collection that may have implications for the building should be consulted with a dedicated specialist (i.e., architect or building physicist). Impact on systems and energy

4. Energy

4.1 Introduction

- Energy as a distinct factor in the C2P approach
- Understanding energy sources, carriers, and conversion efficiency
- The role of energy choices in overall sustainability
- Connection to institutional budgets and long-term planning

4.1. Short-term solutions and long-term impact

Energy source optimization: know your energy source

There are two primary ways to supply the energy required for proper building operation: using either a centralized or local (decentralized) system. In a centralized system, energy such as heat or electricity is provided by an external supplier under conditions defined by contract. The decentralized (i.e., local) system generates the required load on-site, from the selected fuel (e.g., coal, gas), which can be stored on-site, or continuously provided through the grid. No matter the solution selected, it is possible to optimize it or to switch from one to the other (after applying the necessary modifications).

The motivation of our action can be either a better deal, in various spectrums. It can include a more cost-effective offer from a competing energy supplier. Commonly, there is competitiveness between energy suppliers in order to persuade customers to join their network. Therefore, it is possible to receive a cheaper offer by simply switching providers. The connection is typically provided by the same grid. The only catch to be verified is the contract, and the potential withdrawal fees to be considered. Another motivation may be environmental, for instance, selecting a supplier that relies more heavily on renewable or low-emission sources. Similar principles apply to local systems, where fuel suppliers can be changed relatively easily. Typically, it requires substantial modifications to the building's technical systems and supporting infrastructure.

Time-dependent energy prices

Building energy consumption varies over time due to factors such as weather conditions, occupancy, and internal heat gains. Managing peak energy demand is complex and requires advanced control strategies. Because of that, the majority of customers (i.e., buildings) are under fixed-rate energy tariffs. Therefore, no matter the time and no matter the required demand, the cost of energy (per unit) remains the same. However, energy production costs fluctuate throughout the day. During periods of high national or regional demand, energy generation is more resource-intensive and expensive. To reflect this, some suppliers offer time-of-use tariffs, encouraging consumers to shift consumption away from peak hours. Adopting such tariffs can yield financial and environmental benefits by flattening the Load Demand Curve (LDC) and improving overall grid efficiency.

With such an approach, it is possible to switch from a constant energy price tariff to a time-dependent one, pursuing additional savings. However promising, that type of approach seems difficult and impractical for building housing heritage due to its unique preservation mission (typically requiring stable conditions throughout the day, limiting flexibility in adjusting energy use over time).

All the above-mentioned applied primarily to the grid-connected solutions; it is not considered if we generate energy on-site, from the locally stored fuel (e.g., coal).

Power factor correction for electrical efficiency

Power factor optimization involves improving electrical efficiency by reducing reactive power, mainly through adding capacitors to counteract inductive loads from equipment like motors. This process, known as Power Factor Correction lowers energy waste, reduces electricity bills, frees up system capacity by bringing the power factor closer to the ideal value of 1.

Power factor value ranges from 0 to 1 and could be capacitive or inductive. The main electrical counter gives generally an indication of reactive power or power factor. This data could be obtained via your energy provider. Power factor correction becomes increasingly advantageous as the power demand increases and the factor deviates significantly from 1.

4.2. Energy Monitoring and Management

Installing sub-metering for different systems/zones

Sub metering lowers electricity consumption by providing real-time data on energy use, allowing users to identify energy-wasting appliances and peak usage times, Identification of energy consumers is crucial for energy efficiency. The electrical energy can be split per zone or per floor or per building by the implementation of wattmeter in the electrical cabinets. For HVAC systems electricity use, the energy per equipment can be measured. For lighting and plugs, there are generally electrical cabinet for each zone or floor.

In addition to electricity sub metering, heat/cold submetering provides information on which zones use heat/cold at a given period. This enables energy destruction identification. At a building scale, heat and cold could be needed simultaneously, nevertheless at a room/zone scale, this leads to energy destruction.

The metering system should be connected to the BMS to analyze at the same time the energy use and influencing parameters (outside conditions, set points, pumps operation, valve position…)

Identifying energy waste through monitoring

Energy monitoring gathers real-time data on energy use. It gives the possibility to verify that consumption matches usage. In periods where museums are closed or with no activity, the real-time monitoring discovers the energy consumption heel (the energy used without direct added value). Heel consumption typically all over the year, a cut off affects significantly the yearly energy use.

Some examples of heel electricity consumption:

- Standby power consumption of various appliances
- Pumps that run continuously (without any control)
- Appliances that are plugged in but not needed

— Problems with regulating anti-freeze heating elements (terraces, gutters, access routes)

In combination with sub metering, the energy monitoring transforms energy consumption from a hidden cost into a manageable resource. This means the quantification of energy savings is straightforward, thus computation of return on investment becomes easier.

Load management strategies

Energy demand can be shaped over time through various load management approaches, typically referred as Demand Side Management (DSM) or Demand Side Response (DSR) methods. The concept originated in the 2000s, when commercial facilities began temporarily cutting off some non-essential equipment during periods of high electricity prices. While this reduced operating costs, it often compromised productivity. Thus, the concepts of DSM and DSR have evolved toward optimizing energy use without jeopardizing the operation.

There are numerous well-established DSM/DSR techniques, all of which follow the concepts shown in figure. x. Application of a given technique is case-sensitive and should be based on a thorough technical and operational assessment. The most straightforward form of DSM/DSR results naturally from energy efficiency improvement after performing building/system modernization (often classified as a passive DSM/DSR method). The active methods are typically based on optimization of systems, involve dynamic control assuming various setpoint strategies or time-dependent scenarios. Among the most popular solutions, the precooling or preheating can be mentioned; methods using the availability to store energy for later by using building thermal mass. It therefore reduces the load when energy is most expensive or carbon-intensive.

The passive methods always require a thorough case-study assessment, while active methods require careful consideration and might not be the best solution for building housing heritage.

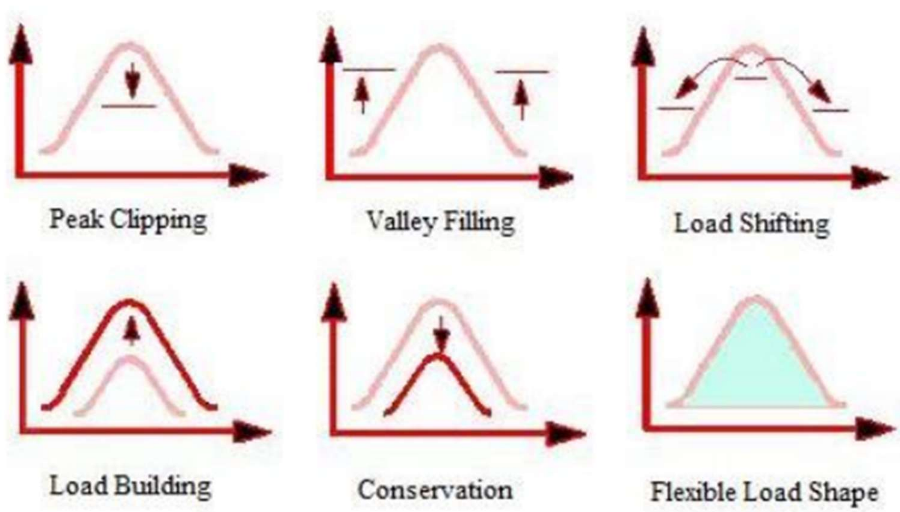


Fig. xxx: Schematic overview of DSM/DSR techniques source: Logenthiran T. et al.)

4.2 Renewable Energy sources

The integration of renewable energy systems (RES) is one of the key elements of sustainable building management. Depending on the scale, renewable technologies can be implemented either as small-scale (i.e., building-integrated) decentralized systems or as part of large-scale centralized infrastructures.

At the building level, small-scale RES can effectively reduce dependence on the grid. Typical applications include solar collectors or photovoltaic (PV) panels installed to harvest solar energy to produce heat or electricity, respectively. Where site conditions allow, a small wind turbine or a shallow geothermal heat pump may also be implemented to supplement energy needs. To balance intermittent generation out of renewables, storage systems (i.e., thermal storage or batteries) can be used for peak shaving. The selection of the solution is case-sensitive; the best possible outcomes are possible when combining several strategies.

At the district or regional level, large-scale systems provide significant potential for decarbonization and operational cost reduction. District-based solutions can distribute renewable thermal energy across multiple buildings through shared infrastructure.

Beyond the typical RES, several advanced technologies can further enhance building performance and sustainability. Heat pumps, including both air-source and geothermal (ground-source), are popular nowadays as highly efficient systems capable of providing both heating and cooling. Combined Heat and Power (CHP) or cogeneration systems can also significantly improve overall fuel efficiency by simultaneously generating electricity and useful thermal energy, thereby reducing primary energy consumption. When appropriately integrated and controlled, these technologies complement renewable energy sources and contribute to broader sustainability.

The overall effectiveness of RES depend on a flexible and intelligent energy infrastructure. Emerging concepts such as microgrids and smart-grid integration allow for partial grid independence. This is yet beyond the scope of this handbook.

4.3 Energy Planning and Investment

Life cycle energy analysis

In a framework of decarbonization of energy source, it is important to have a strategy on both energy usage internally in the institution (replacement of fossil fuel use) and energy procurement. The energy procurement could be low carbon using specific energy contract.

For electrical energy use, it is possible to choose electricity which comes from renewable energy sources (definitely low-carbon energy source). Some of the energy suppliers offer "green tariffs" or "renewable energy plans". This must be certified by Guarantees of Origin (GoOs) to ensure you really have renewable energy. The certificate has to detail the type of energy source as well as its location.

Energy performance contracting

The European commission defines energy performance contracting as follows: "Energy performance contracting means a contractual arrangement between the beneficiary and the provider of an energy efficiency improvement measure, verified and monitored during the whole term of the contract, where investments (work, supply or service) in that measure are paid for in relation to a contractually agreed level of energy efficiency improvement or other agreed energy performance criterion, such as financial savings."

In other words, this is a contract where an Energy Service Company (ESCO) implements energy efficiency or renewable energy projects for a client (e.g. a museum), financing the upfront costs and getting paid from the guaranteed energy cost savings generated by the project. This approach helps bridge investment gaps, mobilizes private financing, transfers technical risks to the ESCO, and makes finally some energy savings.

4.4 Professional communication: collaboration with specialists

Often, free energy audits are available to cultural heritage institutions. However, reality shows us that many of these audits are not tailor-made for historic buildings, neither collection care institutions. Therefore, most probably, an audit for either industry or offices will be performed.

These audits can give a skewed image of reality and are often not in line with the needs of your institution. While they are useful in their own right, it is wise to stay critical and reflect on the impact on your building and collections before implementing changes.

Considering the unique requirements of buildings housing heritage collections, and the fact that many of them are historic, a specialized assessment approach is required. Instead of a conventional energy audit, a dedicated expert evaluation is more appropriate, carried out by a multidisciplinary team of experts. Such an assessment can be inherently case-specific, focusing on the most relevant or critical aspects of the examined building. Nevertheless, certain standardized documents, such as the Energy Performance Certificate (EPC), remain mandatory.

4.5 Cross-domain considerations: how energy affect buildings, systems, and energy use

Impact on buildings

The integration of RES in historical buildings is difficult, yet possible. RES such as solar collectors, PV panels, small wind turbines, or geothermal installations can affect both the physical fabric and heritage value of historic buildings. Structural interventions, added mechanical loads, or visible alterations may compromise architectural integrity and authenticity. To mitigate these risks, appropriate protective measures should be implemented, including reversible and non-invasive mounting systems, installation on secondary or hidden surfaces, and thorough prior assessment of structural capacity. RES can be installed outside the building if there is any unoccupied piece of land. Still, the preservation of the building's cultural and aesthetic significance, in accordance with heritage conservation principles, should be a priority here.

The most commonly applied RES for buildings housing heritage are solar collectors and PV panels mounted on roof surfaces. Their installation requires expertise in mechanical and structural engineering to evaluate the additional load, as well as coordination with architectural conservation specialists to ensure compliance with the integrity and authenticity of the building.

Impact on systems

Modification on energy side a priori does not affect greatly the systems. Producing renewable electricity on site will be beneficial to the environmental balance of the building.

Replacement of a heat furnace by a renewable one with the same capacity do not modify the way the heat is distributed and emitted in the building.

The use of an heat pump for replacing an existing system (e.g. gas boiler) is a particular case, it affects the heating system. The temperature level commonly reachable by an heat pump is 45-55°C. This means the distribution of heat needs to be adapted to this temperature level (which is quite lower compared to gas boiler systems where 80°C water is easily reachable).

CONCLUSION

The C2P handbook demonstrates that cultural heritage institutions can achieve significant energy savings while maintaining or even improving collection care through an integrated approach addressing buildings, systems, collections, and energy management. The key lies in understanding that energy efficiency and preservation are not opposing forces, but complementary strategies that require coordinated implementation.

Successful institutions following C2P principles share common characteristics: they start with comprehensive data collection about their actual climate performance rather than theoretical requirements, they implement changes gradually while monitoring collection response, and they invest in staff training to transform everyday personnel into active participants in both preservation and sustainability goals.

Energy savings achieved through C2P strategies are highly project-specific and depend on numerous factors, including outdoor climate, building envelope performance, existing system efficiency, collection requirements, and institutional operational patterns. Results cannot be directly transferred between institutions due to these variables. A setpoint adjustment that yields substantial savings in one temperate climate building may produce different results in another institution with different envelope characteristics or climate control systems. This is precisely why the C2P approach emphasizes individual assessment and gradual implementation with monitoring rather than prescriptive solutions.

The handbook documents numerous approaches with demonstrated potential: strategic zoning allows institutions to treat different spaces according to their actual needs rather than uniform standards; microclimate solutions can eliminate the need for room-wide climate control; and operational adjustments like fan speed reduction, maintenance improvements, and seasonal scheduling can reduce energy consumption with minimal capital investment.

C2P's emphasis on short-term, low-cost improvements means institutions can begin immediately, regardless of budget constraints. Simple measures like improving maintenance practices, adjusting operational schedules, and implementing evidence-based setpoints require no capital investment but can deliver meaningful energy reductions. Combined with honest facility reporting and evidence-based loan agreements, these strategies position cultural heritage institutions as leaders in sustainable practices.

The path forward requires courage to challenge traditional approaches, commitment to monitoring and adaptation, and recognition that the most sustainable collection care practices are often those that work with, rather than against, natural building and environmental systems. Through the C2P framework, cultural heritage institutions can fulfill their preservation mandate while significantly reducing their environmental footprint - proving that responsible stewardship extends beyond collections to encompass the planet that houses them.

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III. Documentation and data: collection and management

INTRODUCTION

Solid documentation lies at the basis of every single project. In some institutions, this might already be a fundamental aspect of their way of working, others might require time to create a new type of methodology, protocol, or structure. It is vital to say that no way of working is wrong, as long as it is durable, consistent, transparent, and understandable for all people involved. This chapter will:

- Help you create such a methodology, structure, or protocol, or help you improve an existing one.
- Go over the basics of data collection. While there are many rules for efficient data management, this chapter focusses on the essentials that are important in all cases.
- Formulate tips to structure your data in order to ensure that the data is reliable, usable, and transparent.
- Indicate which data is essential and what is useful for projects like this.
- Focus in detail on data gathered to document buildings, systems, collections, and energy use.

It is important to mention that all data can be relevant, going from the institutional memory to detailed data, based on interval measurements. Which data is relevant depends on your goal and your research question.

While this chapter focusses on data collection that can have a direct influence on collection care, this does not mean that other risks cannot be (more) significant. If your building is not (at least to a certain degree) wind-and water-tight, it might be important to address this matter first before exploring possible energy saving measures.

1. Data collection and management: the basics

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1.1 The basics

Collecting documentation and collecting data is, in many cases, the bulk of a project. However, in some rare cases, all data required is already available, and one can skip quickly to the analysis phase.

Before you start any type of data gathering or analysis, it is important to identify what you want to know. Discuss with the team:

- What is the purpose of the data collection
- Which data do you need to collect to achieve this goal
- What are the exact deliverables from this data collection

Gathering and analyzing data is probably the most challenging part of these type of projects. But it essentially consists of three different steps:

- Collecting existing resources
- Collecting missing information (measurements, interviews, and testing)
- Analyzing the collected data

If in doubt which data is out there, a list of data types is provided. This is not a complete list, but it can help you identify data that is essential for these types of projects.

Double-check the 'buildings-systems-collections-energy' section. And cross-reference with the 'sources available list in the self-assessment. Make sure the wording is correct. This document has the latest information.

1.2 Formulating your research question

What do you need to know in order to complete this project? From rethinking scenography and management strategies to a complete renovation of the building envelope, the information required can have a very different nature.

When formulating your research question, make sure what you want to achieve is feasible and within your capacity as an institution. Take into account the expertise of the staff, the budget available for hardware and software, and the capacity for data interpretation. It might be easier to consult external experts and limit your responsibilities of data collection and/or analysis. If you can rely on an external firm or building agency, collaboration might proof fruitful.

To give a few examples, experience teaches us that (and this can vary largely on an case-by-case basis) without external help:

- Small to medium size institutions (1-5 employees) can often have impact on decisions on scenography, management and the changing of set-points.
- Medium to large institutions (6-20 employees) can often do the latter and manage small-scale research projects, such as formulating the needs for a new climate system.
- Large institutions (21-100 employees) will often have a larger technical staff that has to address more complex questions on a regular basis. This can go from formulating system renewals to minor building envelope changes. However, smaller yet impactful strategies that have an impact on the museum organization (such as scenography, management, and set-point changes) can become more complex due to the many stakeholders that need to be involved.

Based on your goal being more general or more focused, it can require you to formulate one or more research questions; here are a few things to take into consideration:

- Make sure the C2P protocol can answer this question. Consider the principle of focusing on reducing global energy consumption while keeping collection risk at the current level, unless risk reduction is specifically required.
  For example: can passive climate control methods in our archival storage reduce overall energy use while maintaining current preservation conditions for our paper-based collections? This focuses on total energy reduction rather than just CO2, explicitly considers maintaining current risk levels and addresses a specific collection type.

- Make sure your research question accounts for short-term and/or long-term impacts, as the protocol distinguishes between immediate improvements and longer-term structural changes.
  For example: how can immediate adjustments to our humidification settings reduce energy consumption in the next 6 months, while preparing for long-term integration of more efficient climate control systems? This question addresses both immediate actions and future planning, and balances quick wins with structural improvements.
- Ensure your research question is focused enough to guide your methodology (like comparing energy usage pre/post interventions) but broad enough to capture relevant variables (e.g., seasonal changes, visitor numbers, collection types).
  For example: How does reducing operating hours of our HVAC system during low-visitor periods affect both energy consumption and temperature/RH fluctuations in our painting galleries? The methodology is clear (analyzing HVAC operation patterns) and the question captures key variables (visitor numbers, timing, climate metrics).
- Include measurable aspects in your research question - the text emphasizes the importance of being able to evaluate potential energy savings, either exact (using the C2P tool) or as a percentage based on the existing situation.
  For example: What percentage of energy savings can be achieved by adjusting seasonal temperature setpoints by 2°C in exhibition spaces, and how does this impact RH stability for sensitive objects? This question contains quantifiable metrics (temperature change, energy savings percentage) and enables clear evaluation of results.

1.3 General rules about documentation and data management

Before you decide exactly what you are going to measure and how, it is important to keep in mind:

- There is no need to overcomplicate things. Do not measure what can't be interpreted by the team (or with help from external experts). Do not invest in systems that are too complex to install.
- There is a difference between 'foundational' measurements (what you want to measure from now on until the foreseeable future) and 'periodic' measurements (limited in time, with a more specific goal).
- One cannot share sensitive information without permissions (e.g., floor plans).
- Problems might occur, however, do not let them discourage you.

It is highly recommended to work with a sensor directory and a floor plan. Both of these documents can be a bridge between two sets of information, the first one being data oriented or textual, the second one spacial.

Fig. xxx: Example of a simple sensor directory.

When dealing with complex measurements, it is recommended to collect all sensor manuals in separate folders and indicate the requirements for every type of sensor (e.g., Wi-Fi, electricity, installation height, etc.). For the floor plans, consider plans for emergency purposes is easy because they are already displayed in public and do not require modifications when shared with stakeholders.

While the sensor directory and floor plans should help you automatically enhance your data collection phase, most institutions already have systems in place to record and share information. If all stakeholders follow the same system, there is no reason to reinvent the wheel. Use the standards and methods you are used to, but just consider the following aspects and make adjustments where needed.

Organization & structure

Maintain an overview of available information. First, agree on the usage of a platform that is accessible to all stakeholders and gather the data there. Make sure to create a solid and easy folder structure. Agree on a naming convention that makes sense (e.g., *yymmdd_subject_details_contributor - 220314_KMSKB_SystemComponents_AHU03_ULg*). Add readme files to specific folders with details on, e.g., naming conventions, types of files that can be in the folder, etc.

Fig. xxx: Example of a logical folder structure.

Every (continuous) dataset has metadata. Usually, this data is integrated into the raw data files. Therefore, it is essential to not modify raw data files. Additionally, minimal metadata should be:

- Units: use adequate units for your data analysis as well as an adequate decimal separator.
- Mostly, we have time series data, meaning the first column is a time stamp. Each column is a separate variable. Take care of sample time and time zone. If all your variables have the same sample time (e.g., hourly values), it will be easier to analyze. Some metering equipment are recording in UTC (Coordinated Universal Time), some in legal hour (e.g., Brussels time is UTC + 1 hour in winter, UTC+2 hour in summer).

Fig. xxx: Example of a standard data export including raw data

Furthermore, be aware that data has often holes / error messages / NA values / outliers (due to sensor unplug or any other default), it is important to detect these special values and put them aside before the analysis. Analysis needs to be performed with 'clean' datasets. This might or might not require some manual data cleaning. (add source – Vincent Beltran?)

If possible, work with permissions, so not everyone that has access can modify or delete specific files (e.g., sort the raw data in a separate folder, limit access to this folder, and create open access to a copy of this folder).

Data quality

Make sure your data is reliable and useful. For periodical measurements, try to strive for hourly measurements. Make sure your sensors are calibrated. New sensors do not have to be calibrated.

Documentation practices and connecting data types

To interpret data correctly, contextual information is key. It is essential to document any gaps or anomalies in data and note external factors that might influence measurements. This can be done using a logbook. Whatever method you choose, it is important to cross-reference different data sources. There should be a record of who is responsible for collecting which information and when.

Date (from)	Date to	What, Where, how…
01/11/2022		UPS on the 4th floor = out of order.
28/01/2022		Just before 18u. we had a broken fuse for the general dehumidifier on the first floor. The one serving the whole building, except for the two cold storages. The electrician who happened to be in our depot didn't have the right fuse and will be back on Monday to replace it.
31/01/2022		Fuse repaired. Dehumidifier back in operation.
21/02/2022		Central heating A on the 4th floor is out of order
07/03/2022		Central heating A on the 4th floor is back in operation
07/03/2022		From today on we keep the doors between the offices and the hallway on the 4th floor closed.
10/03/2022		New UPS. Installed in the hallway to the digi lab.
09/05/2022		New airco's installed in our Digilab (21°) and server room (18°).
23/05/2022		Insulating of the emergency exits on the 2nd and 3rd floors.
13/06/2022	17/06/2022	Maintenance HVAC depot C
04/07/2022	07/07/2022	Installation of the new airco extern unit Depot A

table xxx: Example of a log book with system information

Connect different types of data (e.g., energy use with climate data). Additionally, it is advised to document equipment specifications and locations, keep logs of system maintenance or modifications, and include metadata about collection conditions.

Accessibility & Backup

Save the raw data in the original file format. This can vary widely and be linked to your logger software. Also, store data in easily accessible formats that can be read by common software. Make sure to create regular backups or work with a platform that does this automatically. Make the data accessible to relevant stakeholders.

Data type	*DATA*	*TEXT*	*IMAGES*
Preferred file format(s)	*.csv* *.txt*	*.pdf* *.txt*	*.png* *.jpg/jpeg*
Other common file formats	*.xlsx* *.xls*	*.docx* *.doc*	*none*

Table xxx: A representation of the preferred and most commonly used file formats.

Some companies take ownership of the data that you / they collect and it can only be exported by paying a fee. Be aware of this when choosing sensors or systems, either try to work with another company or be aware a part of your data might not be accessible to all stakeholders.

1.4 General rules about data collection

Try to strive for reliable measurements. Based on your situation, you might choose to install sensors that are compatible with your existing system or work with an external firm. Again, there are many things to consider that will influence your outcome. There are a few advantages and disadvantages to certain choices. Additionally, a combination of different methods is always possible:

Choosing sensors:
Working with integrated sensors, separate measurement systems, or both.

The type of sensor system you choose will have long-term implications for data management and analysis. When choosing a measurement device, it is important to consider reliability, accuracy, and drift characteristics of different sensor types. However, it is important to evaluate total cost, including maintenance, calibration, and data management, and match sensor specifications to your measurement needs (accuracy, precision or resolution, range, and response time). The highest precision or resolution sensor is not always the best one for your specific case. It can have other disadvantages (such as cost). The healthy way to think about precision is: 'is a difference of x over an interval of x impactful for my building / system / collection / energy consumption'. For example, If my collection will not react to a difference of 0,5 %RH over 1h and I measure with a 15min interval, I do not need a sensor with over 0,5% precision.

There are more or less four different possibilities:

- The existing institutional loggers are used and additional sensors are connected to this system. This can be, depending on your system, a robust and long-term solution. However, the company you contact might not have all types of sensors required for your project.

- New sensors from another brand are connected to the existing hub collecting new sensor data on a server. This can be a complex exercise and requires a specific expertise.
- New sensors from the same or another brand are not connected to the data hub. They are stand-alone sensors or work with a second data hub. This can be an easy solution in the short-term but requires more follow-up in the long-term.
- Developing your own specific sensor(s) can be an option. These days, there are ample instructions online in order to develop reliable devices to gather environmental information. However, this is a time-consuming process if attempted by people without experience. Therefore, you need to consider this as a separate (additional) project.

Collecting continuous data, periodical data, spot readings / punctual data, or all.

A continuous real time view of your data is always preferred. For data that needs to be collected over long periods of time, that is checked on a regular basis, and is used as a reference for day-to-day tasks, it can be worthwhile to invest in these type of systems. They will help you to know your indoor climate on a daily basis and predict annual recurrences of related phenomena. However, these type of sensors are accompanied by 'data-collection hubs' (simply put machines that collect the signals and send the data to a server that can be consulted on your computer), and often require a larger investment. Whether working with Wi-Fi or radio-waves to transmit their data, we often see that, in historical buildings, data remains spotty and is not always successfully transmitted to some area's. All these problems can be solved if addressed in advance but might require some technical knowledge and interventions.

However, if you have a smaller team and only look at your data on a monthly or even yearly basis, or your institution still does rounds to check the data visually on a daily basis, a sensor with a display that requires a manual read-out can be a good alternative, even on the long term. Reliable sensors can have an internal memory to save data up to one year or longer.

Both of the systems mentioned above can be used to measure continuously. Most projects will require monitoring a building's behavior, indoor climate, and energy demand, which can vary significantly under the influence of outdoor conditions and seasonal changes. Understanding these variations requires a thoughtful approach to data collection. However, if your goal and research question are targeting a specific season, short-term measurements might suffice. The shorter the measurement campaign, the more individual loggers might be helpful.

Spot readings, punctual data, or readings that are conducted manually, can be a helpful addition while conducting tests or measuring other influential factors (such as light or pollutants). However, when measuring essential data (as such defined by the team), it might not be sufficient for an energy savings project. However, it's important to say that this does not mean that choosing not to monitor your indoor climate or energy use in itself is bad practice. It is up to the institution and its staff to determine their priorities which might or might not be indoor climate and energy savings.

For outdoor data, there is a choice to measure yourself (from simple measurements to a fully equipped weather station) or to get weather data from local weather stations.

Choosing where to measure: focus on systems, collections, or both.

Measurement location is critical for obtaining meaningful data. Based on your goals, you could choose for more general long-term measurements that represent the overall trends in a room or consider both representative and worst-case locations. Think about the amount of sensors you deploy. The orientation of a room, the amount of windows present, the amount of the wall exposed to outdoor conditions, a location underground or under a roof, the amount of organic materials present in an enclosed space, the systems that control the climate indoors, etc. All these factors can have a big impact on your indoor climate. However, rooms that are relatively similar in this sense, and that are not isolated from one another (such as big open spaces), can have a very similar climate. They often do not require one sensor per room.

There are about five types of locations where you can measure:

- Typically in 'the middle' of the room. Look for positions that represent typical conditions while avoiding areas near windows, heating/cooling sources, or direct sunlight. Consider the three-dimensional nature of the space. Temperature and humidity can vary significantly with height, especially in tall spaces like historic buildings or churches. Some spaces might benefit from multiple measurement points to understand spatial variations.
- As part of your climate system. Typically, if there is a climate system with air handling, there are sensors in the pulsion and extraction vents. While they can give an impression of the climate in your building, they are mainly there to communicate with your systems about the need for heating, cooling, humidification, or ventilation rate. To understand fluid dynamics, the airtightness of your building or the ventilation rate, a combination of tests and sensor measurements can be performed. These last two can be more advanced to monitor or interpret.
- In a confined space with a specific climate (microclimates). It can be interesting to measure where specific problems occur, such as mold or overheating due to radiation, or when testing potential mitigation strategies, such as the use of specific frames or display cases. It speaks for itself that these sensors need to be placed in the space where the climate needs to be analyzed. If comparison with other sensors is required, this second sensor needs to measure the same global environment, be it a room or a series of rooms.
- Measurements related to the building envelope. These require a more advanced knowledge and are usually installed with a very specific goal.
- Outdoor measurements need to be taken outdoors. Whatever variables are measured if only one device is present, make sure it is located where it is exposed to all elements. A typical location is on the roof. Of course, multiple sensors can be installed here to , for example, if the impact of orientation on the indoor climate is important.

Once the measurement location is chosen, think about accessibility and other technical requirements. Do these sensors need Wi-Fi, electricity, can the signal reach the data-hub, how often do they need regular read-outs and is this place easily accessible by one person.

Selecting a time interval: from short-term intervals to monthly intervals

Selecting an interval has everything to do with your research question. It is easy to say that a 'less than hourly' interval is recommended. The quicker one factor has an impact on another, the shorter your interval should be. Just be aware that data also needs to be stored and analyzed. If you work with devices that store internally, a 5 minute interval will fill the memory three times as fast as a 15 minute interval. Additionally, it will have an impact on the battery life of your logger.

However, energy consumption is often not historically measured on a daily basis. While it is always recommended to do so, hourly if possible, either manually, either digitally, it is usually paid monthly and therefore the monthly energy use is known.

Who is responsible: working with in-house measurements, engaging external firms, or both

For the installation of sensors and data management, you can rely on external firms as well. There are a few possible scenarios. The most common ones are:

- An external firm has installed all measurement equipment; they are (often) responsible for maintenance and deliver a platform that you can access in house to monitor a live data stream. It is possible, in that case, that you do not own your own data and it cannot be exported. For very large institutions, data streams are sometimes united in a building management platform. That platform can be monitored by an external firm or in-house. Establishing clear working relationships with external companies is crucial for successful measurement campaigns. The relationship should begin with clear definitions of roles, responsibilities, and deliverables. Consider not just the technical specifications of the measurements, but also practical aspects like data formats, access protocols, and regular reporting requirements.
- The institution has bought equipment and is responsible for data collection and sensor maintenance. In this case, data is usually accessible on a platform through an export function.
- An engineering firm or other experts conduct specific measurement campaigns in order to evaluate conditions for a specific project. While they are not always obliged to share this data with you, it could be requested for specific purposes.
- Types of consumption are automatically monitored as an integrated part of society. An example here is digital meters for energy consumption. This data can usually be extracted through a governmental platform or through your energy provider.

Whichever scenario you choose, just make sure the choices are feasible. Access to your own data is and remains crucial.

1.5 General rules on collecting spacial information on floor plans

When preparing for an energy savings project it is important to define the needs for every (non)collection space. This will determine what the future energy savings potential is for every separate space.

A space is usually defined as a room, a space that can be isolated from other spaces by walls and doors. Rooms that cannot be separated from one another because of, e.g., open doorways can be considered as one, or several separate rooms. An interesting way to indicate these functions is by the use of a floor plan.

The best way to collect this information efficiently is to walk through the different rooms with the people that are best informed to answer the questions you identify as essential for every different room. This information can be collected directly on a floor plan in an analogue way. Later, if needed, they can be transferred to a digital file

A digital file can be created with simple tools such as PowerPoint or more advanced tools such as Adobe Illustrator, Affinity designer, AutoCAD, or related programs. These last three allow you to create different layers to indicate different pieces of information.

Fig. xxx: An example about an information overlay on a floor plan

Building information

As noted further on in this chapter, building information is varied and can be endless. It is therefore not important to note all information on your floorplan, but rather focus on the aspects that are relevant for your research question. Usually, the building information that is key, and usually already part of a standard floor plan, is:

- Orientation: North, East, South, and West.
- Basic building elements such as: windows, doors, open passages, stairs, etc.
- Floor level: according to the local preferences (starting at level 0 or 1).
- The popular name of the room or a location number (common in cultural heritage institutions). Choose the indication that works best across different departments.
- Current space use is: is it a public, non-public, or low occupancy space.
- Location of the emergency exits.

Further information can be useful such as:

- Volume of a specific space
- Hot and cold bridges
- Presence of light-blocking materials is present
- The presence of vestibules
- The presence of mezzanines

All the modernizations performed, as well as strategies implemented should be precisely recorded and documented, explaining all the changes and the obtained outputs. Preferably, documentation should be updated following the adjustments. Building enclosure refurbishment is a complex assignment, usually performed over a significant time. It is essential to plan this type of modernization considering economic, environmental, aesthetic, and heritage aspects. All the above-introduced information regarding building-related documentation must be completed with the information on the applied building systems.

System information

System-based information is not only important as basic documentation but also as a communication tool. Which systems are present in which area's and what they control exactly. Some of the most important things to note are:

- Climate systems present, such as emission devices or the part of the system that the climate control of this particular room, are connected to.
- What is controlled per room: temperature (heating and / or cooling), humidity, ventilation rate, pollutants, and / or other.

- The system names and numbers: the system itself in the space it is located.
- Where sensors for particular measurements are present
- A logbook preferably with date-time stamps and alarms detecting data outside of a predefined range and server failures

It can further be useful to indicate the:

- Set-point information can be relevant to indicate on a floor plan. Most noteworthy max. and min. or averages.
- Location of pulsion and extraction vents when a system uses air as a medium.
- Current settings (set-points) or the climate that is aimed for in that particular room.
- Duct work, pipes, etc.
- Consider the location and efficiency of district heating.

Collection information

Some institutions have special requirements for certain collection or collection spaces. Furthermore, not all spaces hold collections or are used by staff. Therefore the focus on comfort temperature (or rather to derive from comfort temperature), can be an aim. It is important to:

- Identify a collection / non-collection space, with protected interiors possibly being part of a collection.
- Focus on what type of collection the space holds. Focus on the needs of the collection (e.g. is it permanent or temporary, is it an archival collection and/or does it have special requirements)

It can be useful to indicate:

- What the climate settings for that room are when a climate control system is present
- Display cases that are used or other type of microclimates present
- Other important risks collections can be exposed to
- Focus on scenography and the current visitor flow

Energy-related information

Energy-related information could be tied to system consumption and therefore part of the floor plan (e.g., indicate the total annual consumption per AHU). However, this type of information is not a priority on a spacial level.

1.6 General rules for performing tests

Testing can be an interesting alternative to performing continuous measurements or implementing significant changes when the risks are unknown. Be aware that testing might be a slow process that can require repetition. A test with a scope that is too wide can raise more questions than it can give answers.

Tests can be disruptive for staff and visitors, communication therefore is key. It is recommended to discuss where and when the tests will take place and communicate about why they are performed. A simple document, shared with all stakeholders involved, can be compiled. The same file can be used to communicate about the results.

Preparation

Meet with the team to determine where and when the measurements will take place. It might be interesting to combine tests that require the same stakeholders to be involved. It's important to define:

- Who needs to be present at the tests.
- Who else needs to be present at the time of testing
- Where the measurements are going to take place (location and equipment involved).
- When the measurements are taking place.
- Which equipment are going to be used to complete the measurements
- What is the predicted effect
- What are the risks for collections if those are present: define thresholds that cannot be passed and define why.

It might be needed to create a specific protocol for specific tests since their outcomes on the collection are unknown (such as the impact of a blower door test). This protocol should give a more detailed step-by-step example of the different steps and their respective outcome.

Communication

Think about who these tests impact and share the document that was compiled with all stakeholders. Send a reminder before the test will take place to all people that are required to perform an action. If the tests are performed in a public space, it is recommended to inform the public about what is happening. If doors or windows need to stay open or closed, make sure this is indicated at the door.

Reporting

Often testing can be a confrontation with unknown problems or might need to be performed with a specific interval (e.g., seasonally). Therefore they might need to be performed multiple times.

Use your initial document to report on any issues that occurred and describe if the predicted effects were obtained. If not, describe the phenomena that occurred and integrate data and graphs if possible.

Report on the testing results to the team. Make sure to have a list with actions that can be communicated to improve testing and or / implement some of the desired results on a longer-term basis.

2. Buildings

Author: Dr. Marcin Zygmunt – Catholic University of Leuven

Data on buildings have a wide scope of characterization. The information can be obtained from technical documentation, performed measurements and management, as well as from the people's knowledge of the building (e.g., building managers or owners). It is also common to use archive records to get some information on historic buildings. In a perfect world, complete building documentation is available.

Every newly constructed building must meet a detailed list of requirements, among others, to provide comprehensive building documentation. This obligation was not that rigorous in the past. It is a challenging task to analyze buildings with limited documentation, not to mention ones without it. Finding this information about historical buildings can be challenging and consultation of archival records is required.

In general, the planning permission (or building permit) is a set of documents comprehensively describing the building. Building permits include technical and legal components. The content of the required documentation includes the site development plan, the architectural and construction design, as well as the structural project or engineering design.

2.1 Documentation

The table below summarizes the available building documentation, their application, a description, as well as the level of knowledge required to read/use it.

Imp.*	Document	Diff**	Description	Application
HIGH	Plans: most recent architectural drawings	low	plans, elevations, cross-sections, and details exposing the design intent	to know the shape, size, layout, and components of the building
	Inventory: visual inspection	medium	various expertise on the current condition of the building, including e.g., thermal bridges assessment, air tightness examination, or moisture behavior in building components	to find the best and most effective solution if performed during the design stage; to locate issues to be fixed in the building if performed during the operational stage
	Plans: emergency plans	low	drawings that are generally a legal requirement, that must be shown on each floor; these are usually the most recently edited documents available	outlining safety procedures and protocols such as evacuation protocol, to integrate within the wider scope of emergency procedures

	Inventory: logs of historical events (building-related)	low	a list of historic events such as incidents, repairs, exceptional weather, etc., accompanied by a data-time of occurrence	used in the future planning of the upcoming modernizations, as well as ad hoc solutions (e.g., event planning); can be obtained through interviews and reports overview
	Plans: (human) occupancy per room	low	design on the number of people (high, medium, or low occupancy) targeted to use the building/room	the definition of the occupancy on building/floor/zone/room level is essential for proper indoor climate management (air quality, thermal comfort), as well as for safe and effective emergency planning
MEDIUM	Plans: site plan	low	showing the location of the building on site and neighboring infrastructure	to know the location of the building on-site, its orientation, urban and natural context
	Valuation: the most recent valuation of the building envelope	medium	the value (and degree of protection) of the building façade, components, and interior elements.	to know the current condition of the building façade and to possibly locate the most urgent parts that require modernization or preservation
	Plans: historical floor plans	low	archive documentation presenting the building, including facades and cross-sections	to know the initial shape of the building and to estimate the performed changes in its construction and shape; might be very important for future planning on building modernization
	Inventory: engineering project	medium	providing basic information (e.g., address) as well as an overview of the building, describing briefly components, systems, setpoints, management profiles, etc.	to know the building, its design, function, structure, and systems
	Plans: structural drawings	high	detailed drawings prepared by structural engineers (e.g., stress patterns plots, required construction reinforcements,	to know a detailed structural design (e.g., considered loads and durability)

			foundation loads, soil stress)	
	Plans: mechanical system plans	high	HVAC, plumbing, and fire protection drawings with the layout and specifications of various mechanical systems	to know detailed information on HVAC systems (e.g. precise flows, operational temperatures, duct work, and components)
	Plans: electrical system plans	high	specifications for electrical systems, including e.g., power distribution	to know detailed information on power supply, distribution, and wiring
LOW	Inventory: operational manuals	medium	providing information on the operation of building systems (for efficient use of the BMS) and components (e.g., how to correctly use elevators, fenestration, locking systems)	to know detailed operation schemas for building
	Inventory: maintenance recommendations	low	providing information on the recommended maintenance, usually a list with timetable for necessary inspections and audits	to integrate system maintenance within the institutions planning

Table xxx: building documentation for energy saving projects in order of relevance.
** Importance: high = essential for any type of project; Medium = important information that might not always be required; Low = valuable, but most of the time, not essential.*
*** Difficulty: low = easy to understand the provided information from a given document for other departments; medium = requires some knowledge for full understanding; high difficulty = understood only by experts or well-trained staff for a specific field.*

Different documents from the table above are required depending on the scope of the considered analyses. Preferably, the complete building documentation should be provided. Yet, for many methods limited documentation is sufficient enough. Additionally, some missing information can be replaced by assumptions in order to perform a valuable assessment of the examined building. Methods applied for building assessment and required input data are explained in other chapters of this handbook.

2.2 Measurements

Information on building from the available documentation can be supplemented with the outputs from various measurements. The used materials and their wear-off can be evaluated with visual inspection, as well as via lab tests for samples taken on-site. The actual building energy performance is usually different than the expected (calculated/simulated) demand; documentation can be updated with the energy consumption records and analyses.

Some measurements will be present in the buildings, system, and energy section. This is because they are essential for all three sections. However, different information can be deducted from it by different experts.

Possible to perform building-related measurements are endless, many of which are very unique, performed essentially for a specific case. Therefore, we have focused on some more frequently available and more often used methods.

Imp.*	Document	Diff**	Description	Application
HIGH	Measurements: indoor T and RH (general)	low	measurements performed using dedicated sensors located inside the building	can be used to know about indoor climate management, as well as to plan potential improvements or changes
	Measurements: outdoor T and RH (general)	low	measurements performed using dedicated sensors or the so-called weather stations located outside the building	can be used to know more about building behavior, in particular, how well a building façade performs during various weather conditions
MEDIUM	Measurements: infrared thermography	medium	measurement performed on-site, under preferable weather conditions (to obtain valid results) with the infrared camera (professional models are expensive)	easy-to-perform assessment allowing to locate thermal bridges or air/water leakages; can also be used to examine the systems and their proper operations
	Measurements: building air-tightness	medium	measurement performed on-site with vent-based equipment (the so-called blower door test); performed with expensive equipment	a simple test performed by a qualified specialist with specialized equipment
	Heat loss coefficient (HLC)	high	can be measured on-site or in the lab; measurement performed to evaluate heat losses via the selected component	advanced test allowing evaluation of the examined component due to its thermal resistance; can be performed to evaluate information from building documentation with the real state
	Measurements: surface T and humidity	high	measurement taken on-site with dedicated equipment;	measurements performed to gain knowledge on the real

			surface temperature can be measured with infrared imaging (with lower accuracy compared to the surface measurements)	behavior of T and humidity distribution within the examined component
LOW	Measurements: winter and summer T logging of glazed roof structures	high	specialized measurements taken on-site, typically with surface sensors	to examine the temperature distribution of glazing; performed when intense overheating on the glazed façade is present
	Measurements: contact and sound isolation of floors	high	specialized measurements taken on-site (sound level evaluation in the analyzed room/zone) or lab evaluation for the used material	to evaluate the effectiveness of the examined solution used to provide acoustic comfort
	Measurements: air stream patterns	high	air movement and distribution can be evaluated via complex computational fluid dynamics (CFD) simulation, or with on-site assessment with sophisticated equipment	CFD analysis can be very helpful in terms of proper ventilation management for the building, as well as in evaluating potential air leakages; this approach is suggested only for very sensitive cases, which require special management (e.g., very fragile and valuable collection)
	Lab testing of samples taken on-site	high	samples are taken on-site to be comprehensively evaluated in the lab environment	to know the actual condition of the building or its parts; among the most often lab evaluations the wooden structure and thermal insulation layer wear, as well as material dampness should be mentioned

Table xxx: building-related measurements for energy saving projects in order of relevance.
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2.3 Equipment

Many of these measurements require a high level of expertise for both measurements and modeling (such as CFD), and there are countless sensor types available, varied by their applicability and providers. We will focus here only on a few of them, which are the most popular nowadays. For indoor temperature (T) and relative humidity (RH) measurements, please consult the 'collections' section, and for building management systems (BMS), consult the systems section. We tend to perform non-invasive measurements, as well as to execute the most constructive (valuable and universal) ones. Below, the most common on-site building measurements are briefly discussed.

T and RH measurements

T and RH measurements are up most important for cultural institutions. The measurement can be performed for indoor and outdoor environments, using the same approach. The measurement is performed by the dedicated sensor, and the records are either stored in the inner data storage (built-in memory) or shared (via bluetooth or network) to the connected monitoring device (typically a computer). For indoor climate measurements, we typically use simple probes, while for exterior conditions, it can be performed via weather stations (see figure below).

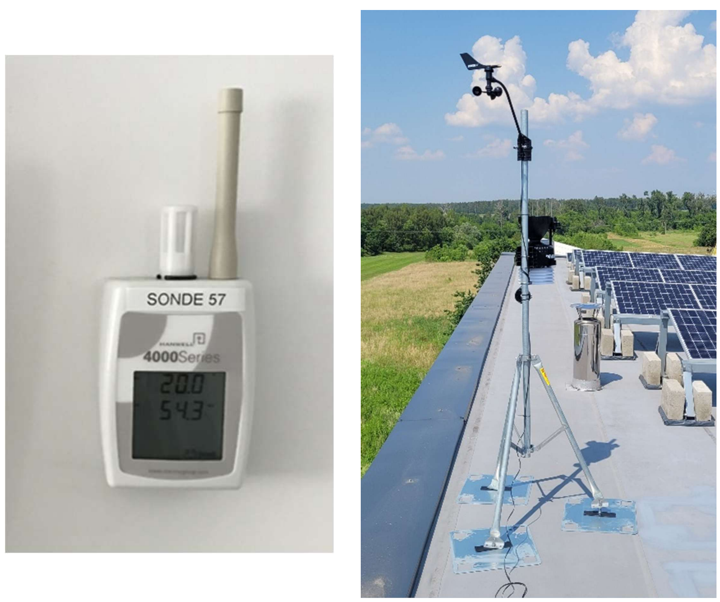


Fig. xxx: T and RH measurements performed on-site: indoors with sonde (on the left) and outdoors with weather station (on the right) (source: own studies).

Infrared thermography

Infrared thermography is a non-destructive diagnostic method that can be successfully used to evaluate the thermal performance of building enclosures. It helps identify thermal anomalies on the examined surface utilizing temperature differences; it is performed by the dedicated infrared camera (see figure below). The measurement must be performed under specific weather conditions, as well as following the ISO 6781-3 or EN 13187 standards.

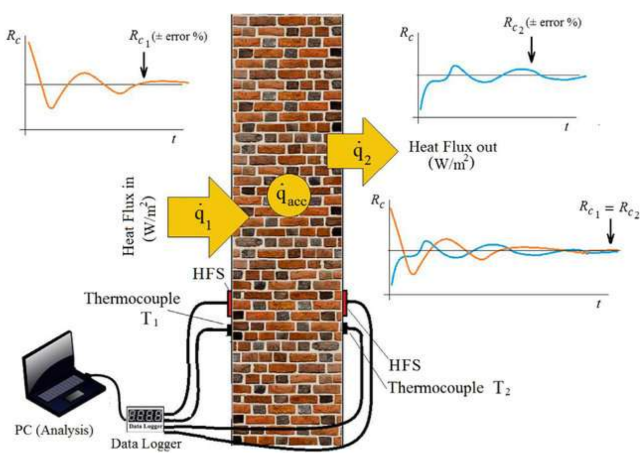
Despite the easiness of image overview, the result assessment should be performed by a trained professional with a detailed report as a final output.

Fig. xxx: Infrared thermography: professional infrared camera (on the left), as well as the imaging: digital image (on the top right) and the corresponding infrared image (on the bottom right) (source: own studies).

Heat loss coefficient: heat flux meter

Heat loss coefficient (HLC) measurement, defined in ISO 9869, is used to evaluate the performance of building envelopes, focusing on thermal transmittance (the U-value) determination, based on the principles of heat losses via building components. It can be measured on-site, as well as in a lab environment with the so-called hot-box apparatus. The measurement itself is performed via heat flux meters (HFM) installed on the internal and external surfaces of the examined component to measure heat transfer (see figure below). Based on the collected records, the necessary calculations are performed.

Fig. xxx: General configuration of the HLC measurement according to ISO 9869 standard (source: Rasooli A. and Itard L; https://doi.org/10.1016/j.enbuild.2018.09.004).



Air tightness: blower door test

Air tightness of the building can be diagnosed with the fan pressurization method, the so-called blower door test, following the ISO 9972 or EN 13829 norms. This relatively easy-to-perform measurement identifies air leakage, and thus the air infiltration rate, which might significantly impact building energy performance and indoor comfort. Despite the ease of the measurement procedure, the initial preparation of the examined zone/building is challenging, the required specialized equipment (see figure below) is expensive, as well as expertise knowledge is required for valuable and reliable reporting.

Fig. xxx: The blower door equipment (on the left, own studies) and the general configuration of the measurement (on the left, source: Yongming J. and Duanmu L.; https://doi.org/10.1080/23744731.2017.1262707).

3. Systems

Author: Dr. Sebastien Thomas – University of Liège

Data collected on systems could be either hard documentation, measurement, or software based (e.g., Building Management System). As a basic rule, each document must have a date and the writer(s) must be known.

3.1 Documents

In a perfect world, an as-built documentation of technical systems should be available, including all plans, technical sheet, commissioning results, and major updates. In the table below, the usefulness of the documentation is mentioned, as well as the level of suggested skills in HVAC for reading them.

Imp.*	Document	Diff**	Description	Application
HIGH	Plans: the most recent HVAC floor plans	medium	Drawings with detailed HVAC equipment and indoor climate requirements.	Understand how the rooms are ventilated, heated, and cooled. Express the mass flow and/or H&C power per room and/or T°/RH requirements
	Generic H&C, ventilation schemes	medium	Generic building scheme with the heat, cold, and ventilation distribution.	Understand how hot and cold water is distributed in the building
	Inventory: logs of historical events (system-related)	low	A list of historic events such as incidents, repairs, exceptional weather, complaints, alarms, etc., accompanied by a data-time of occurrence	xxx. can be obtained through interviews collected automatically (by a BMS system) or manually.
MEDIUM			To be removed: added in the line with the generic H&C scheme	
	Plans: AHU scheme	Expert	For a dedicated AHU, the document details AHU content and links with H&C system	Understand the design capacity and operation of an AHU Ex. AHU scheme
	Inventory: heating and cooling equipment data sheet	Expert	Technical data sheet of an equipment : e.g. boiler, fan coil unit, chiller.	Have information on the efficiency, power of the different devices (boilers, cooling machine, pumps, fans).*** Ex. machine datasheet

	Inventory: building operation description	Medium	Document specifying the control of various equipment in order to reach the required conditions.	Detail the HVAC system operation
	Controls description	Expert	For each part of the system separately (e.g AHU) the document details exactly all the possibilities of entries and parameters and their impact on equipment operation	Details how the various equipment (flaps, valves, pumps, fans) are controlled. Ex. controls explanation
	P&ID ****	Expert	Process and Instrumentation Diagram	Details the metering and controls in a schematic way. Ex. HVAC generic PID diagram

Table xxx: system documentation for energy saving projects in order of relevance.
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**** this can also be found by tacking pictures of the equipment nameplate.*
***** Process and Instrumentation Diagram / rarely met in museums.*
All drawings but the escape plan are produced by the HVAC installer or its subcontractor (e.g. company programming the HVAC controls). These documents are to be used by the facility manager for day-to-day work or for minor/major refurbishment.

3.2 Measurements

Some punctual measurements could be done at a given time. These are mainly a quantification of a variable (pollutant concentration, mass flow, etc.) which is not measured continuously. Date and time should be written down in this data report.

Some continuous HVAC data could be found in some museums, this is a real benefit for analyzing indoor climate. The data could be either coming from room sensors dedicated to HVAC controls or specific probes for collections management. Often, both are implemented.

The question of data redundancy could be asked. Why are there two separated systems for collecting the same data. For HVAC controls there are also probes in the AHU to control the heating and cooling coils as well as the humidification. Furthermore, when individual heaters / air-conditioners / (de)humidifiers are used, it can enhance miscommunication between partners and from the sensors to the system software. Both are reading similar but different information. For example: when mobile humidifiers are activated in the room due to low humidity, the sensor in the extraction vent will signal to the system that no additional humidification is needed. This will require continuously more effort from the mobile systems, which is not their usual task.

Imp.*	Document	Diff**	Description	Application
HIGH	Measurements: T and RH indoor (climate control)	low	Sensor providing continuous data on indoor climate. Data is generally stored in a time series data base	. Indoor climate measurement is compared to requirements, alarms could be set to warn of any deviation.
MEDIUM	Measurements: outside air conditions for fresh air intake	medium	Sensor placed on the building, generally associated with wind direction and wind velocity measurement.	Adapt the HVAC system operation to cope with the outside climate variations.
	Measurements: commissioning measurements	medium	At the end of system installation phase, some measurements are done to verify the adequate equipment behavior according to specifications.	Testing air flow quality, pressure, speed and volume exchange
	Measurements: individual cooling, heating, humidification and ventilation performance	high	More often, a punctual measurement of a mass flow and temperature of a dedicated HVAC equipment	Assess the performance of an equipment and compare to the initial/design conditions. the

Table xxx: system measurements for energy saving projects in order of relevance.
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3.3 Equipment

Building management systems

A building management system is a system that we predominantly find in newer and larger buildings. It's a type of software rather than a piece of equipment. Imagery is generally set to view each part of the building technics. It helps checking the HVAC system operation in real time. Sometimes the imagery allows to plot a graphical temporal view of a dedicated variable.

The imagery enables convenient viewing of the following data :

- Common data: indoor climate - T°, HR (sometimes CO2), HVAC system temperatures (e.g. boiler temperature), pumps, fans operation, register and valves position, alarms
- Specific to some BMS: performance indicators for climate and/or energy, viewing of energy counters with some performance indicators

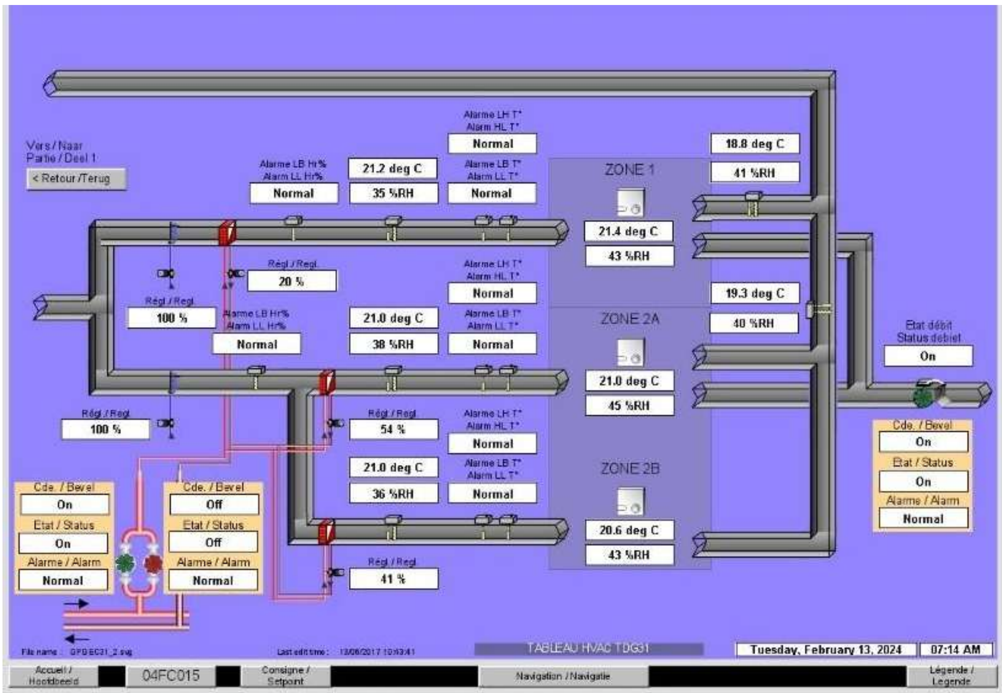

Fig. xxx: BMS imagery example showing temperature and heating coil state of operation.

T and RH sensors for climate control purposes

T and RH sensors for system purposes are usually installed to communicate with the building management system. The simplest form of such a sensor is a regular thermostat. They can be mounted to the wall or integrated in pulsion or extraction vents.

Measure CO2 to determine occupancy

Some indoor sensors integrate carbon dioxide (CO2) measurement. The CO2 measurement is a good indicator of presence or absence of people in a room. CO2 data allows the evaluation of the number of people indoors. Using this measurement, it is therefore possible to control the supply air flow rate to maintain sufficient air quality and manage the increase in humidity and temperature associated with occupancy.

CO2 sensor should measure precisely the CO2 concentration in ppm (part per million) from 400 ppm (outside basis value) to 2000-5000 ppm. A bad air quality is encountered with CO2 concentration above around 1000 ppm.

Additional system measurements

On an energy point of view, the mass flow and temperatures in all HVAC system is important to measure. This leads to a good understanding of the system operation and avoids energy waste (e.g., heating or cooling an inadequate operation schedule).

Ultimately, some measurement could directly show the energy use of heat/cold producers (boilers, chillers) or main energy consuming equipment (fans, pumps). In combination with the abovementioned data, this enables the establishment of energy efficiency indicators.

4. Collections

Author: Annelies Cosaert – Royal Institute for Cultural Heritage (KIK-IRPA)

Data and documentation on collections can be a vast combination of contemporary measurements and historical data. While some institutions have solid documentation on object conditions, linked to their location or to historic climate data, the institutional memory can play a big role as well. While this is not data-based information and has a varying degree of reliability, it is important to understand the problems that have occurred within the collection in the long term.

4.1 Documentation

Based on the research question asked, there are some documents that can play a key role. Be aware that while inventory and assessments can be vast documents, what is needed is might just be a part of that document.

Imp.*	Document	Diff**	Description	Application
HIGH	Plans: collection / non collection / archival or storage	low	Basic floor plans, preferably for emergency purposes, showing floor levels, orientation, doors, windows, and emergency exits	Per room, define what are collection and non-collection spaces. Indicate if it is a public / non-public or storage space.
	Inventory: most recent inventory of the collection composition, types, and quantities, storage / display	low to high	Usually, as part of an archive or in a collection management plan. From basics to detailed this should include at least: type, materials, dimensions.	To determine, for the current or future objects in the room, what the needs and the possibilities are. For rooms with changing exhibitions, loan agreements might be more suited.
MEDIUM	Inventory: logs - can be obtained through interviews or by consulting condition reports	medium	This can go hand in hand with the buildings and systems logbook. Can be an overview of calamities or more extreme outdoor weather events, e.g., large crowds, opening hours, exhibition constructions, etc.	These events will help interpret the T and RH measurements since all of these things can explain peaks in the data.
	Assessment: most recent risk assessments	medium	A risk assessment will describe the risks that a collection is exposed to. This is usually built upon	Understanding the broader risk helps you to understand where other pain points for collection

			the 'agents of deterioration'. Different methods are available to perform a risk assessment.	preservation lie. It will help not increase existing risks. It is important to ask: is obtaining a strict indoor climate a priority?
	Plans: microclimates, display cases, and other types of furniture.	low	Floor plans that contain the location of furniture or other specific microclimates, such as hot and cold bridges	Particularly important if energy savings with display cases or other microclimates are involved
	Plans: overview of the visitor flow and action	low	Visitor flow and action can be either relatively organic, but also strict and are often part of the reception of a certain scenography. Do not forget they are often correlated to the presence of emergency exits.	Certain actions can have a significant impact on the climate. The presence of a cloakroom, certain area's where visitors stay for a longer time (video room), etc. It can also have an impact on possible zoning changes.
	Assessment: recent emergency and calamity planning	low	A planning that describes the actions required when a calamity of a certain proportion occurs. It can describe the actions for both people as objects. It requires contacts with the emergency services. Often linked to a risk assessment.	While this is an essential document for any institution, knowing the basics, such as the location of the emergency exits, might be sufficient. It is important not to block evacuation routes and not increase certain risks.
	Inventory: the most recent overview of the incoming and outgoing loan agreements and or accompanied facility report	medium	The loan agreements describe the requested conditions for both the lender as the borrower. The facility report describes the conditions of the facilities and is shares with the borrower.	This document can give insight on which climate conditions are requested by the borrower when loans are requested. These demands are often strict but also negotiable.
LOW	Assessment: most recent collection assessment / management plan	medium	A document that describes the current state of the collection or the future plans for the collection. It focusses more on the museums collection policy. Often, it also describes different steps to improve collection preservation.	The document is interesting, but might not be required since the before mentioned inventory might suffice.

	Assessment: most recent valuation of the collection on the sub-collection level	medium	A valuation is in essence a non-monetary value of a certain sub-collection or objects. Objects seen as 'key' to a institutions collection can have the highest value. However, a list with insurance values might also be available.	This can help identify those key pieces that require special care.

Table xxx: collection-related documentation for energy saving projects in order of relevance.
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These documents might be present in a museum in different forms. It is not required to create all of these separate documents specifically for the project. However consider what pieces of information might be available to achieve long changes that can be implemented in the long term without conflicting with other important needs of the institution.

4.2 Measurements

Some of these measurements can be obtained by the facilities team as part of their mission. It might not be required to obtain these measurements twice.

Imp.*	Document	Diff**	Description	Application
HIGH	Measurements: T and RH indoor (collections)	low	Minimal hourly (date-time) measurements of temperature and relative humidity in every space or room, considered for energy savings.	This data can help you understand general trends (e.g., daily or seasonal) for every room. To be able to estimate the risks a collection is exposed to.
	Measurements:T and RH outdoor (collections)	low	Outdoor data for collection purposes is often a T and RH logger for outdoor purposes, linked to the indoor system. Often, this data is collected for building or system purposes as well.	This data is meant to contextualize the indoor data, building envelope performance, and energy consumption. The more the climate is controlled, the less the outdoor data will be linked to indoor trends.
MEDIUM	Measurements: daylight exposure levels	medium	These can be punctual or continuous measurements. Often they are monitored in order to estimate the risk	Daylight, combined with, e.g., large window surfaces, can have a large impact on indoor temperature and

			of light damage (discoloration etc.).	subsequently on humidity.
	Measurements: artificial lighting levels	medium	Artificial lighting levels are also measured to estimate risk to light exposure (and perception, e.g., color temperature). However, lighting level are much lower than daylight.	While artificial lighting levels do not often influence T and RH in a larger space, it can do so in microclimates.
	Measurements: visitor numbers	medium	There are two options: CO_2 measurements (see systems) or manual visitor counts.	The amount of visitors in a room can be linked to T and Rh data as well as to the systems ventilation needs.

Table xxx: collection-related measurements for energy saving projects in order of relevance.
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4.3 Equipment

T and RH loggers (indoor and outdoor)

Temperature and relative humidity loggers come in various forms, from simple standalone devices to complex wireless systems integrated with building management platforms. Standalone loggers typically have an internal memory and battery life of 6-12 months, measuring at preset intervals (usually 15 minutes to 1 hour). They record temperature (°C/°F) with accuracies around ±0.5°C and relative humidity (%) with accuracies of ±2-3%. More advanced wireless systems can provide real-time monitoring and alerts, though they require additional infrastructure like data hubs and network connectivity. Outdoor loggers need additional protection from rain and direct sunlight, often housed in radiation shields or specialized enclosures.

Fig. xxx: an example of a thermohygrograph

Thermohygrograph devices consist of a mechanical recording system with a bimetallic strip for temperature and a hair bundle for humidity measurement, which move pens that draw continuous lines on a paper chart mounted on a rotating drum. The drum typically rotates once per week or month. While these instruments have largely been replaced by digital systems, they have the advantage of providing an immediate visual representation of climate fluctuations and don't require batteries or data downloads. However, they need regular maintenance, including calibration, ink refills, and paper changes. Their accuracy (typically ±1°C and ±5% RH) is generally lower than modern digital sensors, and the mechanical components can wear out or get stuck.

Manual spot measurements for temperature and relative humidity can be taken using simple handheld devices like sling psychrometers (which use wet and dry bulb temperatures to calculate relative humidity) or electronic thermohygrometers. While these methods don't provide continuous data, they can be useful for quick checks or verifying the accuracy of permanent monitoring systems. Some institutions still maintain manual recording practices as a backup to electronic systems or in areas where continuous monitoring isn't required.

Light measurements

Light measurements in cultural heritage settings typically involve two main approaches: spot measurements using lux meters and cumulative exposure monitoring using dosimeters.

Lux meters provide instantaneous readings of illuminance levels (measured in lux) and are essential for adjusting display lighting to appropriate conservation levels. Some institutions also use UV meters (measuring in μW/lumen) to monitor potentially harmful ultraviolet radiation, though this has become less critical with modern LED lighting. For continuous monitoring, some data loggers now incorporate light sensors alongside temperature and humidity measurements.

Blue wool coupons (also called blue wool dosimeters) are standardized pieces of dyed wool fabric used to monitor cumulative light exposure. They come in a series of eight different dyes with increasing lightfastness (numbered 1-8, with 1 being the most light-sensitive). When exposed to light, these materials fade in a predictable manner, providing a visual indication of light exposure over time. The fading is compared to an unexposed control sample using a grayscale. While not as precise as electronic light meters, blue wool standards are inexpensive and provide a tangible demonstration of light damage that can be particularly useful for educating staff about light sensitivity. They're often placed alongside sensitive objects in exhibitions to monitor actual exposure conditions.

Fig. xxx: an example of e a lux meter

Fig. xxx: T and RH data logger with integrated lux meter.

Fig. xxx: blue wool coupons exposed and unexposed.

Measuring visitor numbers manually

Visitor numbers can be tracked through several methods, ranging from simple manual counting to automated systems. Manual counting typically involves staff recording entries and exits using mechanical click counters or tally sheets, which can be labour-intensive but provides accurate data for smaller institutions.

5. Energy

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This part covers the basics of energy data collection. While often a less developed task in museums, usually data on a monthly basis is present due to the payment of a monthly consumption. However, sometimes global energy use is measured continuously or even consumption for separate tasks (heating, cooling, ventilation, humidification) is known.

5.1 Documents

Data from the following documents might be present. Be aware that the more detailed data and documents are, and this is often a challenge for these types of documents, the more accurate the predicted energy saving can be.

Imp.*	Document	Diff**	Description	Application
HIGH	Plans: most recent architectural drawings	low	Scaled building drawings	Find out the surface, and use of each zone
	Inventory: past energy, gas, oil bills and / or energy production (if applicable)	medium	All documents related to paid energy by the building owner or renter.	Establish the energy register of the building.

Table xxx: collection-related measurements for energy saving projects in order of relevance.
** Importance: high = essential for any type of project; Medium = important information that might not always be required; Low = valuable, but most of the time, not essential.*
*** Difficulty: low = easy to understand the provided information from a given document for other departments; medium = requires some knowledge for full understanding; high difficulty = understood only by experts or well-trained staff for a specific field.*

The simplest way to collect and analyze energy data is to collect the energy bills (so called "final energy"). For big consumer, the electricity and gas frequencies are usually one month (based on real index reading), this is enough for a basic analysis.

For collection buildings connected to district heating and cooling, a monthly billing frequency is generally met, it should always be based on real index reading (not a flat-rate consumption).

If the building is using gas, oil, or wood tank, the billing is done at each refill, it is not easy to evaluate the final energy use. For oil tanks, some probes could convert automatically the level to have a shorter measurement period[18].

All data must be converted into kWh – MWh – GWh depending on the building.

[18] Example : https://fuel-it.io/en/gauge-connected-fuel-it/

If the gas/oil/wood/district network provider does not communicate the conversion factor, the rough estimations given in the theory chapter can be used. A bill example with analysis is given in annex, if gives the monthly evolution and indexes on peak electricity consumption. Peaks can be a non-negligible part of the bills.

If the facility is equipped with solar photovoltaic collectors, you should take care of their electricity production to analyze your consumption data. In most cases, you should add the photovoltaic production to your global consumption to have the real building electricity use. Photovoltaic has its own energy efficiency indexes that are outside of this document scope.

Some indexes could be set, these are examples of common energy indexes

Index	Units	Meaning
Global electricity use	MWh/year	Total electricity use to be compared throughout years
Global heat use	MWh/year	Total energy use for heating (could be gas, or district heating energy)
Total energy use	MWh/year	Total final energy purchased
Global cold use	MWh/year	Total cold energy used (from district cooling energy or dedicated cooling heat flow meter)
Heat index	kWh/HDD/year*	Efficiency of global heating system including envelope
Cold index	kWh/CDD/year**	Efficiency of global cooling system including envelope
Cold index	kWh/CDD/year**	Efficiency of global cooling system including envelope
Specific final energy use	kWh/m²/year	Specific energy use to take the building floor area into account. Enables benchmarking with other buildings and EPB certificate.
Specific energy use for heating	kWh/m²/year	Specific heating energy use to take the building floor area into account. Enables benchmarking with other buildings and EPB certificate.

Table xxx: collection-related measurements for energy saving projects in order of relevance.
** HDD: Heating degree day19*
*** CDD: Cooling degree day*

Building floor area calculation

Surface heated/cooled definition is key to build a meaningful specific energy use index. The surface computation depends on the EPB certificate rules in the region/country. It could be either total floor surface of the building (including walls), or inside floor surface, or the heated/cooled inside surface. Be careful of the reference surface floor while comparing buildings.

[19] Explanation : https://en.wikipedia.org/wiki/Heating_degree_day

5.2 Measurements

Some built-in sensors could help to find the sharing of the electricity per use. For some cabinet (top picture) or some equipment (bottom picture), a dedicated power meter is available (digital – top; electromechanical – bottom).

If some built-in calorimeter are installed in HVAC system, their data is normally retrieved in BMS imagery. A graphical view enables an analysis of thermal flows.

Imp.*	Document	Diff**	Description	Application
HIGH	Measurements: smartmeter measurements or types of continuous measurements of the global energy usage.	low	For smart meters: export from the energy provider data base with (at least) hourly energy data. For built-in energy meters: view of the time series energy data on BMS	Analysis of the global building energy use in different time scales and assess the global building energy performance.
MEDIUM	Measurements: dedicated energy meters for heating, cooling, (de)humidification, and ventilation (fans)	high	For built-in sensors (calorimeter, wattmeter), the time series of energy data.	Evaluate the energy performance of a dedicated equipment and/or energy usage of the different indoor areas

Table xxx: collection-related measurements for energy saving projects in order of relevance.
** Importance: high = essential for any type of project; Medium = important information that might not always be required; Low = valuable, but most of the time, not essential.*
*** Difficulty: low = easy to understand the provided information from a given document for other departments; medium = requires some knowledge for full understanding; high difficulty = understood only by experts or well-trained staff for a specific field.*

If a smart meter is installed, a 15-minute measurement frequency is generally met, this is also the case for any remote reading counter. The energy provider should, on request, give all the data he has about your point of energy delivery.

Fig. xxx : illustration of a smart meter used for billing electricity and/or gas (or water)

5.3 Equipment

Besides a smart meter, that is usually installed by the company that is responsible for the energy distribution to your home, there are more types of equipment that can be installed.

After examining the possible distribution of energy use in the building, it is probably a good idea to install a dedicated energy meter for the most important energy consumer (e.g., cooling machine). This could be done by either permanent devices or a portable 1-week (as a minimum) measurement campaign. All electrical measurement must be undertaken by a qualified professional.

Fig. xxx : Caption to be completed + source

A cost-effective way to measure energy use of certain parts of the HVAC system is to implement non-intrusive measurement. This does not affect the HVAC system use (no need of a power cut) and permits a quick rough evaluation of the electrical consumption of an electrical device. This can be done with instantaneous measurements or longer periods (1 week at least). In this last case, the equipment should be able to store data to be analyzed afterwards.

Three kinds of equipment can be used depending on the level of accuracy and media to be measured. Some technical document about each device is provided in annex.

Clamp measurements

A simple clamp measurement is used to evaluate the electric current in a cable. The electrical power can be determined with a rough approximation (power factor and voltage not evaluated). The measurement should be done on each phase if a 3-phase device is measured. This is typically used for a pump or fan electricity consumption measurement and schedule verification.

Fig. xxx: Amper clamp measurement (source: Fluke documentation)

Watt meters

A wattmeter measurement could be mono-phased or three-phased, it consists of a current clamp (or current loop) and voltage measurement to have a precise evaluation of both active and reactive energy. This is typically used for energy use measurement of a big consumer (complete AHU, cooling machine,…). Those electrical measurement equipment are installed in electrical cabinet.

Fig. xxx: Wattmeter measurement (source: Chauvin Arnoux documentation)

Ultrasonic flow meter

For measuring heat flow of a cooling or heating water circuit, the only way to have a non-intrusive is to employ an ultrasonic flow meter with two temperature probes. The principle of the ultrasonic flow meter enables measuring the flow by only sticking two magnetic probes at a certain distance. This kind of device is suited to different pipe sizes and materials. It is largely used for evaluating the heat flow of main circuits. It could also be used for water consumption measurement and leakage detection.

Fig. xxx: Ultrasonic flowmeter measurement (source: Micronics documentation)

In the table below is presented the order of magnitude of non-intrusive punctual energy meter equipment costs. Sharing instruments between different entities supports a better use of equipment and a smaller investment for each single entity. Some equipment requires a calibration after several years.

Type of equipment	Measurement	Price order of magnitude (2024)
Amper clamp	Rough electrical power measurement	250-500€
Wattmeter	Precise electrical measurement	1000-2000€
Ultrasonic calorimeter	Mass flow and dedicated thermal energy	3000€-5000€

Table xxx: Rough price estimate of different types of measurement systems

CONCLUSION

Documentation and data management form the cornerstone of successful energy-saving initiatives in cultural institutions. As outlined in this chapter, the key to effective data collection and management lies not in collecting every possible piece of information, but rather in gathering and organizing data that directly supports your institution's specific goals and research questions. Whether working with building documentation, system specifications, collection information, or energy consumption data, the emphasis should always be on maintaining reliable, accessible, and well-structured information.

The systematic approach presented here – from establishing clear research questions to implementing proper documentation practices – provides cultural institutions with a practical framework that can be adapted to their specific needs and capabilities. While the depth and breadth of data collection may vary between institutions, the fundamental principles remain constant: ensure data reliability, maintain proper documentation, and establish clear protocols for data management and sharing among stakeholders.

It's worth emphasizing that successful documentation and data management don't require complex systems or extensive technical expertise in every case. What matters most is consistency, transparency, and a clear understanding of how the collected information will support your institution's goals. Whether you're working with basic temperature and humidity measurements or conducting sophisticated building performance analyses, the key is to maintain organized, accessible records that can inform decision-making and support long-term sustainability goals.

As cultural institutions continue to balance preservation requirements with energy efficiency, proper documentation and data management will become increasingly crucial. This foundation enables institutions to make informed decisions, track progress over time, and adapt their strategies based on concrete evidence rather than assumptions. By following the guidelines and principles outlined in this chapter, institutions can build a robust framework for managing their documentation and data, ultimately supporting their efforts to achieve both environmental sustainability and effective collection care.

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GLOSSARY

A

Absorbed moisture: Water vapor taken up by hygroscopic materials from the surrounding air, contributing to moisture-driven humidity loads in buildings.

Actuators: Mechanical devices that control valves, dampers, or other system components in response to signals from thermostats or building management systems.

Adaptive reuse: Converting a historic building to a new purpose different from its original function while preserving its architectural character.

Agents of deterioration: The ten primary causes of damage to cultural heritage identified by the Canadian Conservation Institute: physical forces, thieves and vandals, fire, water, pests and plants, contaminants, light (ultraviolet, infrared and visible), incorrect temperature, incorrect relative humidity, and dissociation.

Air changes (per hour): The number of times the total volume of air in a space is replaced with fresh air within one hour, indicating ventilation rate.

Air filters: Components that remove particulates and contaminants from air before it enters indoor spaces, protecting both collections and HVAC systems.

Air Handling Fans: Mechanical devices that move air through supply and return ducts in an HVAC system, operating at constant speed or with variable frequency drives.

Air Handling Unit (AHU): The central equipment assembly that conditions and distributes air throughout a building, including fans, filters, heating/cooling coils, and humidifiers.

Air leakage: Uncontrolled air movement through cracks, gaps, and openings in the building envelope, affecting both energy use and indoor climate stability.

Air mass flow: The rate at which air moves through a system or space, measured in mass per unit time, used to calculate heating and cooling loads.

Air-source heat pump: A heating and cooling system that extracts thermal energy from outdoor air and transfers it indoors, more efficient than electric resistance heating.

All air system: An HVAC system that uses only conditioned air (no water or refrigerant) distributed through ducts to control indoor temperature and humidity.

Anoxia: The absence or severe reduction of oxygen, used in specialized storage or treatment environments to prevent insect activity and slow chemical degradation.

Architectural and construction design: Documentation including floor plans, cross-sections, elevations, and material specifications that describe how a building is constructed.

B

Barriers / buffers: Materials or systems that separate objects from environmental fluctuations, ranging from packaging to display cases to entire building envelopes.

Batz law: Physical principle stating that wind turbines can extract maximum of 59.3% of kinetic energy from air flowing through them, limiting renewable energy efficiency.

Biodiversity: The variety of living organisms in an environment, considered in life cycle assessments as buildings and operations can impact local ecosystems.

Biological 'deterioration': Damage caused by living organisms including mold, bacteria, insects, rodents, and plants that consume, stain, or structurally weaken materials.

Biomass energy: Renewable energy derived from organic materials like wood, agricultural waste, or dedicated energy crops that can be regrown.

Blower door test: Diagnostic procedure using a calibrated fan to measure building air tightness by creating pressure differences and detecting leakage rates.

Building assessments: Systematic evaluation of a building's condition, performance, and energy use to identify opportunities for improvement.

Building enclosure / Building envelope: The physical barrier between interior conditioned spaces and the outdoor environment, including walls, roof, windows, and foundation.

Building Management Systems (BMS): Computerized control systems that monitor and manage building operations including HVAC, lighting, and security from a central interface.

C

Capacitive: Electrical term describing devices that store energy in electric fields, used in power factor correction to balance inductive loads.

Cellulose acetate (photographic film): Chemically unstable plastic film base that degrades through hydrolysis, releasing acetic acid and requiring cool storage.

Chemical 'damage' / 'aging': Deterioration through chemical reactions including oxidation, hydrolysis, and corrosion that change material properties over time.

Chemically stable objects: Materials that experience minimal chemical change under normal museum conditions, such as stone, ceramics, and most metals.

Chemically unstable objects: Materials prone to ongoing chemical degradation even in controlled environments, such as cellulose nitrate and some plastics.

Climate chambers: Specialized storage rooms or enclosures with precise temperature and humidity control for vulnerable collections requiring specific conditions.

Cogeneration / Combined Heat and Power (CHP): System that simultaneously produces electricity and useful thermal energy from a single fuel source, improving overall efficiency.

Cold water humidification: Adding moisture to air by evaporating cold water, which consumes energy for evaporation rather than heating water first.

Collection environment: The complete set of environmental conditions surrounding collections, including temperature, humidity, light, air quality, and physical security.

Collection mass: The total volume and hygroscopic capacity of collection materials, which can buffer humidity fluctuations through moisture absorption and desorption.

Collection type: Classification of objects by material properties, vulnerability, and environmental requirements, guiding appropriate climate control strategies.

Combined Cooling, Heat and Power (CCHP): Advanced system producing electricity, heating, and cooling from one fuel source through cogeneration and absorption chillers.

Commissioning: Systematic process of verifying that building systems perform according to design intent and owner requirements through testing, documentation, and training.

Computational assessments: Computer simulations and modeling to predict building performance, energy use, or moisture behavior without physical testing.

Conduction: Heat transfer through direct contact between materials, with rate dependent on thermal conductivity and temperature difference.

Conservation heating: Minimal heating strategy that prevents condensation and high humidity rather than maintaining comfort conditions, reducing energy use.

Contaminants / Pollutants (agent of deterioration): Harmful substances in gaseous, liquid, or particulate form causing chemical deterioration, soiling, and corrosion. Outdoor sources include vehicle emissions, industrial pollution, and agricultural chemicals. Indoor sources include off-gassing from construction materials, cleaning products, storage enclosures, and visitor activities. Particulates soil surfaces and carry reactive chemicals. Gaseous pollutants including sulfur dioxide, nitrogen oxides, ozone, and volatile organic compounds corrode metals, weaken paper and leather through acid formation, and discolor pigments. Damage often appears gradually but is irreversible. Particularly vulnerable are metals (especially lead, copper, silver), calcareous materials, photographs, and acidic papers. Control requires air filtration, selection of low-emission materials, adequate ventilation, and isolation of vulnerable objects from pollution sources.

Controls (climate system components): Devices including thermostats, sensors, and actuators that regulate system operation to maintain setpoint conditions.

Convection: Heat transfer through fluid movement, either natural (warm air rises) or forced (by fans), carrying thermal energy through spaces.

Cool, cold and frozen (storage): Temperature-controlled storage below standard conditions used to slow chemical degradation of vulnerable materials like film and photographs.

Cooling coils: Heat exchangers where chilled water or refrigerant removes heat and sometimes moisture from air passing through an HVAC system.

Corrosion: Chemical deterioration of metals through reaction with environmental moisture, oxygen, or pollutants, forming oxides or other compounds.

D

Deadband: Temperature range between heating and cooling setpoints where no conditioning occurs, reducing energy use through wider acceptable fluctuations.

Deformation: Physical distortion of objects due to moisture changes, temperature extremes, or mechanical stress, potentially irreversible in some materials.

Delamination: Separation of bonded layers in composite objects due to differential expansion, adhesive failure, or moisture changes.

Demand Side Management (DSM): Strategies to reduce or shift energy consumption patterns to improve efficiency and reduce peak loads.

Demand Side Response (DSR): Adjusting energy use in response to grid conditions or pricing signals, reducing consumption during peak demand periods.

Designed airflow: The intended air flow rate specified in HVAC design documents, which should be verified through balancing and commissioning.

Dew point temperature: The temperature at which air becomes saturated with water vapor and condensation begins, critical for preventing surface condensation.

Diagonal direction cooling: Cooling process that simultaneously reduces both temperature and humidity by removing moisture through condensation on cold surfaces.

Direct electrical heating: Heating using electric resistance elements that convert electricity directly to heat without combustion or heat transfer fluids.

Direct radiation: Transfer of energy through electromagnetic waves without requiring a medium, including solar radiation and infrared radiation from warm surfaces.

Dissociation (agent of deterioration): Loss, detachment, or inaccessibility of information relating to objects, leading to loss of understanding, context, or value. Unlike other agents affecting physical state, dissociation affects intellectual, legal, and cultural aspects of collections. Forms include physical separation of labels from objects, loss of documentation through poor record keeping or system failures, separation of object components, misfiling, transcription errors during database migration, and contextual loss through inappropriate handling disrespecting cultural values. Contributing factors include inadequate labeling using impermanent materials, poor inventory procedures, staff turnover without knowledge transfer, and technology changes making old formats inaccessible. Prevention requires rigorous documentation protocols, regular inventories, using archival quality labels and inks, database backups, staff training, and culturally appropriate handling procedures. Once information is lost, recovery is often impossible, permanently diminishing collection value and research potential.

Display cases: Enclosed structures surrounding objects that buffer environmental fluctuations and provide physical protection, ranging from simple boxes to sophisticated climate-controlled systems.

Distribution (climate system): The network of ducts, pipes, or other pathways that transport conditioned air or fluids from generation equipment to spaces.

District-based solutions: Centralized energy systems serving multiple buildings through shared heating, cooling, or electricity generation, improving overall efficiency.

Dry air: The non-water vapor component of air, used in psychrometric calculations to determine moisture content and enthalpy.

Dry bulb temperature: Standard air temperature measured by a thermometer, as opposed to wet bulb temperature which accounts for evaporative cooling.

E

Electronic commutation motor: High-efficiency motor using electronic controls rather than mechanical brushes, reducing energy consumption in fans and pumps.

Embodied carbon: Total carbon emissions released during the complete lifecycle of building materials from extraction through manufacturing, transport, construction, and eventual disposal or recycling.

Emission (climate system): The final delivery of heating, cooling, or air to spaces through terminals like radiators, diffusers, or underfloor systems.

Emission of particulate matter: Release of fine solid or liquid particles into air during construction, manufacturing, or energy production, affecting air quality and health.

End of life stage: Phase in building or material lifecycle involving demolition, deconstruction, recycling, or disposal, with environmental impacts from waste and embodied energy loss.

Energy consumption heel: Baseline energy use that continues regardless of occupancy or conditioning needs, from equipment in standby mode or continuous operation.

Energy demand: The rate of energy consumption at a specific time, typically measured in kilowatts, distinct from total energy use over time.

Energy profile: Pattern of energy consumption over time showing daily, weekly, or seasonal variations, used to identify optimization opportunities.

Energy recovery: Capturing waste thermal energy from exhaust air or water to precondition incoming fresh air or water, reducing conditioning loads.

Energy Service Company (ESCO): Business providing comprehensive energy services including audits, design, installation, and performance guarantees for efficiency improvements.

Energy signature: Energy signatures make a simplified assumption of a linear relationship between a building's energy demand and outside temperature. It is a very simple model to evaluate the performance of a heated/cooled building based on the energy use for heating/cooling and the outside climate (summarized by outside temperature solely).
Energy signature could be set on an hourly, daily, monthly basis depending on the available data. The signature is plot in a X-Y axis where X axis represents the climate (outside t° or Heating Degree Days) while Y axis is the energy use. The Linear regression of the data reveal several things about energy performance of the building:

- The greater the energy efficiency, the shallower the slope of the straight line.
- Points far from the line depicts an energy anomaly (better energy efficiency under the line – worst energy efficiency if upper the line.
- A cloud of points without good linear regression informs your energy use is decorrelated with the outside climate.
- In case of building heating, a high consumption in hot outside period reveals an intense energy use for other needs (domestic hot water, energy destruction in summer…)

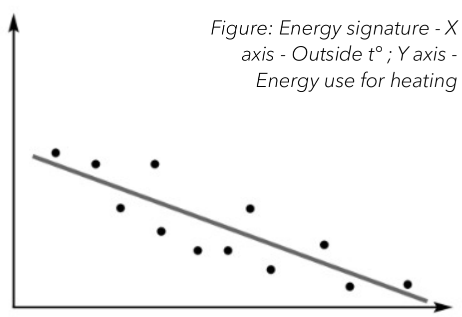

Figure: Energy signature - X axis - Outside t° ; Y axis - Energy use for heating

Environmental chamber test: Laboratory assessment of full-scale building components under controlled temperature and moisture conditions to verify performance.

Environmental control systems: Equipment and strategies used to maintain suitable indoor conditions, ranging from passive approaches to fully automated HVAC systems.

Eutrophication: Nutrient pollution of water bodies causing excessive algae growth, considered in lifecycle assessments of buildings and materials.

Exported energy: Energy generated on-site but sent to the external grid, such as excess solar photovoltaic production, potentially providing revenue or credits.

F

Facility report: Documentation of building conditions, systems performance, and environmental suitability for housing collections, often required for loans.

Fans (climate system components): See Air Handling Fans.

Fick's law: Physical principle describing the diffusion rate of water vapor through materials based on concentration gradients and material permeability.

Final energy / Consumption: Energy purchased and paid for by the end user, after transmission losses but before conversion to useful energy in equipment.

Fire (agent of deterioration): Uncontrolled combustion that can cause catastrophic loss to collections through burning, charring, and melting. Smoke and soot deposit corrosive residues on surfaces, while intense heat damages objects even without direct flame contact. Fire suppression systems, though necessary for protection, can cause secondary water damage to collections. The risk includes structural fires spreading to collection areas, electrical fires from equipment, and arson. Preventive measures include fire detection systems, proper storage of flammable materials, regular electrical maintenance, and emergency response protocols.

Flow magnitude: The volume or mass of air or fluid moving through a system per unit time, critical for calculating heat transfer and ventilation rates.

Foundation and ground interface management: Design and construction details where building meets ground, affecting moisture, thermal, and structural performance.

Fourier's law: Physical principle describing steady-state heat transfer through materials, with rate proportional to thermal conductivity, area, and temperature gradient.

Fresh air intake: Point where outdoor air enters HVAC system, requiring filtration and conditioning before distribution to occupied spaces.

G

Gains: Heat or moisture added to spaces from internal sources like occupants, lighting, equipment, or sun through windows.

Generation (climate system): Equipment that produces heating, cooling, or conditioned air, including boilers, chillers, and air handling units.

Geothermal energy: Thermal energy extracted from the earth's interior, either from hot rocks or relatively constant ground temperatures for heat pumps.

Geothermal heat pump: System using stable ground temperature as heat source in winter and heat sink in summer, more efficient than air-source systems.

Greenhouse gases emissions: Release of gases like carbon dioxide and methane that trap heat in the atmosphere, primary contributor to climate change.

Grid-connected solutions: Energy systems connected to the utility power grid, allowing purchase of electricity and potentially selling excess renewable generation.

Guarded hot box test: Laboratory measurement of thermal transmittance by placing material sample between controlled hot and cold chambers and measuring heat flow.

Guideline: Recommendations for best practices that provide flexibility in application, less prescriptive than standards but more specific than general principles.

H

Heat exchangers: Devices that transfer thermal energy between two fluids without mixing them, used in heat recovery and hydronic systems.

Heat gains: Thermal energy added to spaces requiring cooling, from solar radiation, occupants, equipment, and outdoor air infiltration.

Heat input: Thermal energy intentionally added to spaces through heating systems to maintain temperature setpoints during cold conditions.

Heat loss coefficient: Building characteristic quantifying power needed to maintain one-degree temperature difference across entire envelope, measured in watts per kelvin.

Heat losses: Thermal energy escaping from heated spaces through building envelope, requiring replacement to maintain temperature.

Heat recovery: Process of capturing thermal energy from exhaust air or fluids to precondition incoming fresh air or return water, reducing energy demand.

Heat recovery ventilation: System that transfers heat between exhaust and supply air streams without mixing them, maintaining fresh air while reducing losses.

Heat transfer: Movement of thermal energy from warmer to cooler areas through conduction, convection, or radiation, governed by temperature differences and material properties.

Heating coils: Heat exchangers where hot water or steam warms air passing through HVAC system before delivery to spaces.

Historical average: Typical environmental conditions objects have experienced over extended periods, informing appropriate target ranges for preservation.

Human toxicity: Potential harm to human health from exposure to materials or emissions, considered in lifecycle assessments and material selection.

Humidification wheel: Rotating heat exchanger that transfers both heat and moisture between exhaust and supply air streams, improving efficiency and humidity control.

Humidifier: Device that adds moisture to air through evaporation, steam injection, or atomization to maintain relative humidity setpoints.

Humidity ratio: Mass of water vapor per mass of dry air, expressed in grams per kilogram, used in psychrometric calculations.

Hydrolyses: Chemical degradation through reaction with water molecules, breaking polymer chains and causing physical deterioration.

Hydropower / Waterpower: Renewable electricity generated by capturing energy from flowing or falling water through turbines.

Hygrothermal loads: Combined effects of temperature and moisture that building envelope and systems must address to maintain suitable conditions.

I

Incorrect relative humidity (RH) (agent of deterioration): Relative humidity outside suitable range causing physical and chemical damage through moisture exchange between objects and air. High RH promotes mold growth above 65%, metal corrosion, dimensional swelling, and accelerated hydrolysis reactions. Low RH causes desiccation, cracking, embrittlement, and dimensional shrinkage especially in hygroscopic materials. Fluctuations cause cyclical swelling and shrinkage leading to cumulative mechanical fatigue, warping, cracking, and delamination at material interfaces. Rate and magnitude of fluctuations determine damage severity. Materials respond at different rates - thin papers react quickly while massive wood objects respond slowly. Mixed material objects experience internal stresses from differential response rates. Control strategies depend on collection vulnerabilities, building capabilities, and climate context, ranging from tight control for highly vulnerable materials to wider acceptable ranges for stable collections, often implementing passive buffering strategies.

Incorrect temperature (T) (agent of deterioration): Temperature conditions outside suitable range causing chemical and physical deterioration through multiple mechanisms. High temperatures accelerate chemical reactions including oxidation and hydrolysis, potentially doubling reaction rates with every 10°C increase. Low temperatures can cause brittleness in some polymers and rubbers, and freeze-thaw cycles damage water-containing materials. Fluctuations cause dimensional changes through expansion and contraction, creating mechanical stress especially at material interfaces. Extreme heat can cause melting, softening, or deformation of waxes, plastics, and adhesives. Different materials have different temperature sensitivities. Cool storage significantly extends life of chemically unstable materials like cellulose acetate and color photographs. Control requires understanding material vulnerabilities, appropriate setpoints balancing preservation and energy use, and minimizing fluctuations through building design and system operation.

Inductive loads: Electrical equipment with motors or transformers that create magnetic fields, causing power factor issues without correction.

Infiltration (ventilation): Uncontrolled air leakage into building through cracks and gaps, driven by pressure differences from wind and temperature.

Infrared thermography: Diagnostic technique using thermal cameras to visualize temperature patterns, revealing insulation defects, air leakage, and moisture problems.

Integrated system coordination: Coordinating multiple building systems to work together efficiently, avoiding conflicts and optimizing overall performance.

L

Lab tests (building renovation context): Controlled laboratory measurements of material properties like thermal conductivity, moisture sorption, or structural strength.

Latent cooling loads: Energy required to remove moisture from air through condensation, distinct from sensible cooling that only changes temperature.

Life Cycle Assessment (LCA): Comprehensive environmental evaluation of products or buildings throughout entire lifecycle from extraction through disposal.

Life Cycle Cost (LCC): Total cost of owning and operating a building or system over its entire service life, including initial capital, energy, maintenance, and replacement.

Light (ultraviolet, infrared and natural) (agent of deterioration): Electromagnetic radiation causing cumulative and irreversible photochemical damage through fading, discoloration, embrittlement, and structural weakening. Ultraviolet radiation has highest energy and causes most damage, infrared radiation adds heat stress, and visible light enables viewing but also contributes to deterioration. Damage is proportional to light intensity multiplied by exposure time, meaning even low light levels cause harm over extended periods. Particularly vulnerable are dyes, pigments, paper, textiles, photographs, and natural history specimens. Different materials have varying light sensitivity. Control strategies include limiting light exposure through rotation, using filtered lighting, reducing intensity levels, and eliminating unnecessary UV and IR radiation while maintaining visibility for appropriate use.

Loan agreement: Legal document specifying conditions for lending objects, including environmental requirements, insurance, and handling protocols.

Loans: Temporary transfer of collection objects to other institutions, requiring facility reports demonstrating suitable environmental conditions.

Long term outer limits: Maximum acceptable range of environmental conditions that collections can tolerate indefinitely without significant damage.

Losses: Heat or moisture removed from spaces by building envelope, infiltration, or intentionally through exhaust, requiring system capacity to replace.

Low oxygen (storage / display cases / treatment chambers): Specialized environments with reduced oxygen concentration to prevent insect activity and slow oxidation reactions.

M

Manual scheduling: Manually programmed time-based control of HVAC systems, simpler than adaptive controls but less responsive to actual conditions.

Measured airflow: Actual air flow rate verified through testing and balancing, which may differ from design specifications requiring adjustment.

Mechanical 'damage': Physical deterioration from forces including impacts, abrasion, vibrations, and dimensional changes, potentially sudden or cumulative.

Microclimates: Small-scale environmental conditions immediately surrounding objects, created by packaging, display cases, or even the collection itself through buffering.

Microclimate frames / Climaframes: Sealed frames with moisture-buffering materials that create stable humidity around two-dimensional artworks independent of room conditions.

Microclimate solutions: Strategies creating suitable local environments around vulnerable objects without conditioning entire spaces, reducing energy use.

Mixed air: Combination of return air from spaces and fresh outdoor air in HVAC system before conditioning and redistribution.

Mixed air chamber: Section of air handling unit where return air and outdoor air blend before conditioning, with proportions controlled by dampers.

Mixed collection: Objects with diverse material compositions requiring compromise environmental conditions that balance competing preservation needs.

Moisture-driven humidity loads: Increases in indoor moisture from hygroscopic materials releasing absorbed water when temperature rises.

Moisture transfer: Movement of water vapor through building materials by diffusion or through cracks by air movement, affecting durability and indoor humidity.

Moisture transport sorption: Laboratory test measuring how materials absorb, hold, and release moisture under varying humidity conditions.

Moisture vapor: Water in gaseous form within air, distinct from liquid water, transferring through materials by diffusion.

Multi-zone scheduling: Programming different operating schedules for different building zones based on occupancy patterns and collection needs, improving efficiency.

N

Natural drift: Allowing temperature to vary within acceptable limits without active conditioning, reducing energy use while maintaining safe conditions.

Natural nighttime ventilation: Passive cooling strategy using outdoor air during cool nights to remove heat accumulated during day.

Norm: Technical specification or standard established by standards organizations, more prescriptive than guidelines.

O

Ocean energy: Renewable power from waves, tides, ocean currents, or thermal gradients between surface and deep water.

Organic objects: Items made from materials of plant or animal origin including wood, paper, textiles, and leather, sensitive to humidity fluctuations.

Outside air damper: Controlled opening regulating fresh outdoor air entering HVAC system, modulated based on ventilation requirements and economizer operation.

Oxidation: Chemical reaction with oxygen causing deterioration of metals, oils, rubbers, and other materials, accelerated by high temperature and humidity.

P

Packaging: Protective enclosures around objects including boxes, folders, and wrapping materials that buffer environmental fluctuations and provide physical protection.

Paris Climate Agreement on Climate Change: International treaty committing signatory nations to limiting global temperature rise through emissions reductions.

Passive cooling: Reducing building heat through natural ventilation, thermal mass, shading, and other strategies not requiring mechanical systems.

Passive design strategies: Building design features that improve comfort and reduce energy use through orientation, materials, and form rather than mechanical systems.

Peak energy demand: Maximum rate of energy consumption during a billing period, often charged separately and driving infrastructure costs.

(Peripheral) Chiller: Equipment that removes heat from water through refrigeration cycle, producing chilled water for cooling coils in air handlers or fan coils.

(Peripheral) steam generator: Boiler producing steam for humidification systems, located centrally and distributing steam through pipes.

Pests and plants (agent of deterioration): Biological organisms causing material loss and disfigurement through feeding, nesting, excrement deposition, and physical disruption. Insects including carpet beetles, clothes moths, silverfish, and wood borers consume organic materials leaving holes, channels, and structural weakness. Rodents gnaw objects and contaminate with urine and feces. Birds soil surfaces and introduce insects. Mold causes staining, weakening, and health hazards. Plant roots can damage architectural elements. Damage is often discovered only after significant loss has occurred. Integrated pest management combines environmental control (temperature, humidity, cleanliness), physical barriers, monitoring systems, and targeted treatments while avoiding broad pesticide use that may harm collections and staff.

Photovoltaic cells: Semiconductor devices converting sunlight directly to electricity, forming the basis of solar panel systems.

Photovoltaic panels (PV): Arrays of photovoltaic cells that generate renewable electricity from solar radiation, either grid-connected or with battery storage.

Physical forces (agent of deterioration): Mechanical stresses causing deformation, breakage, abrasion, or structural failure of objects. Forces can be sudden (impacts from drops, collisions, or earthquakes) or cumulative (vibrations during transport, improper support causing stress, or repeated handling). Inadequate storage systems, poor mounting techniques, and unsuitable environmental conditions increasing material brittleness all contribute to physical damage risk. Vulnerable materials include ceramics, glass, textiles under tension, and rigid organic materials at low humidity. Prevention requires proper handling protocols, adequate support systems, vibration isolation during transport, and seismic protection in vulnerable locations.

Portable / mobile humidification devices: Stand-alone units adding moisture to air in specific spaces, simpler than central systems but requiring regular maintenance.

Power Factor Correction: Electrical equipment compensating for phase differences between voltage and current from inductive loads, reducing utility charges and improving efficiency.

Primary energy: Total energy extracted from natural sources before any conversion or transmission, including losses in power generation and distribution.

Product stage: Phase in building lifecycle involving extraction of raw materials, manufacturing of components, and transport to construction site.

Proofed fluctuation: Historical environmental variations that collection materials have tolerated without damage, informing safe operating ranges.

Pumps (climate system components): Mechanical devices circulating water or other fluids through hydronic heating and cooling systems.

Q

Quarantine rooms: Isolated spaces where newly acquired or infested objects are held and treated before joining main collection to prevent pest spread.

R

Radiation: Heat transfer through electromagnetic waves requiring no medium, including solar radiation and infrared radiation from warm surfaces.

Real-time demand response: Automatically adjusting building energy use in response to grid signals or dynamic pricing, reducing peak loads.

(Recirculated) air ratio: Proportion of return air mixed with fresh outdoor air in HVAC system, affecting energy use and air quality.

Relief air damper: Controlled opening releasing excess indoor air when economizer brings in outdoor air, maintaining building pressure.

Remote compressor / condenser (DX) unit: Refrigeration equipment located outside building serving indoor cooling coils directly without chilled water loop.

Renewable Energy Sources (RES): Natural energy flows that replenish on human timescales including solar, wind, hydro, biomass, and geothermal.

Renewable energy systems (RES): Equipment and infrastructure that capture and convert renewable energy sources into usable heating, cooling, or electricity.

Repurposing: See Adaptive reuse.

Return air (ducts): Pathway carrying air from conditioned spaces back to air handling unit for reconditioning and recirculation.

S

Seasonal fluctuations: Environmental variations over annual cycle due to changing outdoor conditions, more pronounced in massive historic buildings.

Secondary energy: Energy in intermediate forms like electricity or district heating delivered to buildings before final conversion to useful energy.

Sensible heating and cooling: Temperature changes in air without altering moisture content, distinct from latent processes involving condensation or evaporation.

Sensible heat losses: Thermal energy leaving building through conduction, air leakage, and ventilation, proportional to temperature difference.

Setpoint: Target temperature, humidity, or other parameter that control system works to maintain through heating, cooling, or other conditioning.

Short term fluctuations: Rapid environmental changes over hours or days from equipment cycling, door openings, or weather events, stressful to vulnerable materials.

Silica gel (for display cases): Desiccant material that absorbs and releases moisture to buffer humidity within display cases, requiring periodic conditioning.

Smart buildings: Structures with integrated sensors, controls, and automation that optimize comfort, energy use, and operational efficiency.

Soil use: Land required for buildings, materials extraction, or energy production, considered in environmental lifecycle assessments.

Solar collectors: Devices capturing solar thermal energy to heat water or air for building systems, distinct from photovoltaic panels producing electricity.

Solar control: Strategies to reduce unwanted solar heat gain through shading, reflective materials, or glazing treatments while potentially admitting daylight.

Solar energy: Radiation from the sun captured for heating or electricity generation through thermal or photovoltaic technologies.

Solar Heat Gain Coefficient (SHGC): Fraction of solar radiation admitted through glazing, with lower values reducing cooling loads but also daylight.

Stack effect: Natural air movement driven by temperature and density differences, causing infiltration at lower levels and exfiltration at upper levels.

Standard: Formally established technical specifications or requirements, more prescriptive than guidelines, often referenced in building codes.

Steady-state heat transfer equation: Mathematical relationship describing constant heat flow through materials under stable temperature conditions, basis for thermal calculations.

Strategic rezoning: Reorganizing building spaces and collections to group areas by environmental requirements, reducing conditioning costs.

Structural project: Engineering documentation including calculations, construction details, and system descriptions showing how building structure and services function.

Sub metering: Installing additional energy meters on specific systems or zones to understand consumption patterns and identify efficiency opportunities.

Supply air (ducts): Pathway delivering conditioned air from air handling unit to spaces, including diffusers or registers for distribution.

Sustainable setpoint strategies: Adjusting temperature and humidity targets to balance collection preservation with energy efficiency and environmental impact.

System hierarchy (set-points): Priority structure when multiple control objectives conflict, typically favoring collection preservation over occupant comfort.

Systems control improvements: Optimizing programming, sensors, and algorithms to reduce energy use while maintaining performance.

T

Temperature (T): Measure of thermal energy in air or materials, affecting chemical reaction rates and material properties.

Thermal bridge: Localized area of higher heat flow through building envelope due to less insulation or more conductive materials, causing cold spots.

Thermal capacity: See Thermal mass / thermal capacity.

Thermal flows: Movement of heat energy through buildings by conduction through materials, convection by air, or radiation from surfaces.

Thermal insulation: Materials with low thermal conductivity that slow heat transfer, reducing heating and cooling requirements.

Thermal mass / Thermal capacity: Ability of materials to absorb and store thermal energy, damping temperature fluctuations in massive buildings.

Thermal resistance: Opposition to heat flow through material or assembly, measured as R-value, with higher values indicating better insulation performance.

Thermostat: Device sensing temperature and signaling heating or cooling equipment to maintain setpoint conditions.

Thermoplastic objects: Items made from plastics that soften when heated, potentially deforming at elevated temperatures or becoming brittle when cold.

Thieves and vandals (agent of deterioration): People who intentionally damage, deface, or remove collection objects without authorization, causing permanent loss or harm. Theft results in loss of objects and associated documentation, breaking contextual relationships within collections. Vandalism includes deliberate destruction, defacement, or inappropriate alteration motivated by various factors including ideology, mental illness, or opportunism. Risks exist from both external intruders and internal actors including staff, contractors, and researchers. Protection requires layered security including access control, surveillance systems, inventory management, background checks, and security awareness training. The risk increases during moves, loans, and public events.

Time-of-use tariffs: Electricity pricing with different rates for peak, off-peak, and shoulder periods, incentivizing load shifting to reduce costs.

Trigeneration: Advanced system producing electricity, heating, and cooling from single fuel source, extending cogeneration concept.

U

Use stage: Longest phase of building lifecycle including operations, maintenance, repairs, and replacement of systems over decades.

Useful energy / Net demand or need: Final energy actually used for heating, cooling, lighting, or other services after all conversion losses.

V

Valves (climate system components): Mechanical devices controlling fluid flow in hydronic systems, modulated to regulate heat delivery.

Variable frequency drives (VFDs): Electronic controllers varying motor speed to match actual load requirements, dramatically improving efficiency over constant-speed operation.

Ventilation (natural or mechanical): Introduction of outdoor air to spaces for air quality, either through openings or forced by fans.

Ventilation mass flow: Rate of air exchange measured in mass per time, accounting for density variations with temperature and altitude.

W

Waste management strategies: Approaches to reducing, reusing, and recycling construction debris and operational waste to minimize environmental impact.

Water (agent of deterioration): Liquid water causing immediate and long-term damage through saturation, staining, dimensional changes, and creating conditions for mold growth. Sources include roof leaks, plumbing failures, floods, rising damp, condensation on cold surfaces, and fire suppression system discharge. Water damage is often irreversible, causing warping, cockling, delamination, bleeding of inks and dyes, corrosion of metals, and loss of structural integrity. Particularly vulnerable are paper-based materials, textiles, photographs, and organic objects. Prevention requires regular building inspection, proper drainage, humidity control to prevent condensation, water detection systems, and emergency response plans with rapid drying protocols.

Water loads: Moisture added to or removed from indoor air by occupants, processes, outdoor air, and hygroscopic materials.

Water management: Strategies for controlling water in and around buildings including drainage, waterproofing, and moisture barriers.

Water resources: Freshwater consumption during building materials production, construction, and operations, considered in sustainability assessments.

Water vapor: Gaseous form of water in air, invisible unlike liquid water or steam, transferring through materials and affecting indoor humidity.

Water vapor pressure: Partial pressure exerted by water vapor in air, driving force for moisture diffusion through materials.

Water-side heat recovery: Capturing waste heat from chilled water return or condenser water to preheat domestic hot water or other loads.

Whole building life cycle analysis (WBLCA): Comprehensive environmental assessment of complete building from construction through demolition including all systems and materials.

Wind energy: Renewable electricity generated by wind turbines converting kinetic energy of air movement, subject to Batz law efficiency limits.

Wind velocity: Speed of air movement outdoors, creating pressure differences that drive infiltration and affecting building heat loss.

Window and opening maintenance: Regular care of windows, doors, and other envelope penetrations to maintain air tightness, weather resistance, and operability.