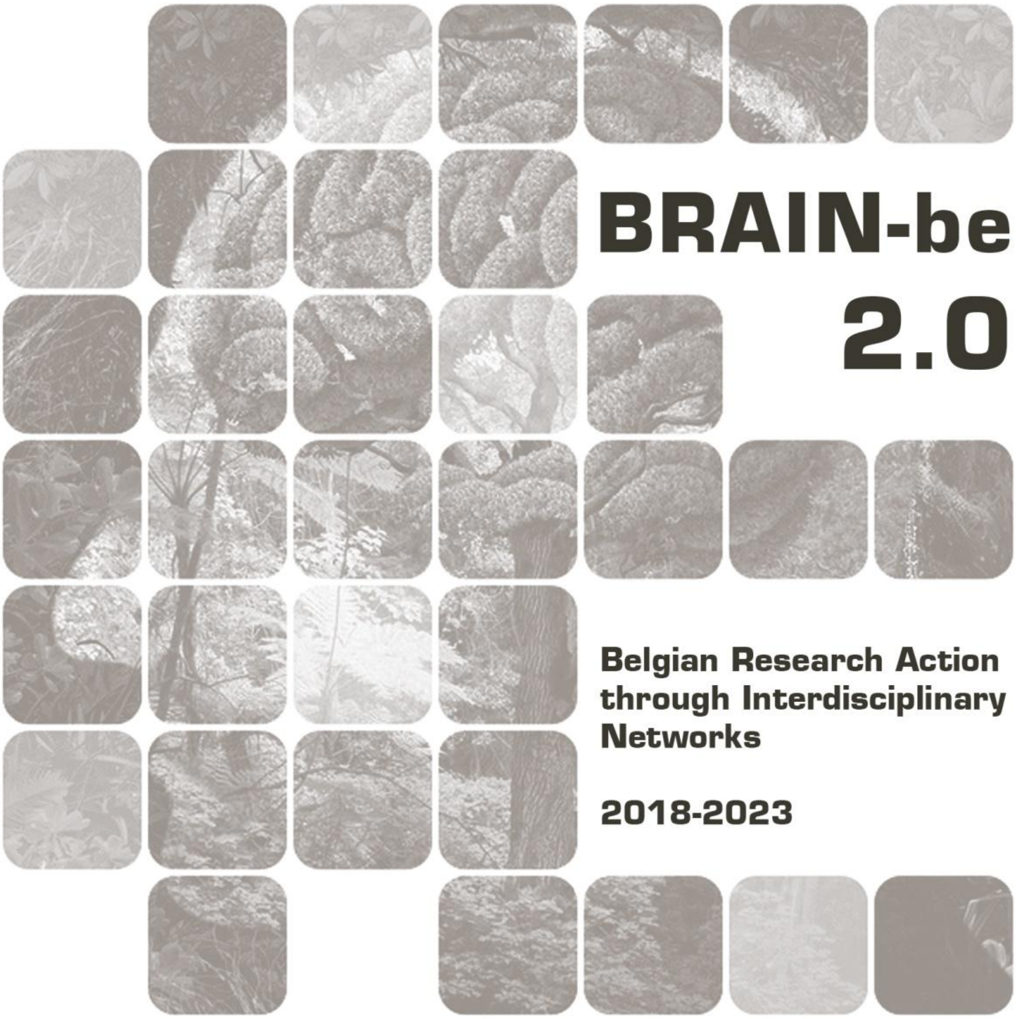

BRAIN-be 2.0

Belgian Research Action through Interdisciplinary Networks

2018-2023

C2P

Climate2Preserv

Sustainable Climate Management Strategy to Preserve Federal Collections

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Pillar 2: Heritage science

Royal Institute for Cultural Heritage

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NETWORK PROJECT

C2P

Climate2Preserv

Sustainable Climate Management Strategy to Preserve Federal Collections

Contract - B2/202/P2/Climate2Preserv

FINAL REPORT

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ABSTRACT (ENG)

Context

Cultural heritage institutions face the challenge of preserving collections while reducing energy consumption. Strict climate control standards lead to high operating costs and energy use. Recent research advocates for relaxed climate specifications based on risk assessment, but practical implementation guidance remains limited.

Objectives

The project developed a flexible methodology for climate and energy optimization in Belgian Federal Scientific Institutions through case studies at KMSKB-MRBAB (system performance), Wiertz Museum (building envelope), and CINEMATEK (collection vulnerability). The interdisciplinary team included KIK-IRPA, KU Leuven and The University of Liège and specialized architecture firms.

Conclusions

Climate2Preserv produced three integrated deliverables: the Climate2Preserv Handbook providing guidance across buildings, systems, collections, and energy domains; the Collection Environment Assessment Model (CEAM), an open-source tool for predicting energy savings; and templates supporting measurement planning and more. Case studies demonstrated energy savings of 10-50% through strategic setpoint adjustments and system optimization while maintaining preservation standards. The methodology addresses six sector challenges including stakeholder fragmentation, limited analytical capacity, and value-based constraints in historic buildings. Outputs are available online through open repositories and the KIK-IRPA website, and have been shared through international conferences and ICCROM's Our Collections Matter initiative, with continued dissemination planned.

Keywords

Cultural heritage preservation, energy optimization, climate control, sustainable collections management, preventive conservation

1. INTRODUCTION

Cultural heritage institutions must preserve collections for future generations while responding to demands for energy reduction and sustainability. The Climate2Preserv project developed practical methodologies to help Belgian Federal Scientific Institutions optimize climate management in collection spaces. Working through real-world case studies, the project created integrated tools that address both preservation requirements and energy efficiency.

Climate2Preserv brought together expertise from multiple disciplines and institutions. The project team included KIK-IRPA (Royal Institute for Cultural Heritage) as coordinator, KU Leuven (Building Physics), the Royal Museums of Fine Arts of Belgium (KMSKB-MRBAB), the Royal Film Archive of Belgium (CINEMATEK), ICCROM (International Centre for the Study of the Preservation and Restoration of Cultural Property), Academia Belgica (Rome), and specialized architecture firms (Origin and Daidalos). This collaboration included conservators, building physicists, engineers, architects, and facilities managers. The interdisciplinary approach was necessary because climate optimization requires knowledge across technical systems, building performance, collection care, and energy analysis.

Fig. 1: Three main case studies

The project tested its methodology through three case studies. At KMSKB-MRBAB, work focused on HVAC system performance. The Wiertz Museum case examined building envelope interventions in a historic structure. CINEMATEK provided insight into collection-specific climate vulnerabilities. These practical applications shaped the project's deliverables and revealed both opportunities and persistent challenges in heritage climate management.

The Climate2Preserv approach is built on **six core principles:**
- It focuses on reducing global energy consumption, not solely on CO_2 emissions reduction.
- It starts from existing contexts and infrastructure rather than ideal scenarios.
- It aims to keep collection risk at current levels unless specific risk reduction is required.
- It respects institutional missions while suggesting practice changes where energy impacts are significant.
- It can prioritize maintaining robust and resilient climate systems even when powered by fossil fuels, considering the full energy cost of manufacturing new equipment.
- It requires motivated teams with both technical and collections expertise, supported by management.

Climate2Preserv is a suggested protocol that can be followed from start to finish or used in a modular way to tackle specific problems. It focuses on maintenance, short-term and medium-term solutions. It emphasizes sharing basic concepts to improve communication across allied fields. It offers both high-end and low-end solutions, from simple to complex approaches.

Climate2Preserv does not attempt to reinvent existing tools and refers to them where applicable. It focuses on what institutions can do themselves. For example, it provides information on different options and communication strategies for new builds, but does not aim to make conservators into building engineers. It does not address energy savings beyond climate control.

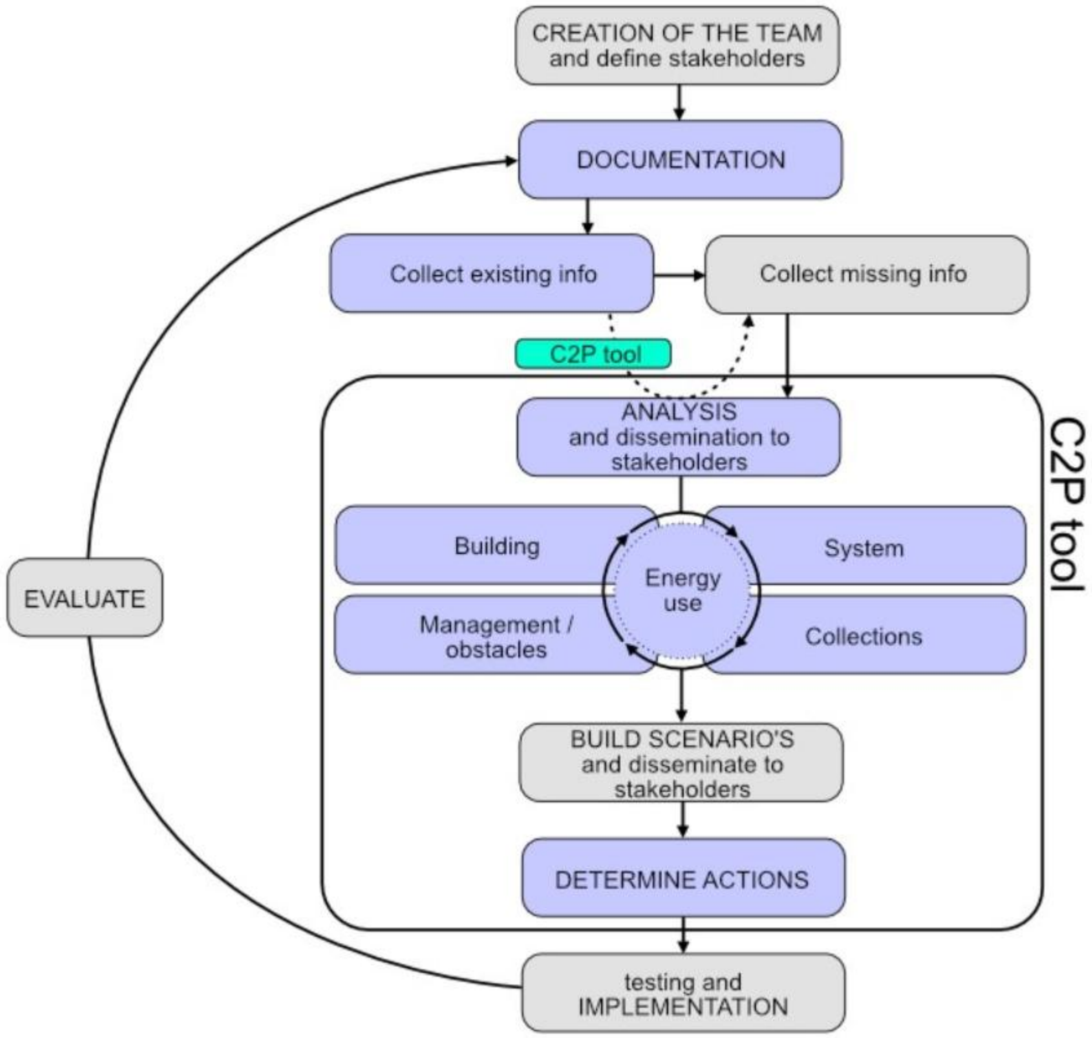

Fig. 2: C2P protocol presenting the different steps to facilitate energy savings in cultural heritage institutions.

Climate2Preserv produced **three main outputs.** The Climate2Preserv Handbook provides guidance across buildings, systems, collections, and energy domains. The Collection Environment Assessment Model (CEAM) is an open-source tool for data-driven decision support on energy optimization strategies. A suite of templates supports measurement planning, facility documentation, and communication with contractors.

The project's work occurred during a period of heightened concern about energy costs and sustainability. The 2022-2023 energy crisis created urgent demand for practical guidance. Climate2Preserv contributed to sector-wide initiatives including the Climate Declaration, developed in collaboration with the Dutch Cultural Heritage Agency. The project deliverables have been shared through international networks including ICCROM's Our Collections Matter initiative.

Throughout the project, national and international training and valorisation activities were organised to disseminate the knowledge and tools developed, with a particular focus on data collection methods and energy optimization strategies. These activities primarily targeted collections managers and preventive conservation professionals, as well as energy and facilities managers.This report presents the project's objectives, methodology, results, and recommendations. It documents the scientific approach, the outcomes from case studies, and the practical tools developed for the heritage sector.

2. STATE OF THE ART AND OBJECTIVES

2.1. State of the art

Years of research showed that temperature and relative humidity significantly impact collection longevity. Climate affects collections in three ways. Mechanical damage (cracks, delamination, deformation) occurs suddenly and is easily visible. Chemical aging (hydrolysis, corrosion, oxidation) happens slowly and is less perceived as damage. For chemically stable objects like quality oil paints, this is barely noticeable. For unstable materials like cellulose acetate film, remarkable changes occur within 5 to 10 years. Biological deterioration (mold growth) develops when temperature and relative humidity remain persistently high. However, unsuitable temperature and relative humidity are just two of ten agents of deterioration. Risk analysis often shows they are not the biggest risks for most collections but have a significant financial impact.

The conservation field changed significantly over the past two decades. From 2008 onwards, international organizations placed environmental sustainability at the forefront. ASHRAE Handbook Chapter 24 (Museums, Galleries, Archives, and Libraries) remains the most referenced technical document in loan agreements. ISO/CEN standards (EN 15757, EN 16883, BS PAS 198) define specifications and methods. The Bizot Green Protocol (2014) established more relaxed loan standards to enable energy savings. The IIC-ICOM CC environmental guidelines (2014) provided scientific context with evidence-based recommendations. Risk management methods like CPRAM, the ABC Method, and QuickRiskScan (QuiskScan) shifted focus from absolute environmental control to assessment of actual collection vulnerability.

Despite this robust framework, a critical gap exists between available knowledge and practical implementation. Cultural institutions lack methodologies that connect buildings, HVAC systems, collections, and energy management. Assessment tools exist for each domain separately. No holistic approach connects them. Existing guidance describes strategic thinking but lacks practical implementation instructions. A 2018 ICCROM-CCI survey[1] of 444 professionals, from predominantly conservation backgrounds, from 70 countries confirmed the need for hands-on preservation tools and methodologies. To this day, no study provides a comprehensive roadmap for sustainable storage and exhibition spaces.

The Belgian context adds specific challenges. Only 5 institutions in Europe offered preventive conservation training programs anno 2021. Museum professionals face complex situations without practical frameworks.

Cultural heritage institutions vary significantly in size, systems, and constraints. Large museums typically have complex HVAC systems controlling both temperature and humidity, maintain year-round comfort temperatures (18-20°C) for public spaces, face strict loan requirements, and employ internal facilities teams. Small to medium museums and religious buildings often have only heating systems with mobile (de)humidifiers, show high variability in system types,

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[1] Lambert, Simon, Catherine Antomarchi, Kathryn Johnson, Jane Stevenson, Marjan Debulpaep, and Theocharis Katrakazis. *Survey of Preventive Conservation Tool and Resource Users: Summary of Findings*. Rome: ICCROM and Canadian Conservation Institute, 2018. https://www.rit.edu/ipi/sites/rit.edu.ipi/files/documents/iccrom_precon_tools-resources_eng.pdf.

sometimes lack systems entirely, but can operate more flexibly (visitors keep coats on, winter closures occur). Archives, depots, and heritage libraries benefit from collection mass that moderates climate and non-public spaces that eliminate comfort temperature requirements.

Stakeholder fragmentation complicates decision-making across all institution types. Building owners, building users, system maintenance responsibilities, and energy bill payers are typically different entities. This creates information gaps, communication difficulties due to jargon, and misunderstanding of departmental priorities. Collection managers struggle to formulate realistic requirements. Facilities teams lack preservation expertise. Building agencies prioritize different concerns than occupants. Good collaboration between facilities and collections teams remains rare, but when present, proves to be very effective.

Belgian Federal Scientific Institutions exemplify these challenges with added complexity. Shared responsibilities between Building Agency, occupants, and external management firms split authority. Heritage-protected buildings were not purpose-built for collections. Regulatory pressures compound: Belgian institutions must meet EU and national energy reduction objectives while maintaining or improving collection preservation. However, the case studies revealed that these challenges were not unique to federal institutions. Small museums, religious buildings, and municipal collections face similar or greater obstacles with fewer resources.

2.2. Project objectives and planned deliverables

Climate2Preserv aimed to help Federal Scientific Institutions undertake an optimization process for indoor climate and energy consumption, then disseminate results to contribute to ongoing international efforts.

WHAT DO HERITAGE PROFESSIONALS (collections and facilities) KNOW?

WHAT DO HERITAGE PROFESSIONAL NOT KNOW?

WHICH HELP DO THEY NEED TO KICKSTART PROJECTS?

WHICH HELP DO THEY NEED TO BE A VALUABLE STAKEHOLDER IN A LARGER PROJECT?

WHERE AND WHEN DO THEY NEED HELP FROM EXTERNAL STAKEHOLDERS?

HOW CAN WE BEST FACILITATE INTERDISCIPLINARY COMMUNICATION AND COLLABORATION?

Fig. 3: As the project evolved the following essential questions emerged. These questions were considered leading to a changed approach, mainly in relation to the creation of deliverables.

The original project proposal defined four main research objectives:

- **RO1: Develop a user-friendly and flexible methodology** to guide all actors concerned by federal collections infrastructures (architects, engineers, preventive conservation experts, sustainability consultants, directors, collections managers, technicians, conservators).

- **RO2: Implement the methodology** in two case studies (KIK-IRPA and KMSKB-MRBAB) throughout the project.
- **RO3: Train Federal Scientific Institutions and Building Agency staff**
- **RO4: Disseminate the methodology** nationally and internationally.

The original proposal planned an integrated C2P Toolbox. This online platform would combine the C2P Protocol (methodology), assessment tools (data analysis, impact prediction), templates (documentation and communication), and case study documentation. The toolbox would function as a single comprehensive platform guiding users through the entire optimization process.

These objectives and deliverables evolved significantly during project implementation. Opportunities emerged from the energy crisis context and sector feedback. Section 3 describes how the project adapted its methodology and deliverables to meet actual needs rather than assumed needs. The single C2P Toolbox concept transformed into a suite of complementary deliverables: a comprehensive handbook, a focused analytical tool (CEAM), and practical templates. Additionally, extended impact deliverables emerged including the Climate Declaration initiative.

3. METHODOLOGY

3.1. Case study design

The project selected three case studies from Belgian Federal Scientific Institutions. Each case study addressed a different research question.

KMSKB-MRBAB (Royal Museums of Fine Arts of Belgium) - System Performance Phase 3 of the museum complex spans 7-8 floors with restoration workshops, exhibition spaces, offices, depots, and archives. Climate control systems are located on the fourth and fifth floors. Ice water production is shared centrally with the Royal Library of Belgium (KBR). The case study focused on understanding how to measure energy consumption of complex climate control systems with separate functions (heating, ventilation, cooling) and how to estimate the impact of proposed measures. Surface area: approximately 4000m². Energy usage: 90,000 m³ gas/year and 300,000 kWh electricity/year (based on DIN V18599 for heating).

Wiertz Museum - Building Envelope A former artist studio housing large-format paintings. The building has an inherently leaky envelope with skylights. The case study focused on how to create a better collection environment while saving energy in a building not purpose-built for collections. Climate control uses radiators combined with natural ventilation. Surface area: approximately 750m². Energy usage: 18,000 liters fuel/year and 15,000 kWh electricity/year.

CINEMATEK - Unstable Collections Acetate film collection stored in a former parking garage under a residential care center. Acetate film is chemically unstable, and natural decay can be slowed by cool temperatures. The building shell was minimally adapted for collection needs. The case study focused on how to preserve an unstable collection in a building unsuited for energy-friendly cool/cold preservation. Surface area: approximately 1300m²/floor over 5 levels (6500m² total). Energy usage: unknown.

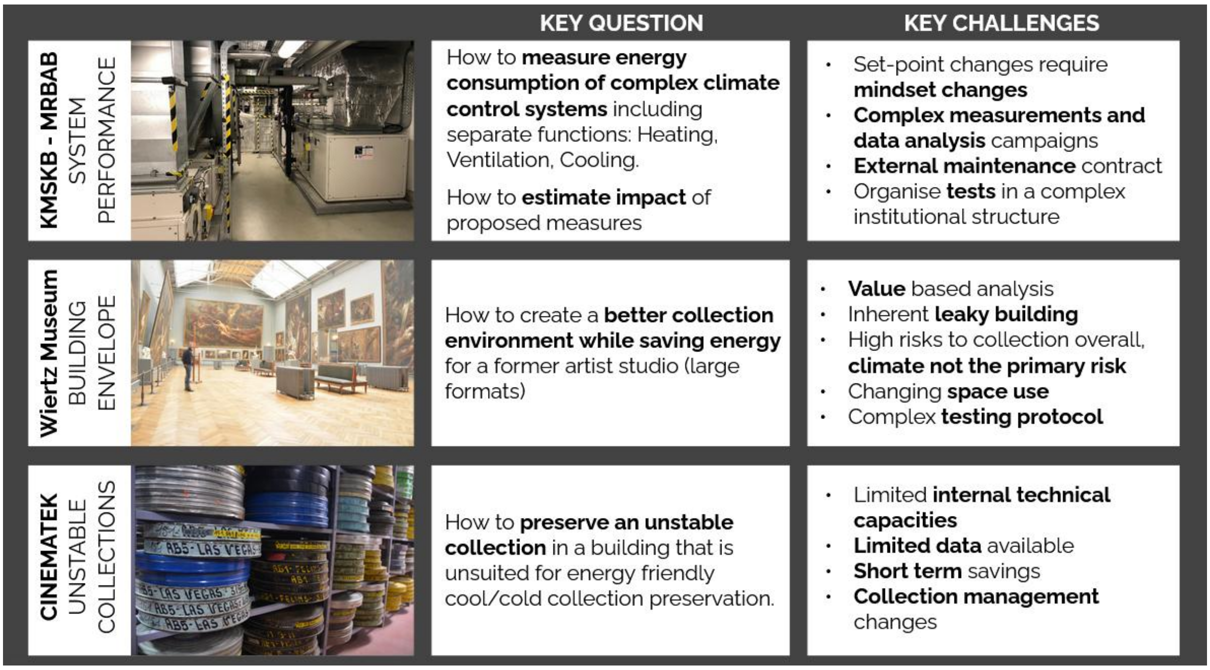


Fig. 4: Three main case studies leading to the formulation of key questions and key challenges

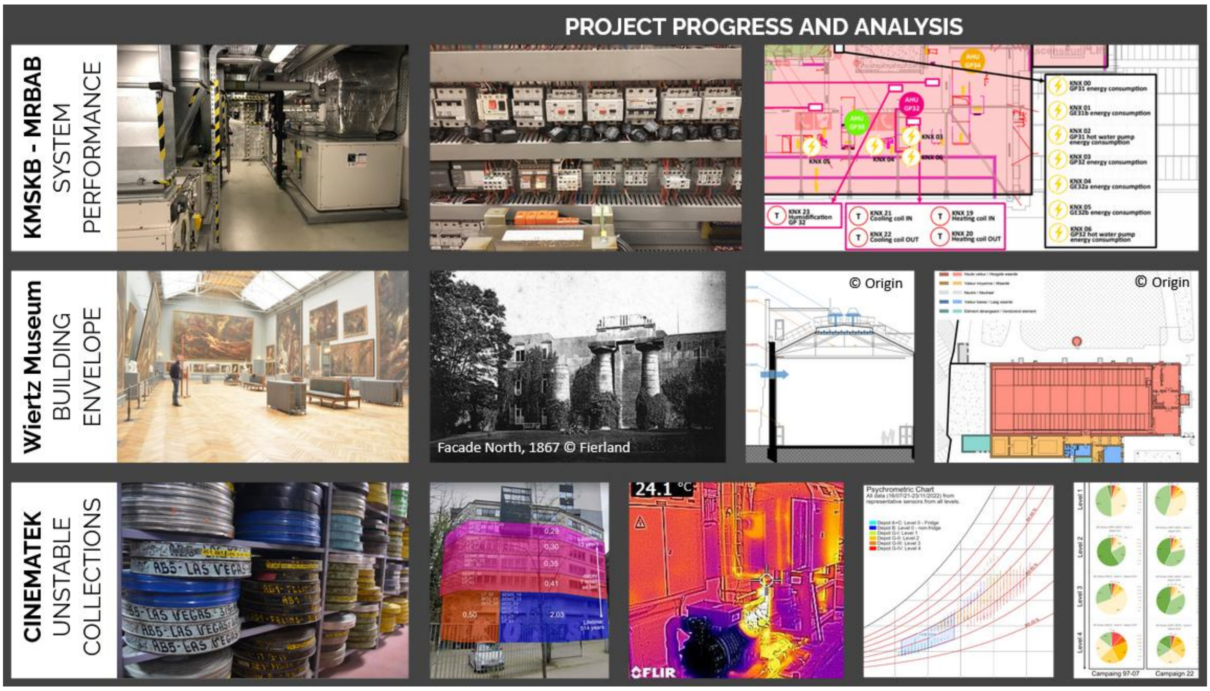


Fig. 5: Fundamentally different challenges lead to a variety of approaches. Focusing on the overlapping issues, real world challenges were identified.

3.2. Real-world challenges identified

Through the case studies, six persistent challenges emerged that shape energy optimization projects in cultural heritage institutions:

- **Set-point changes require mindset changes.** Adjusting temperature and humidity targets means challenging deeply held beliefs about collection care. Facilities teams fear equipment failure. Collections teams fear object damage. Both need evidence that changes are safe.
- **Complex measurements and data analysis campaigns.** Understanding current performance requires extensive monitoring. Institutions lack equipment, expertise, and time for comprehensive measurement campaigns. Data analysis requires specialized skills most institutions do not have in-house.
- **External maintenance contractors.** Many institutions depend on external contractors who maintain systems but lack preservation knowledge. Communicating collection needs to contractors is difficult. Contractors may resist changes that complicate their routines or require new knowledge.
- **Organizing tests in complex institutional structures.** Testing new approaches requires coordination across multiple departments and stakeholders. Building owners, occupants, maintenance contractors, and energy bill payers are often different entities. Getting approval for tests can take months.
- **Value-based constraints.** Historic buildings have heritage value that limits intervention options. Installing new ductwork may damage historic interiors. Modern HVAC equipment may be visually inappropriate. Some improvements are simply not possible in protected buildings.
- **Limited internal technical capacity and data availability.** Small to medium institutions have no technical staff. Data on building performance, system specifications, energy

consumption, and historical indoor climate conditions is often incomplete, scattered, or non-existent. Building documentation from past renovations may be lost.

These challenges fall into two categories. Some are pain points requiring ongoing management (stakeholder complexity, value-based constraints). These cannot be solved but must be worked with. Others can be addressed through knowledge-building and practical tools (data analysis capacity, contractor communication, understanding what tests to run).

3.3. Project evolution: from concept to deliverables

The project encountered significant obstacles and unexpected opportunities that led to strategic redefinition of deliverables.

Challenges encountered

Software development proved slower than anticipated. Initial plans to build the C2P Toolbox as a comprehensive online platform underestimated the complexity of data ingestion from different monitoring systems used in pilot projects. Hiring difficulties delayed progress. KU Leuven opened a first vacancy end of 2021 but found no suitable candidate. Marcin Zygmunt joined in 2022, bringing expertise in building energy modeling, energy audits, and thermal comfort analysis. The measurement campaign for KMSKB Phase 3, originally scheduled for August 2022, deployed by April 2023.

Data availability challenges affected all case studies. Obtaining building documentation, historical climate data, and energy consumption records took longer than expected. Old buildings with multiple refurbishments lack comprehensive documentation. Digitization of building-related documents would significantly ease future analysis.

Opportunities seized

The 2022-2023 energy crisis created urgency and receptiveness. Institutions suddenly needed practical guidance on immediate energy-saving measures. The project team rapidly produced "Energy Crisis: Potential Energy Savings in Indoor Climate Management for the Cultural Heritage Sector" in two languages. This document, based on C2P lessons learned and developed with FARO. Vlaams steunpunt voor cultureel erfgoed collaboration, provided short to medium-term measures institutions could implement immediately.[2] The crisis validated the project's relevance and created demand for practical tools.

The Climate Declaration initiative emerged from collaboration with the Dutch Cultural Heritage Agency (RCE). This document translates international guidelines to local context and expresses how to think about indoor climate more sustainably. Published in three languages and shared with Belgium's regions, it was voluntarily signed by around 50 heritage organizations, museums, libraries, archives including Federal Scientific Institutions (and many other mid-size to large-scale museums). It represents sector-wide commitment to sustainable practices.

[2] For project related publications: see publications section.

Fig. 6: Most of the cultural heritage institutions that signed the climate declaration including Belspo and the Federal Scientific Institutions.

Strategic redefinition

Working with case studies revealed that the original C2P Toolbox concept was too ambitious and not aligned with sector needs. A single comprehensive online platform would require institutions to have complete data, technical capacity for analysis, and time to learn complex software. Most institutions lack these prerequisites. The project pivoted to three complementary deliverables addressing different knowledge gaps and capacity constraints:

Climate2Preserv Handbook provides the comprehensive methodology. It covers theory (buildings, systems, collections, energy), documentation approaches, and implementation strategies. Organized around short-term versus long-term measures and the four-domain framework, it serves as the complete protocol. Institutions can use it independently or with support from consultants. The handbook addresses the "what you need to know" and "what you need to do" gaps.

CEAM (Collection Environment Assessment Model) focuses specifically on data analysis for decision support. Rather than attempting to cover all aspects of energy optimization, CEAM addresses the most common pain point: understanding whether proposed changes will work. It requires minimal data input, selects appropriate analytical models based on available data, and provides clear outputs for decision-making. A dedicated data chapter explains requirements. CEAM addresses the "how you do analysis" gap for institutions lacking in-house capacity.

Templates and practical tools provide ready-to-use resources. Measurement plan templates guide monitoring campaigns. Facility report templates help communicate with contractors. Testing protocol guidelines explain how to organize tests. Flowcharts describe the decision-making process for implementing changes in indoor climate preservation management. These tools reduce the barrier to starting energy optimization projects. They address the "how you get started" gap and support structured decision-making.

This redefined suite of deliverables emerged directly from understanding sector challenges. Rather than assuming what institutions need, the project team learned through case study work what actually helps. The result is more modest in ambition but more useful in practice. Different institution types can use different combinations. A large museum with technical staff might use the handbook independently and CEAM for complex analysis. A small museum might engage consultants who use the handbook and templates. The flexibility serves the sector's diversity better than a single comprehensive platform would have.

3.4. Redefined objectives

The four main research objectives remained constant, but their interpretation and implementation evolved:

- **RO1: Develop a user-friendly and flexible methodology** was achieved through three complementary deliverables rather than one integrated toolbox. The Climate2Preserv Handbook provides the complete protocol (RO1a). CEAM addresses data-based assessment of key performance indicators (RO1b) for institutions lacking analytical capacity. Templates and tools complete the methodology (RO1c).
- **RO2: Implement the methodology** expanded beyond the original two case studies. The three case studies (KIK-IRPA photographic storage, KMSKB-MRBAB Phase 3, and Wiertz Museum) provided deep learning about challenges. However, implementation revealed that the methodology needed to serve not just Federal Scientific Institutions but all collection-holding institutions facing similar challenges.
- **RO3: Train staff** was fulfilled through the Summer School (July 2023, Brussels). The training, organized in partnership with ICCROM and Academia Belgica, expanded to include both Belgian and international professionals, testing the methodology's broader applicability.
- **RO4: Disseminate the methodology** succeeded through multiple channels. The Summer School introduced the approach to international experts (RO4a). The Handbook, CEAM, and templates are published online in three languages (RO4b). Integration discussions with ICCROM's Our Collections Matter initiative continue (RO4c). The Climate Declaration and energy crisis document extended dissemination beyond original plans (RO4d). The project and its results were presented at various national and international conferences and workshops (listed in section 5)

The evolution from original to redefined objectives reflects a shift from "build a comprehensive tool for Federal Scientific Institutions" to "provide flexible, practical resources for diverse cultural heritage institutions." The ambition remained the same. The approach became more realistic and universal.

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

Introduction: Addressing knowledge gaps in the heritage sector

Working with case studies revealed fundamental questions about what practitioners know, what they don't know, and how they can become better stakeholders in energy optimization projects. Facilities staff understand technical systems. Collections staff understand preservation needs. Both groups lack sufficient knowledge of the other's domain. Both struggle with data analysis. Neither fully grasps how buildings, systems, collections, and energy interact as an integrated whole.

These knowledge gaps translate directly into the six challenges identified in section 3.3. The Climate2Preserv deliverables map to these challenges as integrated solutions:

- **The Handbook** addresses foundational knowledge gaps. It provides theory on buildings, systems, collections, and energy. It explains how these domains interact. It guides decision-making processes. The handbook tackles the "what you need to know" challenge.
- **CEAM** addresses analytical capacity gaps. Most institutions lack in-house expertise for complex data analysis. CEAM provides decision support with minimal data requirements. It delivers concrete predictions of energy savings. CEAM tackles the "how you analyze performance" challenge.
- **Templates and tools** address implementation gaps. Templates provide structure for measurement campaigns, facility documentation, and contractor communication. Templates tackle the "how you get started" challenge.

Together, these deliverables transform abstract knowledge into practical capability.

4.1. Climate2Preserv Handbook

Purpose and structure

The Climate2Preserv Handbook provides the complete methodology for energy optimization in cultural heritage institutions. It addresses the foundational knowledge gap: practitioners need to understand not just their own domain but also adjacent fields to make effective decisions.

The handbook can be used from start to finish or to address specific topics. Its structure follows three main sections:

1. C2P Protocol explains the overall methodology, helping users understand the protocol, materials, and decide between short-term/long-term or modular approaches.

2. Theory: Buildings, Systems, Collections, and Energy has two purposes. "Understand what you have" means reading the relevant chapter matching your expertise, but more importantly reading basics about allied fields. "Understand what you can do" means discovering options within your own field while considering impacts on allied fields, from maintenance to long-term measures. Each of these four chapters is written specifically for practitioners from other fields—

the collections chapter helps HVAC technicians understand preservation needs, while the buildings chapter helps conservators understand envelope performance.

3. Documentation and Data: Collection and Measurement covers basic rules for formulating research questions, documentation and data management, data collection, collecting spatial information on floor plans, and performing tests. It specifies required documentation, measurements, and equipment from essential to relevant for each domain (buildings, systems, collections, energy).

The handbook concludes with a **Glossary** providing standardized terminology across all four domains. Creating common vocabulary is essential for interdisciplinary collaboration. Terms familiar to engineers may be opaque to conservators and vice versa. The glossary bridges these language gaps, ensuring all team members can participate meaningfully in discussions.

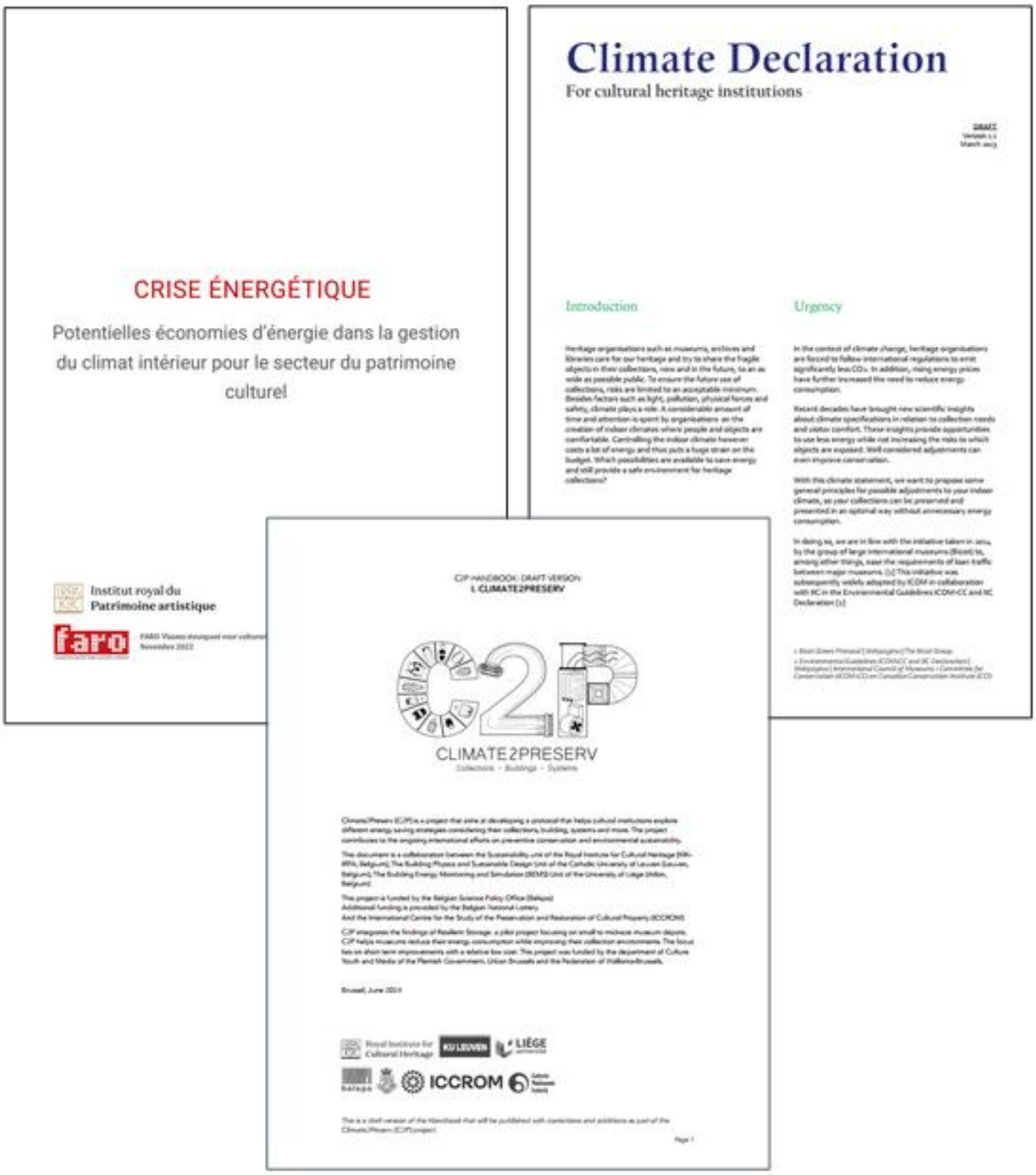


Fig. 7: The essential readings produced for the project.

Cross-disciplinary learning design

The handbook explicitly designs content for cross-disciplinary learning. Each theory section begins: "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."

The buildings chapter covers building physics fundamentals without assuming engineering training. The systems chapter introduces climate control and psychrometric principles with clear diagrams. The collections chapter provides risk assessment frameworks without assuming conservation training. The energy chapter introduces lifecycle analysis concepts.

Most importantly, each chapter emphasizes interconnections. Building envelope performance affects system efficiency and collection environments. System operation influences both energy consumption and preservation conditions. Collection requirements drive system design. Understanding these interconnections prevents unintended consequences.

Short-term versus long-term framework

The handbook structures interventions along two dimensions: time scale and domain. Short-term measures (immediate to 5 years) require minimal investment and are reversible: adjusting setpoints, optimizing schedules, improving maintenance, using passive strategies like display cases. Long-term measures (5 to 20+ years) require substantial investment and align with replacement cycles: envelope improvements, system replacement, major renovations.

This temporal framework helps institutions plan realistically. Short-term measures generate immediate savings and build confidence. Long-term measures require patience and coordination with building agencies.

Within each timescale, the handbook addresses all four domains (buildings, systems, collections, energy). This prevents optimizing one domain while creating problems in others.

Communication with external contractors

The handbook addresses contractor communication challenges directly. Relevant chapters can be shared with contractors to create common understanding. The buildings chapter includes "Professional communication: collaboration with specialists" explaining how to define needs, contact experts, and structure commissioning. The systems chapter similarly addresses contractor communication.

The handbook also explains typical contractor perspectives. Engineers accustomed to modern construction may not understand traditional building behavior. Maintenance contractors work within fixed schedules. Recognizing these realities helps institutions structure requests appropriately.

Data management capabilities

The Documentation and Data chapter provides practical guidance many institutions need: What should we measure? How should we organize data? What equipment do we need? How do we formulate research questions?

The handbook provides general rules about documentation and data management applicable across domains. It teaches formulating clear research questions before gathering information. It explains data collection principles including sensor placement, calibration, and recording frequencies. It provides detailed guidance on collecting spatial information on floor plans.

For each domain, the handbook specifies required documentation from essential to valuable. Building documentation includes plans and structural drawings. System documentation includes operational manuals and maintenance records. Collection documentation includes inventories and vulnerability assessments. The handbook rates each by importance and difficulty.

Usability and accessibility

The handbook deliberately avoids overly academic language while maintaining technical accuracy. Sentences are direct. Examples are concrete. Diagrams illustrate concepts visually.

The modular structure allows flexible usage. An institution starting short-term optimization can read Protocol, relevant Theory sections, and jump to Documentation and Analysis. An institution planning long-term renovation can focus on building and system chapters.

Published online with printable PDF format. We recognizes that some users prefer paper to digital.

4.2. CEAM: Collection Environment Assessment Model

→ **Input:** 3 CSV files - indoor climate + outdoor climate + energy data
→ **Perform analysis:** download software (windows) → prepare data files → select desired modules → run analysis → review results that are saved in a selected folder.
→ **How does it work:** data → data validation and visualisation (MOD 0-1) → primary calculations (MOD 2-4) → selecting AI model based on accuracy of prediction (DT, NN, LSTM) → Calculate potential energy savings (MOD 5)

Module 0 (Required): Data Overview Part 1
→ Validates your input files
→ Prepares data for analysis
Module 1 data overview part 2 - simple visual graphs of your climate/energy data
Module 2 correlation assessment - relationships between indoor/outdoor climate and energy
Module 3 energy signature - building energy performance overview
Module 4 climate classes - compares your conditions to ASHRAE standards
Module 5 energy optimization - AI calculates potential savings from different scenarios

Fig. 8: A simple overview of how CEAM works

Purpose and technical challenge

Heritage preservation typically requires restrictive indoor climate conditions, resulting in high energy consumption. CEAM addresses a critical gap: how to predict energy savings from less restrictive climate management without expensive building simulations or specialized expertise.

Museums need to answer: "If we relax temperature setpoints by 2°C, how much energy will we save?" Most institutions cannot answer this question. Building energy simulations require specialized software, detailed models, and expert knowledge. Meanwhile, institutions possess years of monitored data that remains underutilized.

CEAM was developed to deliver concrete results with limited data input. The software accepts three CSV files: Indoor Climate Data (temperature and relative humidity), Exterior Climate Data (temperature, humidity, optionally solar radiation), and Energy Data (consumption for heating D1, cooling D2, ventilation D3, humidification D4, total D5). The software supports hourly, daily, or monthly frequencies. More complete input yields more detailed output, but CEAM generates useful predictions even with incomplete data.

Modular structure and analytical methods

CEAM employs six modules providing comprehensive analysis:

- **Module 0: Data Overview Part 1** performs initial verification of input data, computing in 5-30 seconds. This generates graphical overviews across time scales (hourly, daily, monthly, extreme weeks). Users identify system malfunctions, consumption spikes, and data quality issues.
- **Module 1: Data Overview Part 2** provides additional visualization including extreme weeks (driest, most humid, coldest, warmest, sunniest weeks), helping understand building behavior under stress conditions.
- **Module 2: Correlation Assessment** examines relationships between climate parameters and energy consumption. The module generates correlation graphs for all parameter combinations, identifies which factors most strongly influence energy use, and selects best-performing correlations based on R^2 and Pearson coefficients.
- **Module 3: Energy Signature** applies traditional energy signature methods correlating energy consumption with climatic variables to represent actual building behavior and estimate baseload (non-weather-dependent consumption) and base temperature. CEAM employs multiple models: 2-parameter models for heating or cooling, 3-parameter models adding baseload, 4-parameter models with additional complexity, and a universal 5-parameter model for total consumption. The module automatically selects the most accurate model based on R^2.
- **Module 4: Climate Class Assessment** evaluates indoor climate against ASHRAE specifications using scatter plots and psychrometric charts. CEAM generates summaries detailing fulfillment duration for each climate class (AA, A1, A2, B, C, D). Assessment occurs for both historical conditions and proposed optimized conditions.
- **Module 5: Energy Optimization** employs Black-Box Modeling to predict energy savings. This represents CEAM's core innovation.

Black-box modeling approach

Energy optimization uses artificial intelligence to predict consumption under modified setpoints. The approach trains algorithms on historical data to understand relationships between climate and energy use. Trained models then predict savings from short-term climate management strategies.

CEAM employs multiple machine learning algorithms:

- **Neural Networks (NN)**: Feed-forward networks capturing non-linear relationships
- **Recurrent Neural Networks with LSTM**: Specialized for time-series data, capturing temporal dependencies
- **Recurrent Neural Networks with GRU**: Alternative RNN architecture, computationally efficient
- **Decision Tree Regression (DTR)**: Rule-based models, interpretable and robust

During training, the dataset splits: 70% for training, 15% for validation, 15% for testing. This prevents overfitting and ensures models generalize to new scenarios.

Different energy demands use different predictive variables. Heating (D1) correlates with temperature differences, solar radiation, and degree days. Cooling (D2) responds to dry-bulb/wet-bulb temperatures, solar radiation, and humidity. Humidification (D4) depends on absolute humidity differences. Total consumption (D5) integrates multiple factors. CEAM automatically selects appropriate variables based on demand and available data.

The optimization evaluates scenarios following ASHRAE specifications. Users test temperature offsets of ±2°C or ±5°C and humidity offsets of ±5% or ±10%, corresponding to relaxing from Class AA to Class A or B. CEAM generates predictions for multiple scenarios simultaneously.

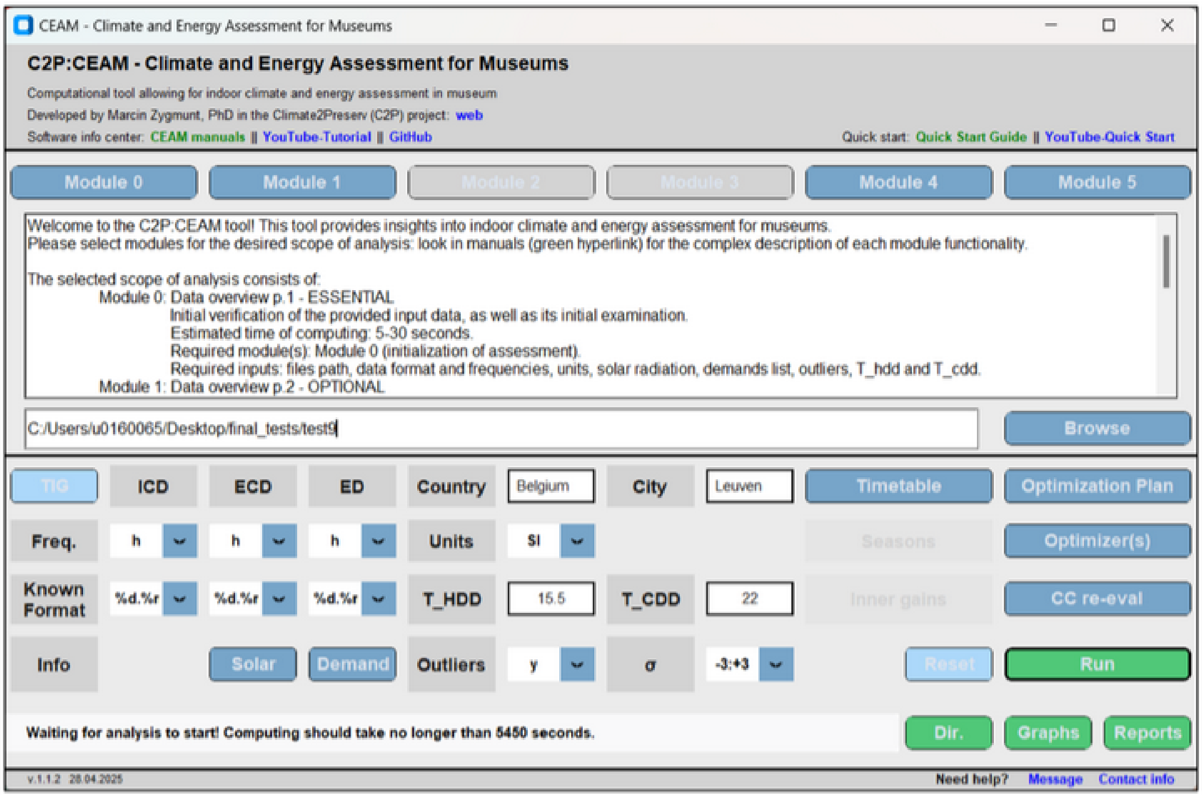


Fig. 9: The simple dashboard of the CEAM tool.

Results include estimated savings versus baseline, accuracy indicators (R^2, RMSE, MAE, CCC), graphical plots of predicted versus actual consumption, and tabular summaries for decision-making. The software generates both numerical outputs (energy predictions for different scenarios, percentage savings, statistical performance metrics) and visual results (time series plots showing consumption patterns, correlation scatter plots, energy signature curves with baseload and base temperature indicators, psychrometric charts for climate class assessment).

CEAM incorporates heating and cooling degree days as predictive parameters—these quantify heating or cooling demand based on outdoor temperature relative to base temperature (defaults 16°C for heating, 21°C for cooling, both adjustable). The energy signature module uses degree days explicitly while the optimization module incorporates them through temperature-based indices combining temperature and solar radiation effects.

Research validation showed CEAM predictions tend to underestimate savings compared to detailed simulations, providing conservative (safer) guidance.

ASHRAE climate class integration

CEAM's ASHRAE integration addresses a critical gap. ASHRAE Chapter 24 defines climate classes but applying specifications to real buildings requires interpretation. CEAM operationalizes climate classes by:

1. **Visualizing compliance**: Scatter plots and psychrometric charts show which data points fall within boundaries
2. **Quantifying fulfillment**: Percentage calculations show how often conditions meet requirements
3. **Comparing scenarios**: Side-by-side assessments show current versus optimized performance
4. **Linking to energy**: Direct connection between climate class relaxation and predicted savings

For example, a museum maintaining Class AA (RH ±5%, T ±2°C short-term) might discover Class A1 achievable with 15% energy savings and Class B with 30% savings. CEAM provides both energy prediction and climate verification in one analysis.

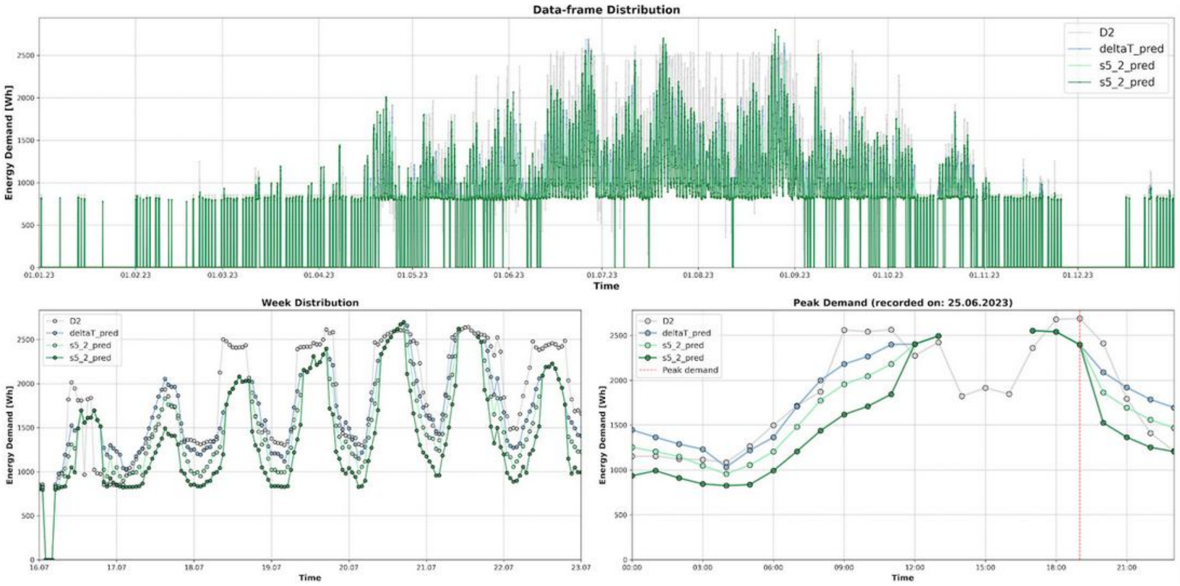


Fig. 10: The output (results) of module 5.

Validation and accuracy

Published validation using EnergyPlus simulations of a representative museum zone (192 m², 902 m³, complex HVAC) tested multiple scenarios: constant setpoints (21°C, 50% RH), flexible setpoints with ±2°C and ±5% RH offsets, and flexible setpoints with ±5°C and ±10% RH offsets, with and without dehumidification.

Neural Networks performed most accurately, particularly incorporating solar radiation. For total demand (D5), CEAM predictions closely matched EnergyPlus: predicted savings of 13-34% versus EnergyPlus estimates of 16-40%. Individual demands showed variable accuracy. Heating predictions were accurate or conservative. Cooling predictions posed greatest challenge due to year-round cooling needs. Humidity predictions consistently fell below EnergyPlus estimates but captured relative differences.

Importantly, CEAM's underestimation tendency provides safer guidance. Overestimating savings leads to disappointment or strategy rejection. Underestimating means implementations perform better than predicted, building confidence.

Practical application

CEAM transforms "How much energy will we save?" from unanswerable to answerable for most institutions. The software requires no specialized training beyond basic CSV preparation. Computing ranges from 5-30 seconds for data overview to several minutes for full optimization.

Users follow logical workflow: prepare input files, run Module 0 to verify data quality, run Modules 1-3 to understand current performance, run Module 4 to assess climate compliance, run Module 5 to predict savings, and compare scenarios. The modular structure means institutions use only relevant modules.

CEAM addresses the analytical capacity gap across the sector. Small institutions lacking technical staff generate professional-quality assessments. Large institutions perform rapid scenario testing without expensive consultants. Both use CEAM outputs to communicate with stakeholders using concrete numbers rather than vague promises.

4.3. Templates, practical tools, and the decision flowchart

Purpose and scope

Templates address the "getting started" barrier. Many institutions understand they need to optimize energy use but don't know where to begin. The Climate2Preserv templates and tools provide ready-to-use structures for common tasks, embodying best practices learned through case study work.

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

The poster serves as a visual decision-making tool answering the sector's most frequently asked question: how do I determine new setpoints for my institution that don't pose risk to my collections? The flowchart guides users through systematic assessment based on real collection risk in relation to budgetary means, technical staff capacity, building envelope performance, and outdoor climate.

The poster complements CEAM by focusing on the decision-making process itself while CEAM provides numerical predictions of potential savings. Together, they transform abstract concepts about climate relaxation into concrete, defensible strategies.

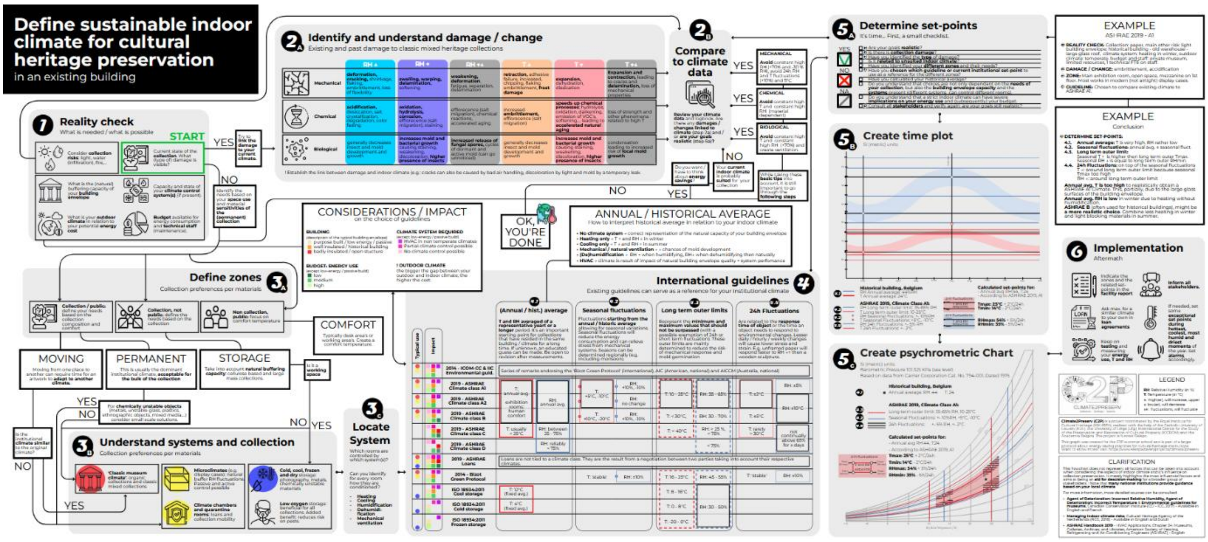


Fig. 11: Overview of the poster sized flow chart 'Define sustainable indoor climate for cultural heritage preservation in an existing building'.

Measurement plan template

The measurement plan template guides institutions through designing monitoring campaigns. The template prompts users to define research questions before selecting sensors. It provides structured format for documenting sensor types, locations, installation dates, measurement frequencies, calibration requirements, and responsible personnel.

The template prevents common mistakes: sensors installed without clear research questions generate data nobody analyzes; undocumented sensor locations make interpretation difficult months later; missing calibration records undermine reliability; unclear responsibilities lead to gaps when staff change.

Testing protocols

Testing protocol templates guide specific assessments: blower door testing for air leakage, thermography for envelope evaluation, system performance tests for HVAC efficiency, and indoor climate surveys for collection environment documentation.

Each protocol specifies required equipment, step-by-step procedures, safety considerations, data recording formats, and interpretation guidelines. They translate technical standards into accessible instructions.

Testing protocols particularly help institutions working with external specialists. Sharing protocol templates ensures aligned expectations, specifies deliverables and data formats, reducing miscommunication.

Integration with handbook sections

Where possible, templates and examples were integrated directly into the handbook rather than existing as separate documents. The handbook includes specific practical sections such as "how to determine your institutional setpoints" (integrated with the flowchart poster methodology), "sustainability of different energy carriers, distribution and emission systems" (providing comparative assessment frameworks), and "list of all energy optimization options from short to long term per theme" (organized by collection, building, systems, and energy domains). This integration means users access practical tools within the learning context rather than searching for separate resources.

Communication aids for contractors and commissioning

Communication templates bridge language gaps between preservation and technical professionals: system commissioning briefs, building assessment requests, maintenance schedule templates, and contractor briefing documents.

Particular emphasis will be placed on commissioning. the systematic process of ensuring building systems perform according to design intent and operational needs. Proper commissioning helps institutions reach sustainable agreements with external contractors by establishing clear expectations, verification procedures, and ongoing maintenance requirements at project outset. This prevents the common problem of systems installed without adequate understanding of heritage building constraints or collection requirements.

Integration with handbook and CEAM

Templates function as practical implementations of handbook guidance and CEAM inputs/outputs. The handbook teaches principles; templates provide structures. CEAM requires formatted data; measurement plans ensure compatible formats. CEAM generates predictions; facility reports include sections for documenting analyses.

This integration means institutions move smoothly from learning (handbook) through planning (templates and flowchart) to analysis (CEAM) without reformatting information.

4.4. Case study results and validation

KMSKB-MRBAB: System performance and ongoing analysis

Key question: How to measure energy consumption of complex climate control systems including separate functions (heating, ventilation, cooling)? How to estimate impact of proposed measures?

Key challenges: Setpoint changes require mindset changes; complex measurements and data analysis campaigns; external maintenance contracts; organizing tests in complex institutional structures.

The KMSKB-MRBAB Phase 3 case study focused on understanding energy consumption in complex HVAC systems. The team developed protocols for isolating energy consumption by function within integrated systems, requiring submetering on individual air handling units and tracking operating hours under different modes.

System complexity itself presented significant challenges. Documentation of modifications over decades was incomplete. Control logic had evolved organically as occupants requested adjustments. Different departments had different understandings of operations. Creating comprehensive system documentation became prerequisite for optimization analysis, a process that consumed substantial project time.

Due to the complexity of the required analysis and the hiring delay of Marcin Zygmunt (who joined in 2022), final analysis of over 1.5 years of measurements still needs to give conclusive results. The measurement campaign generated valuable data, but transforming that data into actionable recommendations requires sophisticated analysis accounting for the interactions between multiple air handling units, shared systems with the Royal Library of Belgium (KBR), and different environmental requirements across spaces (restoration workshops, exhibition rooms, offices, depots, archives).

Tests examining adjusted setpoints in specific areas showed some spaces could tolerate wider ranges without increased collection risk. However, institutional structure, building agency responsibility for systems, museum responsibility for collections, shared energy billing. complicated decision-making about implementing changes. This validated the stakeholder fragmentation challenge identified across the sector.

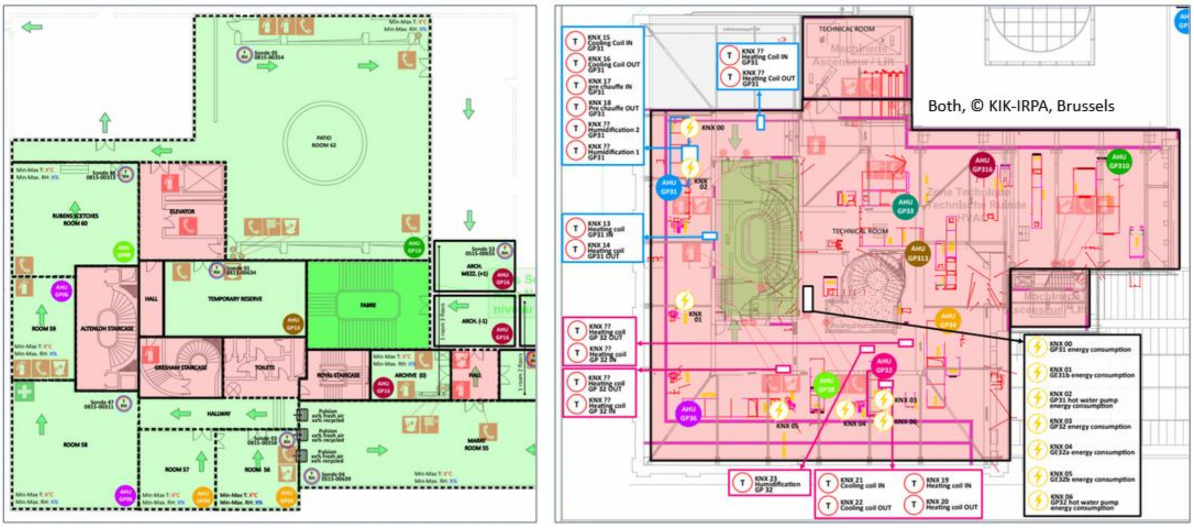


Fig. 12: (left) shows part of the 2nd floor of 'Phase 3' with various public and non-public spaces. These are controlled by air handling units. This plan also indicates which sensors are located in which rooms.
(right) shows the fourth floor, the location of the different air handling units and the complex measurements performed within these groups. Energy consumption for heating and cooling are measured separately here.

Wiertz Museum: Building envelope, collection analysis, and renovation complications

Key question: How to create a better collection environment while saving energy for a former artist studio housing large-format paintings?

Key challenges: Value-based analysis; inherently leaky building; high risks to collection overall (climate not the primary risk); changing space use; complex testing protocol.

The Wiertz Museum case study addressed multiple interconnected challenges. Light analysis and pigment analysis focusing on binding medium investigated whether light exposure (a significant risk) still impacts the "peintures mattes" or if decay has stagnated. Understanding this risk informs decisions about natural lighting through the large skylights.

The building experienced significant problems throughout the project. Major leakage occurred. Renovation of the neighboring building impacted the Wiertz structure substantially. Currently, major structural problems exist requiring comprehensive intervention.

Architecture firms Origin and Daidalos analyzed problems when the building agency seemed open to renovation. Analyses covered implementation of new roof structure and systems for multiple occupation scenarios: current museum use, future occupation by small groups (concerts, 50 people), and operation as event location (150 people) including catering facilities. The consequences for the building ranged from mild to significant, with the latter scenario resulting in a proposed new-build annex at the rear housing systems and fully equipped kitchen.

Fig. 13: Value based analysis performed by Origin.

The new roof structure provided several options to limit lighting while addressing thermal performance. Origin's proposition focused on values-based assessment of the building envelope. The initial study enabled a better understanding of the values at stake, including the importance of the overall character of the site and its historical evolution. It provided essential insights into what types of architectural interventions are possible, acceptable, and desirable without compromising the integrity of the place. Due to the building's character changes over time, insulating the facade (on the outside) was deemed possible to enhance thermal performance. However, this must coincide with roof renovation since the roof represents the source of major heat loss.

Comprehensive assessments included blower door testing, thermography, and long-term monitoring relating indoor climate to outdoor weather. Energy signature analysis demonstrated strong correlations between outdoor temperature and heating demand, with solar radiation through skylights significantly impacting cooling needs even in moderate weather.

The experience demonstrated that heritage building energy optimization occurs within broader contexts of structural stability, changing use patterns, and stakeholder negotiations. Energy analysis provides essential input but cannot proceed independently of these other concerns.

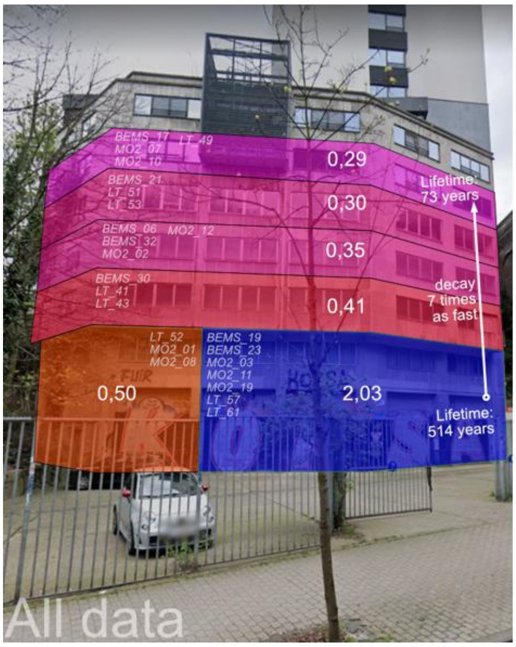
CINEMATEK: Unstable collection and building incompatibility

Key question: How to preserve an unstable collection in a building unsuited for energy-friendly cool/cold collection preservation?

Key challenges: Limited internal technical capacities; limited data available; short-term savings opportunities limited; collection management changes most viable approach.

The CINEMATEK case study addressed preserving chemically unstable acetate film collections in a former parking garage. The storage facility demonstrates extreme challenges: minimally adapted from original purpose, cooling provided only to lowest level with upper levels benefiting indirectly, no humidity control, limited insulation and ventilation.

Measurement campaigns documented dramatic condition variation by level. The cooled lowest level maintains moderate temperatures but humidity fluctuates seasonally. Upper levels experience temperatures and humidity approaching outdoor conditions during summer. Storage conditions fail to meet recommended preservation standards for this vulnerable material type, though cool storage (below typical museum temperatures) provides meaningful life extension compared to room temperature.



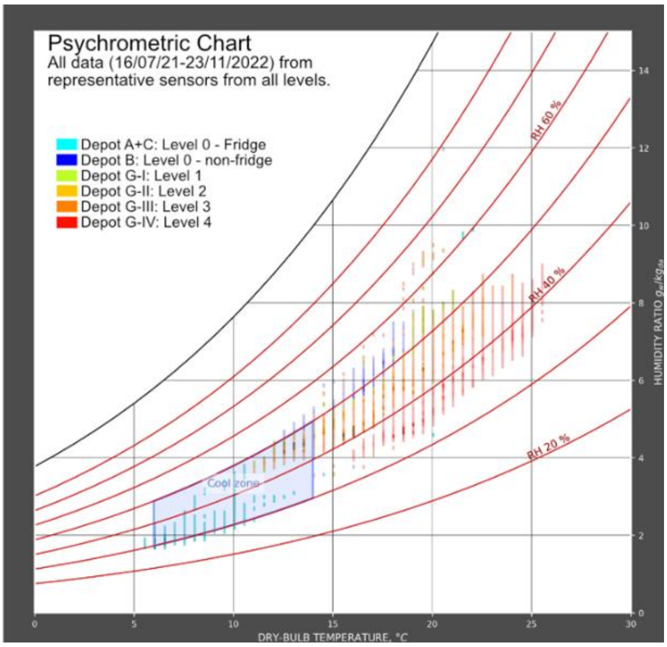


Fig. 14 and 15: (left) an overview of the collections theoretical lifetime based on the chemical decay of acetate film. (right) a psychrometric chart of the different depots and their climate compared to the desired (not optimal) 'cool' climate.

Analysis of A-D strip results (acid detection strips used to monitor acetate deterioration) over two measurement campaigns showed no significant acceleration of acetate decay during the monitoring period. Lifetime and relative lifetime calculations for objects in different rooms indicated lifespan of a new acetate film exceeding 500 years in the cooled room versus approximately 72 years in the warmer spaces. This significant difference demonstrates that cooling the entire collection should be the goal, possibly combined with selection based on value (partially already implemented).

Daidalos proposed building insulation improvements combined with short-term changes proposed by ULiège. However, the main issue remains fundamental building-collection incompatibility. The parking garage was never designed for long-term cool storage of vulnerable materials. Any optimization occurs within severe constraints.

Analysis of collection vulnerability versus actual conditions revealed pragmatic reality: ideal cold storage (below 5°C with low humidity) is not economically feasible for the entire collection in this building. Risk assessment focused on identifying which collection items face highest degradation risk under current conditions and prioritizing improvements for those materials. Some acetate film is stable enough to tolerate warmer storage. Highly degraded materials require coldest available space.

The case study validated that not every collection environment challenge has satisfactory energy optimization solution. Sometimes honest conclusion is that the building is inappropriate for the collection function, long-term solutions require major investment in different facilities, and interim strategies focus on risk management (prioritizing most vulnerable materials, accelerating digitization) rather than achieving optimal preservation conditions for everything.

Cross-case patterns

The case study key questions and challenges (summarized at beginning of each case description) reveal patterns validating the integrated approach. All three demonstrated that institutions need multiple deliverables rather than single comprehensive tool. They need foundational knowledge (handbook), analytical capability (CEAM), practical implementation guidance (templates and flowchart). They need flexibility to use different combinations based on project phase, institutional capacity, and specific challenges.

The case studies also revealed limits of what the project could address. Some challenges. particularly stakeholder fragmentation and value-based constraints. are persistent pain points requiring ongoing management rather than solvable problems.

4.5. Recommendations

For cultural heritage institutions

— **Communicate across organizational boundaries persistently.** Building agencies, collection managers, and facility operators all make decisions affecting energy and preservation. Maintain ongoing dialogue, share information, and seek opportunities for aligned interests even when organizational structures resist coordination. This is not optional. stakeholder fragmentation will prevent progress unless actively managed.

- **Build interdisciplinary teams early.** Energy optimization requires collaboration between collections, facilities, management, and often external specialists. Establish communication channels and shared vocabulary before crises force hasty decisions.
- **Start with documentation before measurements.** Comprehensive building, system, and collection documentation enables effective analysis. Gathering existing records and compiling information systematically provides foundation for subsequent work.
- **Choose systems matching your technical capacity.** Some institutions can handle complex systems, but this requires appropriate technical knowledge and budget. Well-maintained simple systems often outperform neglected complex systems. Regular maintenance, control optimization, and operations training generate savings with minimal investment. Select system complexity matching available expertise, not aspirational capabilities.
- **Accept wider climate specifications when appropriate.** Most collections tolerate broader ranges than institutions currently maintain. Use ASHRAE climate class frameworks and collection vulnerability assessments to identify realistic requirements.
- **Use measurement campaigns strategically.** Monitor to answer specific questions rather than collecting data indiscriminately. Formulate research questions, design measurement plans targeting those questions, and analyze data promptly.
- **Leverage natural system replacement cycles.** Plan long-term improvements to coincide with end-of-life replacements, building renovations, or space repurposing.

For policymakers and building agencies

- **Recognize heritage building constraints in energy mandates.** Standard energy efficiency requirements designed for modern construction often cannot be met by heritage buildings without unacceptable heritage impact. Develop alternative compliance pathways recognizing that heritage buildings achieve sustainability through longevity and adaptive reuse.
- **Support interdisciplinary training programs.** The shortage of professionals understanding both preservation, buildings, climate control systems and energy consumption creates implementation barriers. Fund training programs and professional development courses.
- **Facilitate building documentation digitization.** Historical building records are essential for energy analysis but often exist only as deteriorating paper in archives. Support systematic digitization and open access to building agency records.
- **Align building maintenance responsibilities with energy billing.** When building owners, system operators, and energy bill payers are different entities, optimizing becomes nearly impossible. Restructure responsibilities or create incentive structures aligning interests.
- **Fund pilot projects demonstrating feasibility.** Risk-averse institutions need proof that relaxing specifications won't damage collections. Support well-documented demonstration projects with rigorous monitoring.
- **Create dedicated funding for heritage building energy optimization.** Standard energy efficiency programs focus on quickly achievable reductions. Heritage buildings require longer timelines, value-based analysis, and specialized expertise.

For research community

- **Develop simplified assessment methods for small institutions.** CEAM requires data most large institutions possess but small institutions lack. Research accessible monitoring approaches and simplified models enabling resource-limited institutions to benefit from optimization frameworks.
- **Expand validation across building types and climates.** Current validation uses simulation and limited case studies in temperate climates. Test CEAM and handbook approaches across diverse contexts: hot-humid regions, cold climates, different heritage building typologies, and varied collection types.
- **Investigate cooling demand modeling challenges.** As demonstrated in the validation studies, cooling demand (D2) predictions posed the greatest challenge. Due to HVAC system complexity in buildings with year-round cooling needs regardless of season or climate conditions, CEAM struggled to identify accurate cooling demand patterns influenced by various climate factors. Research improved modeling techniques for this specific challenge or develop alternative assessment approaches.
- **Study long-term outcomes of climate relaxation.** While short-term studies show no increased degradation risk from relaxed setpoints, long-term validation (decades) is needed. Support multi-institutional monitoring programs tracking collection condition in various climate regimes.
- **Research the impact of visitors on indoor climate.** Visitor presence affects both temperature and humidity through metabolic heat and moisture release, and CO2 levels through respiration. Integrate CO2 measurements as visitor counting proxies. Investigate how occupancy patterns influence energy consumption and whether visitor comfort requirements conflict with collection preservation and energy efficiency goals.
- **Investigate stakeholder governance models.** The stakeholder fragmentation challenge appears structural across many countries. Research governance models successfully aligning building owner, operator, and occupant interests. Identify policy interventions or contractual structures improving coordination.

4.6. Future developments

CEAM enhancements

Future CEAM development will address identified limitations. As noted in validation studies, cooling demand prediction in complex systems with year-round cooling needs poses persistent challenges. Research will test alternative machine learning architectures or hybrid approaches combining physical models with data-driven predictions to improve accuracy for this specific demand type.

Integration of visitor thermal comfort assessment will expand CEAM's decision support scope. Current analysis focuses only on collection preservation and energy consumption. Adding visitor comfort evaluation enables institutions to balance competing priorities explicitly. This requires comfort model integration, survey protocols, and multi-objective optimization frameworks.

Expanded validation using real case study data will strengthen confidence in predictions. Initial validation used EnergyPlus simulations providing controlled comparisons. Validation with actual museum buildings introduces real-world complexities (incomplete data, unknown system behaviors, measurement uncertainties). The KMSKB-MRBAB analysis, once completed, will provide crucial real-world validation.

Enhanced uncertainty quantification will help users understand prediction reliability. Current accuracy indicators (R^2, RMSE) show model fit but don't convey confidence intervals or sensitivity to input data quality. Probabilistic approaches providing prediction ranges would support better-informed decision-making.

Parametric analysis capabilities will allow systematic exploration of multiple variables. Current CEAM analyzes user-specified scenarios. Future versions could automatically generate and evaluate comprehensive scenario sets, identifying optimal strategies considering multiple objectives.

Case study follow-up

The project will provide feedback and more comprehensive reports to case study participants. While measurement campaigns and analyses have been conducted, final reports synthesizing all findings. These reports will consolidate data collection, testing protocols, and optimization analyses into actionable guidance tailored to each institution's specific context and constraints.

Handbook publication and professional training

The handbook requires additional funding for professional publication. All chapters are complete. The focus will be using the handbook as guideline for training courses, particularly targeting facilities personnel. Facility managers in heritage buildings need specialized knowledge beyond standard building operations training. Developing courses specifically for this audience, covering preservation principles, heritage building physics, and collection environment requirements, would build sector capacity.

The handbook serves as comprehensive reference and teaching tool. Professional publication ensures quality editing, clear graphics, accessible formatting. Training programs built around the handbook transform written knowledge into practical skills through exercises, case discussions, and hands-on applications.

Template expansion: facility reports and loan agreements

Template development will focus specifically on facility reports and loan agreements. Since these documents consist of well-defined sections, systematic improvement is feasible.

For facility reports, each section will be examined to identify opportunities for presenting more sustainable options and encouraging honest documentation. The emphasis is transparency: building agencies benefit from understanding actual conditions rather than receiving information only when problems become crises. Templates will structure straightforward, complete documentation enabling productive long-term planning rather than emergency responses.

For loan agreements, each section will be revised to incorporate current conservation science on climate specifications. Many loan agreements still mandate obsolete constant setpoints. Template revisions will continue to use international climate class frameworks, explain why these provide adequate protection, and standardize language facilitating negotiation about sustainable options between lenders and borrowers.

Additionally, commissioning will receive greater emphasis. Commissioning templates and protocols help institutions reach sustainable agreements with external contractors by establishing clear expectations, verification procedures, and ongoing maintenance requirements from project start. This prevents common problems where systems are installed without adequate understanding of heritage constraints or preservation requirements.

The goal is to establish a network of international professionals to guide the template development process. Once templates are finalized, relevant committees and institutions (ICOM, ICCROM, and others) will be asked to endorse them, lending authority and encouraging sector-wide adoption. International endorsement from major conservation organizations will help lenders and borrowers negotiate from shared standards rather than institutional preferences.

Sector-wide initiatives

Energy savings training for facility managers addresses persistent need across the sector. Courses tailored to heritage building context would build capacity more effectively than generic building operations training. Collaborative development with professional organizations ensures training reaches target audiences and maintains relevance to real operational challenges.

Collaborative benchmarking networks would enable institutions to compare performance anonymously and share strategies. Building trust frameworks for data sharing allows institutions to assess performance relative to peers without exposing sensitive institutional information. This reveals improvement opportunities and validates that challenges are sector-wide rather than institution-specific.

Honest facility reporting collaboration with building agencies needs diplomatic advocacy. Cultural change enabling routine transparent communication requires building trust over time. Recognition programs celebrating productive agency-occupant partnerships could demonstrate benefits and encourage broader adoption.

Climate Declaration follow-up implementation needs sustained momentum. The Declaration established principles; translating principles into widespread practice requires continued engagement through workshops, case study documentation, and recognition of early adopters.

The fundamental question remains: how do cultural heritage institutions preserve collections responsibly while contributing to climate change mitigation? Climate2Preserv demonstrated that energy optimization and collection preservation are compatible goals when approached systematically with appropriate knowledge, tools, and institutional commitment. The deliverables provide means. Sector adoption requires sustained effort building on this foundation.

5. DISSEMINATION AND VALORISATION

Introduction: Targeting key stakeholder groups

Climate2Preserv dissemination strategically targeted two primary stakeholder groups: facilities professionals and collections professionals. These groups work in parallel within heritage institutions but often lack shared vocabulary and understanding of each other's constraints. Energy optimization requires both groups to collaborate effectively.

Dissemination activities distinguished between Federal Scientific Institutions (FSIs) and small to medium-sized museums. FSIs possess greater technical capacity, larger staffs, and more complex building systems but face unique challenges including stakeholder fragmentation between building agencies, facility operators, and collection managers. Small to medium museums typically lack in-house technical expertise and operate with limited resources, requiring simplified approaches and external support networks.

The valorisation strategy combined training programs, publications, conference presentations, guest lectures, and community building initiatives. Each activity reinforced others, creating comprehensive support system for sector transformation.

Essential project contributors

Project core team

- Annelies Cosaert (KIK-IRPA): Follow-up coordinator, collection-based research, handbook coordination and author
- Estelle De Bruyn (KIK-IRPA): Initial coordinator, administration and financial responsibility, sector network engagement
- Marcin Zygmunt (KU Leuven): CEAM software development, handbook author, building-related research
- Sebastien Thomas (University of Liège): Case study measurements and analysis, handbook author, systems and energy research

Partner institution contributors:

- Geert Bauwens (KU Leuven): Building physics expertise, CHARP technical architecture
- Philippe André (University of Liège): Coordination ULiège, teacher Summer School, HVAC systems analysis, energy optimization strategies
- Staf Roels (KU Leuven): Coordination KUL, building performance assessment, hygrothermal modeling

Architecture and engineering consultants:

- Erik Hendrickx and Cécile Mairy (Origin Architecture & Engineering): Wiertz Museum building analysis, envelope assessment, renovation scenarios
- Filip Descamps (Daidalos Peutz): Building physics consultancy, thermography, energy simulations

Follow-up Committee members, providing advices on the project progresses and outputs

- Ann Deckers (FOMU Antwerp)
- Céline Gustin (Belgian Federal Building Agency)
- Eric Hagan (Canadian Conservation Institute)
- Bhavesh Shah (V&A Museum, UK)
- Roald Hayen (KIK-IRPA, Monuments Laboratory)

These contributors brought complementary expertise enabling the integrated approach addressing buildings, systems, collections, and energy simultaneously.

5.1. Training and knowledge transfer

Summer School 2024: Brussels

The international Summer School took place July 1-12, 2024, at KIK-IRPA in Brussels. Co-organized with ICCROM with Academia Belgica support, the two-week intensive course brought together 20 participants from 10 institutions representing diverse contexts and professional backgrounds.

The program structure integrated theory, practical exercises, case study visits, and tool applications across five thematic days covering Collections, Systems, Buildings, and Energy. Participants worked in interdisciplinary teams, reflecting the cross-departmental collaboration essential for successful implementation.

Participants were facilities and collections experts from: Catholic University of Leuven, Belgium; Reinwardt Academie, Netherlands; Museu Nacional d'Art de Catalunya, Spain; Canadian Conservation Institute / Queen's University, Canada; Musée du Louvre, France; Fotomuseum, Belgium; Musée d'Ethnographie de Genève, Switzerland and M Leuven, Belgium.

Pedagogical approach emphasized facilitation skills, enabling participants to navigate institutional negotiations upon return. Role-playing exercises prepared teams for stakeholder discussions involving conflicting priorities. Participants applied C2P Protocol, flowchart poster, and CEAM software to real institutional contexts, generating concrete implementation plans.

Guest lectures and curriculum integration

Project partners delivered guest lectures at universities, transferring methodology knowledge to emerging professionals:

University of Antwerp: Guest lectures on collection environment analysis for conservation students (Annelies Cosaert, 2022, 2023, 2025)

5.2. Publications and academic dissemination

Project results generated substantial academic and professional output ensuring research findings contribute to conservation science and building engineering literature. Check the publication section for references.

Publications reached diverse audiences including conservators, building engineers, sustainability consultants, and heritage policy professionals.

		Collections	Systems	Buildings	Energy
	DAY 1 10/07/2023	DAY 2 11/07/2023	DAY 3 12/07/2023	DAY 4 13/07/2023	DAY 5 14/07/2023
09:00	Intro / Welcome *Estelle De Bruyn, Annelies Cosaert*	Collection environments basics *Names*	HVAC basics *Names*	Building envelope basics *Names*	Energy sources and energy savings basics *Names*
09:30	Participants present themselves and their institution as a duo (15 min each)				
10:30		Break	Break	Break	Break
11:00	*Names*	Introducing tools: CHARP, EMS and other T and RH analysis tools. *Names*	Introducing tools: Energy ID and RETscreen (?) *Names*	Introducing tools: Energy ID and Retscreen (?) *Names*	Group exercise: Visualize energy consumption *Names*
12:30	Lunch	Lunch	Lunch	Lunch	Lunch
13:30	Project intro: C2P, Sustainability, handbook *Names*	Group exercise: collecting and understanding collection information *Names*	Group exercise: collecting and understanding HVAC Information *Names*	Group exercise: collecting and understanding building envelope Information *Names*	Heading for and visiting KMSKB: museums and systems
15:00	Break	Break	Break	Break	
15:30 (- 17:00)	Presenting the Case-Study: KIK-IRPA *Names*	Presenting your findings to the group (15 min per group) + Q and A *Names*	Presenting your findings to the group (15 min per group) + Q and A *Names*	Presenting your findings to the group (15 min per group) + Q and A *Names*	*Names*
					Drink in center of Brussels (17:00h)

	DAY 6 17/07/2023	DAY 7 18/07/2023	DAY 8 19/07/2023	DAY 9 20/07/2023	DAY 10 21/07/2023
09:00	Speed dating: what have we learned *Names*	Collection based short and long term energy savings *Names*	Building envelope based short and long term strategies for energy savings *Names*	Communication, stakeholders and leadership: making sure your plans are heard *Names*	Volunteer catch-up for questions around tools *Names*
10:30	Break	Break	Break	Break	Break
11:00	Focus on constraints: value, budget, staff, time, visitor (comfort), mission *Names*	System based short and long term strategies for energy savings *Names*	Group exercise: weiging descisions. Work with tools: cost - benefit - implications *Names*	Group exercise, roleplay: uniting different interests. Goal oriented diplomacy *Names*	Institutional exercise: making your battle plan. Creating a team and indentifying stakeholders *Names*
12:30	Lunch	Lunch	Lunch	Lunch	Lunch
13:30	Group exercise: Identifying influencial factors *Names*	Visiting Cinematek: short term and long term aspirations	Group exercise: weiging descisions. Developing 2 possible strategies for energy savings *Names*	Presenting common plan (for KIK-IRPA) to stakeholders as a team *Names*	Presenting your institutional plan to the group (20 min)
15:00	Heading for the Wiertz Museum		Break	Ending of day	
15:30 (- 17:00)	Visiting the Wiertz Museum: value set bounderies *Names*	*Names*	Presenting your findings to the group (20 - 30 min per group) *Names*	Volunteer catch-up for questions around tools *Names*	Presenting your institutional plan to the group (20 min) *Names*
				Dinner (19:00h)	

DECISION MAKING

Fig. 16: Schedule of the summer school courses.

5.3. Conference presentations and symposia

Project partners delivered presentations at major international and national venues:

International conferences:

- ICOM-CC 19th Triennial Conference (Beijing, 2021): Annelies Cosaert, Vincent Beltran (presentation)
- International Conference on Collection Care (Valencia, 2021): Annelies Cosaert, Geert Bauwens, Estelle De Bruyn (presentation)
- Getty Conservation Institute workshops (Los Angeles, 2020; Brussels, 2022): Annelies Cosaert, Vincent Beltran (co-organization and teaching)
- ICOM-CC 20th Triennial Conference (Valencia, 2023): Annelies Cosaert (presentation)
- 3rd International Symposium on Museum Environmental Science (Beijing, 2025): Annelies Cosaert, Bhavesh Shah (presentation)
- International Building Physics Conference (Toronto, 2024): Marcin Zygmunt, Staf Roels, Geert Bauwens (presentation)
- 19th IBPSA Conference (Brisbane, 2025): Marcin Zygmunt, Staf Roels (presentation)

National and regional symposia:

- WTA VL-NL Conference on Building Renovation and Monument Care (Netherlands, 2024): Annelies Cosaert, Sebastien Thomas, Marcin Zygmunt (presentation)
- Samlingsforum: Sustainable Collection Management in Practice (Stockholm, 2023): Estelle De Bruyn, Annelies Cosaert (workshop)
- Bevaringstenestene Annual Seminar (Bergen, Norway, 2023): Estelle De Bruyn, Annelies Cosaert (presentation)
- Calouste Gulbenkian Museum Conference on Sustainable Heritage (Lisbon, 2023): Estelle De Bruyn, Annelies Cosaert (presentation)
- Brussels Museums Study Day on Museum Storage (Brussels, 2022): Annelies Cosaert, Estelle De Bruyn (presentation)
- Symposium Slim Geregeld: Indoor Climate Developments (Eindhoven, 2022): Annelies Cosaert, Estelle De Bruyn (presentation)

Presentations established Climate2Preserv methodology within broader heritage sustainability discourse across Europe and internationally.

5.4. Community building and sector initiatives

Climate Declaration

The Climate Declaration represents major policy translation effort developed collaboratively with the Dutch Cultural Heritage Agency (Rijksdienst voor het Cultureel Erfgoed). The Declaration translates international guidelines on sustainable heritage management to Belgian context, providing practical guidance informed by Climate2Preserv research.

Published in French, Dutch, and English, the Declaration was circulated to Belgian museums and Federal Scientific Institutions for voluntary signature. The signing process created public institutional commitment to sustainable practices and established community of practice among participating organizations.

Follow-up to the Declaration included three concrete recommendations accepted by Belspo directorate:

1. Share Climate Declaration materials with Building Agency (Regie der Gebouwen)
2. Organize training sessions on facilities, collections, and climate for FSI staff
3. Analyze indoor climate data collected by FSIs to identify challenges and communicate findings to Building Agency

Energy Crisis guidance document

During the 2022-2023 energy crisis, the project rapidly produced practical guidance on short- and medium-term energy-saving measures. This document focused on actions institutions could implement quickly to reduce consumption during crisis conditions.

The guidance was organized by type of climate control system, acknowledging that optimization strategies differ substantially between institutions with sophisticated HVAC systems, those with basic heating only, and those with minimal climate control. Recommendations balanced energy reduction with collection risk management.

Developed in collaboration with FARO, Monumentwacht, Dutch Cultural Heritage Agency, engineering firm Ingenium, and several Belgian museums, the guidance was widely distributed through heritage networks and demonstrated Climate2Preserv's responsiveness to urgent sector needs.

NEMO and international network engagement

Project partners actively engaged with Network of European Museum Organisations (NEMO), participating in workshops and conferences on museum sustainability. Annelies Cosaert delivered workshops at NEMO events in Slovenia (2024) and Romania (2024), introducing C2P methodology to broader European museum networks.

These engagements connected Climate2Preserv to parallel European initiatives on heritage sustainability, enabling knowledge exchange and identifying opportunities for collaborative development. NEMO's broad membership provided dissemination channel reaching museums across Europe beyond direct project contact.

ICCROM Our Collections Matter initiative

Integration with ICCROM's Our Collections Matter (OCM) platform extended project reach to global audiences. OCM compiles methods and tools for sustainable collection management, providing framework for international heritage institutions. Climate2Preserv methodology integration into OCM ensures visibility among ICCROM's international network.

Annelies Cosaert served as ICCROM Visiting Researcher (2022), facilitating OCM integration and presenting Climate2Preserv to ICCROM staff and partners. This collaboration established ongoing relationship supporting continued international dissemination. The C2P materials will be integrated on the OCM platform.

5.5. Digital dissemination

Open-source software and documentation

CEAM software is publicly available through GitHub repository, providing both user-ready versions and complete source code for technically capable institutions. Open-source approach promotes transparency, enables peer review, and facilitates adaptation to diverse contexts.

Project website and online resources

The Climate2Preserv website (hosted by KIK-IRPA) serves as central access point for all project deliverables: handbook, CEAM software, flowchart poster, templates, and documentation. Users access resources directly without registration barriers.

Project information and deliverables were also disseminated through partner institutional websites (KU Leuven, University of Liège, ICCROM), ensuring multiple access pathways and reinforcing institutional commitments.

5.6. Continuing dissemination

Dissemination continues beyond formal project conclusion. Project overview presentations are scheduled for several international conferences, maintaining momentum and reaching new audiences. Partner institutions continue networking through professional organizations, conferences, and collaborative projects.

The handbook and associated materials will continue to evolve as partners develop additional content based on implementation feedback and emerging research. CEAM software will receive ongoing maintenance and feature enhancements based on user needs.

All project deliverables remain accessible through the Climate2Preserv website, ensuring long-term availability supporting sector capacity building. Partner institutions maintain commitment to methodology promotion through teaching, consulting, and continued research, extending project impact far beyond formal conclusion.

6. PUBLICATIONS

Peer-reviewed publications:

- Zygmunt, M., Roels, S. (2025). Optimizing indoor environment and energy consumption in a museum building using specialized data-driven software. Proceedings of the 19th IBPSA Conference, Brisbane.
- Beltran, V., Linden, J., Cosaert, A. (2025). Developing Conservation-Focused Curriculum to Advance Analysis of Temperature and Relative Humidity Data. Springer Proceedings in Archeology and Heritage.
- Cosaert, A., Bauwens, G., De Bruyn, E. (2025). Enhance Performance and Reduce Energy Use in Storage Areas: Two Belgian Case Studies. Springer Proceedings in Archeology and Heritage.
- Cosaert, A., Shah, B. (2025). Preserving for Eternity, Coding for Today: The Role of Pseudo-Developers in Cultural Heritage Institutions. 3rd Symposium on Museum Environmental Science, National Museum of China.
- Zygmunt, M., Roels, S., Bauwens, G. (2024). Grey-box models for optimal heritage preservation. International Building Physics Conference, Toronto.
- Cosaert, A., Gerard, R., Deparis, O., Mayer, A. (2023). A Comparison of Preservation Metrics Expressing Mechanical, Chemical and Biological Damage. ICOM-CC 20th Triennial Conference Preprints, Valencia.
- Cosaert, A., Beltran, V.L. (2021). Comparison of Temperature and Relative Humidity Analysis Tools to Address Practitioner Needs and Improve Decision-Making. ICOM-CC 19th Triennial Conference Preprints, Beijing.

Research reports and professional publications:

- Cosaert, A., Thomas, S., Zygmunt, M. (2024). Energy Savings for Collection Care Institutions: Climate System Choice and Collection Policy in Line with Museum Policy. WTA VL-NL Conference Proceedings.
- Cosaert, A., Beltran, V.L., Bauwens, G., King, M., Napolitano, R., Shah, B., Wickens, J. (2022). Tools for the Analysis of Collection Environments: Lessons Learned and Future Development. Research Report. Getty Conservation Institute.
- Cosaert, A., De Bruyn, E. (2021). Climate2Preserv and Resilient Storage, Towards a Happy Marriage Between Energy Reduction and Adequate Collection Environments. Bulletin BRK-APROA.
- De Bruyn, E. (2020). The Sustainable Storage Space, Methodology for the Management of Small Cultural Institutions. Conservation-restauration des biens culturels (CRBC).

7. ACKNOWLEDGEMENTS

Climate2Preserv owes its success to the exceptional collaboration, dedication, and expertise of numerous individuals and institutions. The project benefited from sustained support and active engagement throughout its four-year duration.

Case study partners

The project's foundation rests on the generous collaboration of three Belgian Federal Scientific Institutions that opened their buildings, collections, and operations to intensive study. These partnerships transformed theoretical methodology into practical, validated tools.

Royal Museums of Fine Arts of Belgium (KMSKB-MRBAB), including the Wiertz Museum, provided two complementary case studies. Maarten Lousbergh (Facility Manager), Yves Vandeven (Facility & Security), Liesbeth De Belie (Conservation Manager), and Davy Depelchin (technical coordination) dedicated significant time coordinating measurements, facilitating access, and testing optimization protocols. Their openness to examining system performance and building limitations honestly enabled realistic methodology development.

CINEMATEK, the Royal Belgian Film Archive, confronted fundamental incompatibility between collection requirements and building capacity. Tomas Leyers, Victor De Vocht, Marjolijn Barbier, Bobbie Noe, and Bruno Mestdagh provided unrestricted access and participated honestly in discussions about building limitations and value-based prioritization. Their transparency enabled development of guidance for institutions facing impossible choices.

These partnerships required institutional trust, staff time, and willingness to examine uncomfortable truths. The insights gained transformed abstract methodology into field-tested practical guidance.

Research and academic partners

- **KU Leuven** provided building physics and energy modeling expertise. Geert Bauwens led CEAM technical architecture, Marcin Zygmunt developed grey-box modeling and handbook building content, and Staf Roels contributed building performance assessment expertise.
- **University of Liège** contributed HVAC systems analysis. Philippe André provided systems expertise, Sebastien Thomas led case study measurements and testing protocols, and Claude Scheuren provided technical coordination.
- **ICCROM** brought international perspective and pedagogical expertise. José Luiz Pedersoli Junior collaborated on Summer School design and connected Climate2Preserv to Our Collections Matter initiative. **Academia Belgica** provided a venue for the work at ICCROM

Architecture and engineering consultants

Origin Architecture & Engineering (Erik Hendrickx and Cécile Mairy) conducted building envelope analysis for Wiertz Museum. **Daidalos Peutz** (Filip Descamps) provided building physics consultancy, thermography, and energy simulations.

Follow-up Committee

The Follow-up Committee provided strategic guidance and critical feedback through annual meetings, case study visits, and deliverable reviews:

- **Ann Deckers** (FOMU Antwerp)
- **Céline Gustin** (Belgian Federal Building Agency)
- **Eric Hagan** (Canadian Conservation Institute)
- **Bhavesh Shah** (V&A Museum, UK)
- **Roald Hayen** (KIK-IRPA, Monuments Laboratory)

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- **KIK-IRPA** provided institutional home, administrative support, and preventive conservation expertise. Henri Pierard developed Python code for data analysis. Camille De Clercq and Céderic Doutrelepont contributed to Summer School organization.

Sector networks and collaborators

Sector organizations facilitated dissemination and provided feedback: **FARO**, **Musées & Société en Wallonie**, **ICOM Belgium Flanders**, **ICOM Belgium Wallonie-Bruxelles**, **Brussels Museums**, **Dutch Cultural Heritage Agency** (Bart Ankersmit and Marc Stappers, Climate Declaration partnership), **Getty Conservation Institute** (collaborative tool development), and **Network of European Museum Organisations (NEMO)**.

International network

Summer School participants from 10 institutions tested methodology and will extend impact through implementation: Catholic University of Leuven (Belgium), Reinwardt Academie (Netherlands), Museu Nacional d'Art de Catalunya (Spain), Canadian Conservation Institute / Queen's University (Canada), Musée du Louvre (France), Fotomuseum (Belgium), Musée d'Ethnographie de Genève (Switzerland), M Leuven (Belgium), and Musée des Beaux-Arts de Bordeaux (France).

Additional contributors

Additional contributors: **Vincent Laudato Beltran** (Getty Conservation Institute, collaborative tool development and teaching), **Michał Łukomski** (Getty Conservation Institute, monitoring research), **Renaud Gérard** (UNamur, intern for preservation metrics research), and **Simon Lambert** (Canadian Conservation Institute).

Closing acknowledgement

Climate2Preserv succeeded because institutions and individuals embraced the challenging premise that heritage preservation and environmental sustainability need no conflict. The case study partners' willingness to examine their facilities critically, the committee's constructive feedback, and the network's engagement transformed research into practical guidance. The

project represents collective wisdom, and its lasting contribution will be measured in the institutions that find courage to optimize energy use while protecting collections.

8. ANNEXES

DELIVERABLES

A. Handbook and glossary
B. C2P manual, download and GitHub link
C. Poster
D. Testing template
E. Measurement template

OTHER

F. Climate declaration
G. Energy crisis document
H. Data management plan
I. Bibliography