FINAL REPORT

Smart control: new methods for climate control and impact assessment

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PREFACE

Spara och bevara (Save and preserve) is a research and development programme initiated by the Swedish Energy Agency to increase knowledge about energy efficiency in culturally and historically valuable buildings. The programme aims to develop and disseminate knowledge and technical solutions that contribute to improved energy efficiency in these buildings without damaging or altering their historic values or furnishings.

This careful approach to energy efficiency is to be achieved through interdisciplinary collaboration, where technology meets conservation. The goal is to establish a lasting knowledge base in the field of energy efficiency in culturally and historically valuable buildings, and to contribute to the long-term, sustainable management of the older building stock.

The programme is coordinated by Uppsala University.

This report presents the project’s results and conclusions. Publication does not imply that the Swedish Energy Agency or Uppsala University endorses the conclusions, results, or any opinions expressed.

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ABSTRACT

In historic buildings, indoor climate control is a relatively simple energy efficiency measure that should be considered before major and more intrusive measures are implemented. Smart indoor climate control not only saves energy, it also facilitates long term preservation of building and interiors. The overarching aim of this projects was to lay the ground for an integrated and sustainable approach to indoor climate control in historic buildings. This involved interdisciplinary collaboration in four intertwined fields: Monitoring and risk assessment, building simulations, machine learning and climate control.

The main outcome of the project was to develop and demonstrate a practically useful method for impact assessment based on a combination of monitoring, simulations, risk assessment and machine learning. Using this method, the project demonstrates how smarter control of the indoor climate can provide lower energy and power requirements as well as retained or improved comfort. More specifically, the project has delivered:

- Guidelines för risk assessment
- A method to use building simulations for impact assessment and smart control
- Methods to use machine learning to optimize climate control
- Novel control strategies and prototype for a control unit

The guidelines för monitoring and risk assessment provide knowledge and know-how knowledge about monitoring options for buildings, with an emphasis on showing what different methods can contribute in practice. Machine learning can be applied in multiple, practical ways to minimize risk in historic buildings and optimize climate control strategies. The case study has verified the technical function of the control unit. Potentially it could be further developed to a commercial product as it adds several novel aspects beyond the state of the art.

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1. INTRODUCTION AND BACKGROUND

1.1 BACKGROUND

The existing building stock is facing an increasing pressure for adaptation caused by a complex combination of energy targets, climate change and increasing demands for comfort, including cooling. These changes will together affect the indoor climate and the hygrothermal balance of the buildings. Historic buildings are often considered to be resilient, but these buildings were not constructed with the new conditions in mind. Even though this is a global problem, risks and responses are specific to the local context, and have to be identified and quantified in order to facilitate an informed decision making. If we learn from the past and prepare for the future, older buildings will get smarter.

When it comes to reducing energy and power requirements as well as improving the indoor climate in historic buildings, indoor climate control is often a relatively simple measure that should be considered before major and more intrusive measures are implemented. Indoor climate control can be carried out through active measures (using technical equipment) or passive measures that utilize the hygrothermal buffering capacity of the building envelope.

The fundamental challenge for this project is to find a balance between society's goals and aspirations in terms of energy transition on the one hand and the long-term preservation of historic buildings on the other hand. Understanding the building envelope and the humidity sensitive materials as a physical system is fundamentally necessary to facilitate an effective management of historical buildings. This understanding will allow both to mitigate risks and maintaining high preservation standards when adapting for future demands.

Indoor climate control in historic buildings received a lot of attention in several projects during the first two stages of Spara och bevara [1]. The research was focused mainly on monumental buildings with none or limited demand for comfort. The European project, Climate for Culture, dealt with effects of climate change on the indoor climate in historic buildings resulting in a systematic approach for quantitative risk assessment both for individual buildings and for groups of generic buildings [2].

The Norwegian National Heritage Board has initiated a long-term monitoring of the effects of climate change on historic buildings [3]. Drawing on the results and expertise gained in the abovementioned projects, the project contributes to a better understanding of adaptation in historic buildings and to the development of appropriate tools for impact assessment. Furthermore, smart indoor climate control has a potential that is yet to be demonstrated in a wider range of buildings, both to reduce moisture related damage such as mould growth, and to reduce energy use and peak power. Given that we need to consider the long-term effects of climate change, impact assessment should to be carried out over much longer periods of time than what is commonly used in techno-economic assessments.

Building simulations are potentially a cost-effective way assess impact of climate change and to optimize indoor climate control. As shown in the Climate for Culture project, there is a tradeoff, in terms of time and cost, between complex and more simple simulations models.

Machine learning (ML) is an established method to build useful models of very complex systems relying on data from the actual performance of the system rather than on theoretical models. Based on physical models, the ML models can learn the actual behavior of the buildings and make more accurate predictions on the effects of internal and external changes in the buildings in order to reduce energy demand and minimizing risks. In this context, ML can be used to design new indoor climate control strategies optimize the daily operation of indoor climate control in buildings.

Generally, there is a considerable research base on specific and limited aspects of indoor climate control in historic buildings. However, there is still a need for an integrated and usable approach of indoor climate control in historic buildings that combines:

- Monitoring and Impact assessment
- Building simulations
- Adaptive optimization
- Bespoke technical solution

1.2 PURPOSE AND OBJECTIVES

The overarching aim of this projects was to lay the ground for an integrated and sustainable approach to indoor climate control in historic buildings. In a first stage this involved the development of practically useful methods for impact assessment of energy related adaptation measures that also take into account climate change and changing comfort requirements. The novel aspect was to integrate state of the art knowledge on long term monitoring and simulations with the application machine learning. In a second stage, using the outcome of the first stage, we aimed to develop smart indoor climate control strategies and technical solutions applicable to a wide range of building types. Specific project goals were:

- Strengthening the national knowledge base of how historic buildings actually work and how they respond to change.
- Practically useful methods for assessing the impact of adaptation measures
- Best practices for both long-term and short-term monitoring of hygrothermal risk presented as a guideline
- Assessment of innovative methods for indoor climate control
- Impact assessment for selected categories of buildings and for different future scenarios.

1.3 SCOPE AND DELIMITATIONS

The scope of the project was not limited to monumental buildings; rather it considered a range of buildings built between 1850 and 1950. Results from previous projects in Spara och bevara indicate that these buildings account for 20-25% of the total energy among Swedish properties. Thus, even small savings in many buildings would give a considerable national potential. Every percentage saved would correspond to 160-200 GWh.

2. IMPLEMENTATION

The project was coordinated by Uppsala University (UU) with Magnus Wessberg as administrative project coordinator and Gustaf Leijonhufvud as Scientific coordinator. Project partners were Norwegian Institute for Cultural Heritage Research (NIKU), Norwegian University of Science and Technology (NTNU) and Fraunhofer Institute for Building Physics (FBP.

Project group

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The project was divided into five work packages (WP):

Work package 1: Coordination, overall method development and dissemination (UU): Coordinating the different parts of the project towards an integrated methodology that is useful in practice and to ensure that the results are communicated to the end users.

Work Package 2: Monitoring and Risk Assessment (NIKU): Monitoring and assessment of indoor climate and building envelope in selected case studies. Defining criteria and indicators for risk assessment. Assessment of data from previous monitoring campaigns.

Work Package 3: Simulation (FHG): Based on results from WP 2 this WP demonstrates how whole building simulations, in connection with long term monitoring, can be used for impact assessment and development of novel control strategies. The main tools used were WUFI Plus and WUFI Bio.

Work package 4: Machine learning (NTNU). Based on input from work packages 2 and 3 a methodology a novel methodology was developed where Machine Learning is used to optimize new indoor climate control strategies and also for continuous optimization of HVAC systems.

Work package 5: Climate control (UU): Development, assessment and demonstration of new smart control strategies that are practically applicable. This solution is prepared for integration in commercial platforms for climate control and building management.

Cutting across all work packages are case studies (real buildings) and investigations in the laboratory buildings at the Fraunhofer laboratories in Holzkirchen.

3. RESULT

The main outcome of the project was to develop and demonstrate a practically useful method for impact assessment based on a combination of monitoring, simulations, risk assessment and machine learning. Using this method, the project demonstrates how smarter control of the indoor climate can provide lower energy and power requirements as well as retained or improved comfort.

Work Package 2: Monitoring and Risk Assessment

The project includes the development of a Guideline that provides an overview of available monitoring options and what they can be used for. It is not training in monitoring methods, but a tool to provide knowledge about existing solutions.

The main outcome of WP 2 is a guideline on long-term monitoring and risk assessment. The guideline:

- Collects and systematizes existing knowledge about monitoring methods.
- Conveys practical experiences from larger national monitoring projects on different building types, situations and climate conditions.
- Provides building managers with a concrete tool for assessing and selecting appropriate monitoring methods.
- Contributes to a better decision-making basis for planning, maintenance and damage prevention.

Work Package 3: Simulation (FHG)

Measurements, simulations and climate control experiments were carried out in the baroque 18th century Fraunberg chapel in Sufferloh, located in the south of Germany in upper Bavaria. The moisture measurements in the chapel showed extreme moisture load of the walls from wind driven rain due to the exposure near the Bavarian mountains and summer condensation as a second driver. Even though the plaster was refurbished by a water repellent system, moisture in the wall stayed high. Therefore, controlled ventilation and Temperierung heating (wall heating at the base of the wall) were installed which lead a clear lowering of relative humidity inside. Through optimization of the indoor climate control, with dewpoint control algorithm of the wall heating, a sufficient reduction of energy consumption was achieved.

The effects of the above measures on the indoor climate cannot be isolated only with in situ measurements. Therefore, a hygrohtermal whole building simulation model of the chapel was carried out in order to separate the influence to the indoor climate. With passive and active measures combined the best results are achieved compared to only active or only passive measures.

Additionally, a climate change scenario was simulated based on the RCP 8.5 scenario available for Sufferloh. The simulation shows that RH will can be expected to increase over time. The best control option is still active and passive measures combined.

The results in full are presented in appendix A

Work package 4: Machine learning (NTNU)

The combined approaches - explained in detail in the publications developed within the WP4 and listed here in the references - have delivered a range of significant results relevant to ML-enhanced climate risk assessment as follows.

Focusing on the Climate-Induced Mechanical Risk Models**,** Califano et al. (2022a; 2022b; 2022c) developed SED-based physical models and empirical risk functions that quantify climate-induced mechanical stress and fatigue in wood. These tools created by NTNU were implemented in Ringebu and Heddal stave churches, these models identified critical indoor RH fluctuation thresholds beyond which the fatigue life of wooden elements significantly decreases.

Then, the application of unsupervised learning i.e., the VAE was used for Historical Climate Reconstruction. In fact, Manara et al. (2022) applied Variational Autoencoders to fill gaps in historical indoor climate records, capturing seasonal patterns and extreme events – as an example occurrence of visitors' presence, celebration, concerts – that not always are recorded by the churches manager and that would otherwise be lost. The reconstructed datasets allowed more accurate long-term mechanical wood decay simulations, essential for damage prognosis. This approach was tested with input datasets with gaps and proved to be robust even when >30% of the original data was missing, outperforming traditional interpolation.

After that, the work of NTNU focused on Microclimate Event Detection via ML**.** The methodological approach published in Miglioranza et al. (2022) combined feature engineering (rate-of-change, volatility, signal energy) with classification algorithms to detect events such as visitor influx or HVAC activation. The results showed such an approach successfully flagged short-duration RH spikes (>5% within 15 min) i.e., those events that may pose high mechanical stress risk, enabling early warning and therefore intervention.

In addition, NTNU studied the Damage Evolution Prediction capability in Califano et al. (2022f) where Random Forest regression models were trained on environmental parameters and known damage metrics (e.g., crack propagation rates in panel paintings). These models predicted short- and medium-term deterioration trends with $R^2 > 0.85$, enabling dynamic updates to conservation priorities.

Finally, NTNU and all the Spara och Bevara team worked on Fatigue Damage Quantification in Wooden Painted Surfaces in Califano et al. (2023; 2024). In these published works climate data have been combined with computational fatigue models to estimate cumulative fatigue damage over decades of (microclimate) exposure in wooden churches. The models confirmed that high-frequency RH cycles, even of small amplitude, significantly accelerate damage in painted wooden layers that can guide indoor climate stabilization strategies.

To conclude collectively, these results demonstrate that machine learning not only enhances detection and reconstruction capabilities and tasks but also it integrates seamlessly with mechanical risk assessment tools, producing actionable outputs for early warning and heritage preservation.

Work package 5: Climate control (UU):

The main outcome of WP 5 was a flexible control system suitable for general use in historic buildings. The control system was developed, applied and tested in the Frauenberg chapel Bavaria. Technical specifications are provided in appendix A.

4. UTILIZATION OF THE RESULTS

Work Package 2: Monitoring and Risk Assessment (NIKU)

One of the purposes of this WP was to make available knowledge about monitoring options and to highlight what different monitoring methods can contribute. The resulting guideline, yet to be finalized, is intended to function as a practical guide to spreading monitoring knowledge, based on both theoretical foundations and practical experiences. A significant part of the knowledge base is based on experiences from major national monitoring projects carried out on different building types, under varied situations and climatic conditions. It builds directly on experiences from large-scale monitoring projects – most notably the Norwegian Klima-MOV project – and translates them into a practical, accessible tool for building managers and heritage professionals.

The guideline för long-term monitoring provides knowledge and know-how knowledge about monitoring options for buildings, with an emphasis on showing what different methods can contribute in practice. The guideline is intended to contribute to increased competence among building managers and other relevant actors, so that they can make better decisions about the choice and use of monitoring methods. This will strengthen preventive maintenance and damage limitation through more targeted and knowledge-based management.

The guideline is designed as a practical tool that shows how the project's results can be translated into usefulness in planning, designing and managing buildings. It provides an overview of available monitoring methods, their areas of application, strengths and limitations, and shows what different methods can contribute in practice.

The guideline addresses a key challenge in the field: while there is a growing range of monitoring technologies, many building managers lack clear, comprehensive guidance on what methods exist, how they function in practice, and how they can be applied to improve preventive conservation.

The guideline provides:

- A brief overview of climate-related risks that threaten historic buildings, including both extreme events (e.g. storms, floods) and slow processes (e.g. mould, rot, insect damage, salt crystallization, chemical degradation).
- A structured approach to monitoring, starting with baseline documentation and condition assessment ("zero-status"), followed by stepwise choices of monitoring methods adapted to different building types, risk profiles, and available resources.
- Brief descriptions of practical methods ranging from simple, low-cost measures (manual inspection, photography, use of reference markers) to more advanced technologies (sensors, dataloggers, RTI, photogrammetry, 3D documentation).
- Guidance on data management and follow-up, highlighting how collected data can be stored, analyzed, and compared over time to detect changes, evaluate interventions, and support decision-making.

By combining technical knowledge with concrete examples and checklists, the guideline makes monitoring actionable and scalable. Larger institutions such as churches, museums, and public property managers can adopt more advanced programs, while smaller owners and local societies can still benefit from simple, cost-effective approaches based on the same principles.

In this way, the WP2 results provide a usable framework that turns long-term monitoring from an ad hoc activity into a systematic, knowledge-based process. This contributes directly to better preventive maintenance, reduced risk of costly damage, and a longer lifespan for cultural heritage buildings. The guideline is not yet finalized and is planned to be published during spring 2026.

Work Package 3: Simulation (FBP)

The results WP 3 will help architects, engineers, and heritage professionals to better preserve historic buildings with severe moisture problems. The new method and climate control system with the combination of Temperierung heating and controlled ventilation offers a low invasive possibility for long-term preservation by improvement of the conditions and long-term reduction of moisture. The main aspect here is the correct choice of control parameters to get the optimum result for preservation vs. energy use and related costs. Therefore, also the parishes profit from the new system by better and more cost-effective preservation of built heritage. Fraunhofer IBP will use this system in future projects and make sure that is is well known by referring to it in teaching, e.g. at Bamberg University, Stuttgart University or Technical University Munich. Also, this knowledge will be used and disseminated via training and Lifelong learning offers like the Program QualiBene at the Fraunhofer Centre Benediktbeuern (www.denkmalpflege.de).

Work package 4: Machine learning (NTNU-

The outcomes of WP4 can be applied in multiple, practical ways to minimize risk in historic buildings and optimize climate control strategies. The application that we suggest are the following:

Proactive Conservation via Early Warning Systems. As an example, the event detection framework (Miglioranza et al., 2022) can be embedded into the building's monitoring system to trigger alerts when dangerous RH/T fluctuations occur, enabling preventive action for churches managers before mechanical damage accumulates. In practice, these Alerts can inform staff to adjust HVAC settings, restrict visitor access temporarily, or deploy local humidification measures.

Data Gap Mitigation for enhancing Long-Term monitoring value. Another example is the potential of the VAE-based climate reconstruction (Manara et al., 2022) that ensures that even incomplete historical microclimate datasets can be used for mechanical decay simulations, improving the accuracy of long-term preservation forecasts. In practice this helps heritage managers in reusing data that are not perfectly collected or incomplete. The potential of completing or eventually – with future research work – correct spurious data signal – may offer the capability of recreate the most complete climate exposure history available indoors thus warrantee for conservators/restorers to prioritizing restoration work based on reliable historic climate.

Dynamic Risk Mapping and HVAC optimization. Following example of use of NTNU produced results is that combining SED-based models with ML predictions (Califano et al., 2022a; 2022f; 2024) and an extended database, will become possible in the future to create a dynamic risk maps inside churches or historical buildings, highlighting zones with the highest probability of damage within the next week – or as a trend within next month. In practice this sort of spatial (dynamic) risk mapping could help allocate maintenance budgets more efficiently or propose zoning HVAC. In fact, such dynamic risk mapping outcome could feed directly into HVAC control systems, enabling real-time optimization of setpoints to minimize both energy consumption and damage risk. Just as an example, if the model predicts that a 1% RH reduction in fluctuation amplitude could extend fatigue life by 10%, the HVAC system could be adjusted accordingly.

Work package 5: Climate control (UU):

The control system developed in this project is flexible and well-suited for general use in historic buildings. Unlike conventional PLCs that support the standard programming languages defined in IEC EN 61131-3, this PLC can be programmed in Arduino C. While this may present challenges for operators accustomed to standard PLC programming environments, it offers a straightforward, flexible, and user-friendly solution for embedded systems developers familiar with the C programming language.

The control unit continuously monitors and compares temperature, relative humidity, and absolute humidity indoors and outdoors. Based on specified requirements for relative humidity and temperature, it automatically activates actuators such as ventilation or heaters when needed. The system also enables data logging of any parameter or control variable and can easily meet complex control requirements by combining temperature and relative humidity management with spatial resolution across several microclimate zones.

The case study has verified the technical functionality of the control unit. With further development, it could potentially be commercialized, as it introduces several novel features beyond the current state of the art. Nevertheless, based on the appended technical report, a control engineer could readily build a smart control unit for applications in historic buildings.

5. CONCLUSIONS

The main objective of this project was to establish a foundation for an integrated and sustainable approach to indoor climate control in historic buildings.

One major outcome is the strengthening of the national knowledge base of how historic buildings function and how they respond to change. Through case studies, long-term monitoring, and the development of innovative machine learning models, the project has shown how buildings react to variations in temperature and humidity. This contributes to a more evidence-based understanding of risks and adaptation options.

Best practices for long-term and short-term monitoring of hygrothermal risk have been compiled into guidelines for long-term monitoring of climate-induced risks. These guidelines translate technical expertise and research findings into structured and accessible information for building managers, showing how to design monitoring programmes at different levels of ambition. They cover both simple, low-cost approaches and advanced methods, and emphasize the importance of baseline documentation, systematic follow-up, and proper data management.

The project has further assessed methods for indoor climate control through the development and testing of a flexible prototype control system. This system demonstrated that adaptive regulation of temperature and humidity can reduce energy demand while maintaining or improving preservation conditions. The control strategies tested in the project illustrate that passive and active measures, when combined, are more effective than either approach alone.

6. LIST OF PUBLICATIONS

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