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A Methodology for Long-Term Monitoring of Climate Change Impacts on Historic Buildings

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Abstract: A new methodology for long-term monitoring of climate change impacts on historic buildings and interiors has been developed. This paper proposes a generic framework for how monitoring programs can be developed and describes the planning and arrangement of a Norwegian monitoring campaign. The methodology aims to make it possible to establish a data-driven decision making process based on monitored decay related to climate change. This monitoring campaign includes 45 medieval buildings distributed over the entirety of Norway. Thirty-five of these buildings are dated to before 1537 and include wooden buildings as well as 10 medieval churches built in stone while the remaining 10 buildings are situated in the World Heritage sites of Bryggen, in Bergen on the west coast of Norway, and in Røros, which is a mining town in the inland of the country. The monitoring is planned to run for 30 to 50 years. It includes a zero-level registration and an interval-based registration system focused on relevant indicators, which will make it possible to register climate change-induced decay at an early stage.

Keywords: climate change; long-term monitoring; Norwegian protected buildings; medieval buildings; zero status; warning report

1. Introduction

The impact of climate change on a built cultural heritage must be considered in the long-term management of historic buildings. Most buildings are not constructed to resist "new" climate conditions and risks associated with climate change should, therefore, be identified and quantified in order to facilitate relevant adaptation measures.

A long-term strategy to adapt to climate change must be based on risk assessment, adaptation measures, and monitoring. Adaptation defines any adjustments in a system in response to actual or projected climatic stimuli [1,2] including changes in socio-environmental processes, practices, and actions to reduce potential damages.

Advanced simulations can be used to predict the future climate and its effect on historic buildings [3,4]. However, due to the high degree of uncertainty in simulations, this approach is not sufficient. Long-term monitoring of actual climate change impact is necessary to better understand the effects of climate change on historic buildings. Monitoring can be used to observe and analyze decay progress and changes to make them "visible" and to provide reference data to improve the results of simulation models. Additionally, monitoring can be used to inform decisions on adaptation actions and/or corrective actions. Furthermore, the outcome of monitoring provides results that can be communicated in order to raise awareness among property owners, heritage managers, and citizens and to gain political and economic support locally, regionally, and nationally.

Effective monitoring methods for the built heritage need to be identified and developed and indicators were specified. A good monitoring method for a built heritage may also be applicable to cultural heritage in general.

Climate model projections for Northern Europe indicate trends of increasing temperature and relative humidity and of extreme weather events such as floods triggered by local intense precipitation events and windstorms leading to direct and indirect damages on the built environment. Direct effects of climate change are manifested as physical changes to building structures and finishes. These can further increase once the actual local climate ceases to match the past environmental conditions that inspired the building design (SMOOHS Project, www.smoohs.eu, Predicting and managing the effects of climate change on World Heritage). Both direct and indirect effects may affect the value of the built environment, which further drove the loss of important components of individual and collective identity of a historic site.

The impacts of climate change may be greatly amplified on the aged and fragile materials that are present in historic buildings. Advanced adaptation techniques, which are commonly used for modern buildings and structures, cannot always be applied due to legal requirements of preserving the original features of historic buildings.

The need to use traditional materials, construction systems, and craft skills during maintenance and refurbishment interventions is already well recognized in Norway. We suggest that there is now an urgent need to evaluate successes and failures of such interventions in the face of climate change. Long-term monitoring can provide essential insights into how traditional materials and construction systems might be modified to cope with more aggressive climate conditions.

Despite the growing interest in understanding the effects of climate change on cultural heritage, there have been few attempts to assess actual impacts through long-term monitoring [5]. According to a recent review by Fatorić and Seekamp 2017 [6], there has also been a lack of studies focusing on the implementation and documentation of adaptation measures taken to protect cultural heritage from climate change. Long-term monitoring is key to better understanding both impacts and the need for adaptation measures. Moreover, monitoring is essential for determining the causality between climate and damage at individual sites [7]. Long-term site-based monitoring, therefore, elucidates necessary feedback loops for the evaluation of adaptation planning and for the calibration of impact risk assessments.

An additional challenge for the monitoring of impacts of climate change is the long time frame needed to discern the climate change signal from the natural variability of the climate. This time frame (>30 years) exceeds the scope of most research funding schemes and there are also practical difficulties in maintaining such long projects with regard to administration, staff continuity, data retrieval and storage, etc. [5].

The objective of this paper is to present a novel methodology for monitoring long-term effects of climate-induced degradation on historic buildings and interiors. The first part of the paper presents a generic framework for the development of monitoring programs. This framework is based on a review of existing approaches to climate change monitoring of cultural heritage as well as the experiences from the Norwegian project known as "Methods for Monitoring the Effects and Consequences of Climate-Related Degradation of Buildings" (Metoder for overvåking av effekter og konsekvenser av klimabelastninger på bygninger, Forprosjekt, NIKU-rapport 197/2016). The second part of the paper presents, as a case study, the implementation of a newly started long-term monitoring campaign on the impacts of climate change on historic buildings in Norway.

State-Of-The-Art

Comprehensive approaches that consider the connection between structural and environmental aspects in the built environment are used to develop frameworks to continuously monitor the operational performance of buildings. These commonly concentrate on the energetic aspect of modern buildings in operation. Within such frameworks, real-time monitoring is proposed to collect data about building performance with the final objective being to better control operations within the buildings, which ensures a reduction of building energy consumption.

The impacts of future climate change on cultural heritage is an expanding research field where the majority of studies over the last 10 years have dealt with climate change impact assessment and adaptation planning [6]. A number of European studies have performed regional risk assessment (RRA), which is a methodology to appraise the risk posed mainly by hydrological-related climate change impact [8,9], but also by a range of mechanical, chemical, and biological damage on a set of generic building types and mixed materials [3]. The methodology, in the case of risks related to the hydrological cycle (e.g., storm surge, floods, sea level rise, moisture, rainfall, and coastal erosion), is based on the concept that risk is a function of hazard, exposure, and vulnerability. It integrates the output of various hydrodynamic and climatic models with site specific geophysical and socio-economic indicators (e.g., key performance indicators as in Gandini et al., 2017 [10]) to develop risk indices and GIS-based maps [9]. The focus has often been on wide areas where multiple objects are located, i.e., recent and new buildings, historical buildings, monuments, infrastructure, and landscape. Over the last 10 years, the projects dealing with this approach have included ADVICE and KULTURisk. Their objectives were to improve knowledge of vulnerability by using, for example, the LIDAR (Laser Imaging, Detection and Ranging) technique to obtain a high-resolution coastal topography on exposure by using a wide range of key performance indicators on hazards by improving hydro-climatic models and on developing a culture of risk prevention by proposing structural and non-structural mitigation measures. The method, in the case of outdoor and indoor multiple risks, is based on dose-response and damage functions. It integrates the output of climatic models using moderate emission scenarios (considering socio-economic factors that may influence the magnitude of climate variables) with a set of generic building and material specific indicators [3,11,12] to develop risk indices as well as risk and decay maps. Its focus is on a single object category, i.e., cultural heritage, with the aim of improving knowledge of cumulative and slow climate-induced mechanisms of decay on a wide range of materials and of building simulation. Specifically, the building simulation is based on monitored data from existing buildings used to effectively transfer outdoor climatic conditions to indoor conditions.

A recent review [13] showed the variety of ways that climate change might have an impact on the cultural heritage. The review summarizes how different hazards that are intensified by climate change (temperature change, precipitation change, storm surge, flood frequencies, coastal erosion, sea level rise, carbon dioxide levels, and combined stressors) can have an impact on different cultural resources. This review is useful for identifying and selecting which phenomena to monitor in long-term monitoring campaigns of climate change impacts.

Over the last 10 years, two major European projects have attempted to assess the future climate change effect on tangible cultural heritage including The Noah's Ark project, which focuses on outdoor risks, and the Climate for Culture project, which deals with both indoor and outdoor risks.

A few other European studies have assessed the impacts of climate change on buildings and interiors by combining the projections of future climate change with damage functions [4] and, more recently, in combination with hygrothermal building simulations [3,14–16]. These top-down impact studies, which are mainly focused on predictions rather than monitoring, show that assessments of climate change impacts on historic buildings and interiors are both complex and uncertain. Nevertheless, taken together, these studies show that climate change will cause significant damage to historic buildings and historic interiors in Europe unless plausible adaptation measures are implemented.

Based on a literature review and three national adaptation strategies, Klostermann et al., 2018 [17] presented a generic strategy for monitoring based on four key factors.

(1) definition of the system of interest,
(2) selection of a set of indicators,
(3) identification of the organizations responsible for monitoring,
(4) definition of monitoring and evaluation procedures.

Although this review mainly concerns the monitoring of climate change adaptation, it provides a generic approach that we suggest is also applicable to the monitoring of climate change impact. Table 1 shows how each of the four key factors are specified by a number of questions. In Table 2, general challenges are presented as well as general proposed solutions.

Table 1. Questions for the design of a monitoring program from Klostermann et al. (2018).

	Questions
System of interest	1. Is the description of the monitoring context based on a transparent and structured overview of:
	a. Current and future climate (preferably on the basis of downscaled climate models)?
	b. Important climate impacts on socio-economic and environmental systems including exposure and sensitivity?
	c. Socio-economic and environmental vulnerabilities?
Indicators	2. What indicators are selected for monitoring and evaluation?
Responsible organization	3. Which organization(s) is/are responsible for monitoring?
	4. What financial and other resources are available to the organization for monitoring?
	5. What are the arrangements that provide legitimacy and credibility for the monitoring?
Procedures	6. Are information needs and monitoring objectives clearly described?
	7. Are monitoring procedures clearly specified including data collection and reporting?
	8. Do the procedures prescribe stakeholder involvement and, if so, where in the monitoring process?
	9. Is the notion of adaptive monitoring incorporated?

Table 2. General challenges and solutions for monitoring. Adapted from Klostermann et al. (2018).

General Challenges for Monitoring	Proposed Solutions
Useful information: salient and context sensitive to specific information demands.	• Involve stakeholders to check information needs. • Research mechanisms in system(s) of interest.
Technical quality of indicators: accurate, valid, precise, robust, meet SMART criteria. (SMART stands for: Specific, Measurable, Assignable, Realistic, Time related)	• Use/develop review procedures. • Use existing indicators/data sources. • Research physical mechanisms in system(s) of interest.
Communicative value and efficiency of indicators: simple and straightforward to understand.	• Test communicative value of indicators. • Use existing well-known indicators.
Credible production of information: unbiased, legitimate, transparent, objective/independent.	• Scientifically sound methods. • Independent operation of the monitoring organization.
Monitoring must be feasible: availability of data and limited financial and human resources.	• Limit the set of indicators. • Use existing datasets. • Evaluate usefulness of indicators.

There are some challenges to overcome when monitoring climate change impacts on cultural heritage related to the time scales involved and to the connected problem of data retention. The need for improved monitoring is often emphasized in reports and guidelines that are produced by agencies and organizations in charge of cultural heritage and is aimed at decision makers and stakeholders without giving much detail about how such monitoring should be carried out in practice (e.g., National Park Service 2010 [18], English Heritage 2006 [19]).

To our knowledge, the only research project that has focused solely on the long-term monitoring of climate change impacts on cultural heritage is the PhD project of Cathy Daly [5,7]. Daly developed a methodology and a tool for monitoring the impacts of climate change on archaeological sites. The methodology consisted of a vulnerability and impact assessment framework to be used for each site and the suggested monitoring tool is a sacrificial stone object, which tracks surface changes caused by recession, salt crystallization, and microbiological growth. The monitoring tool is supposed not to require maintenance. The most important contribution from Daly is that she identified and analyzed the needs of a robust method that is supposed to be applied in practice. Her study clearly demonstrates that cultural heritage managers cannot rely on existing approaches to monitoring and that there is a need to think in new ways about how monitoring should be carried out.

An overview of a recent project to monitor climate change impacts on cultural heritage in Egypt and the UK is presented in Mahdjoubi et al., 2017 [20]. It is unclear how the presented methodology was developed, but, nevertheless, it argues for some innovative ways of monitoring the long-term degradation of heritage buildings with the use of laser scanning, photogrammetry, air permeability measurements, and U-value measurements.

The state-of-the-art approaches reported above highlight an urgent need for the heritage sector to initiate long-term monitoring campaigns about the impacts of climate change to historic buildings. The review also shows that, while there is abundant knowledge about theoretical cause–effect relationships between microclimates and building damage, there is a lack of knowledge and experience about how to set up and manage long-term monitoring projects and to plan and implement a data driven decision-making and adaptation process.

A data-driven decision-making method focused on the monitoring of climate-induced decay in valuable buildings will have to take into account the fact that the historic value of historic buildings restrict the range of possible and allowable interventions. Conservation interventions cannot be standardized. They need to be tailored, non-invasive, effective, and sustainable in term of costs and resource use. Additionally, a team with interdisciplinary knowledge and expertise is required since the understanding of the monitoring results and the conservation needs are based on an integrated and comprehensive assessment of climate change impact. Several factors have to be considered when interpreting the results of monitoring at individual sites: the building structure and constituting materials, the possible existence of induced natural decay, the decay rate assessment, the history of past maintenance intervention, and the expected or predicted building lifetime.

2. Materials and Methods

2.1. Development of a Method for the Long-Term Monitoring of Climate Change Impacts on Cultural Heritage

2.1.1. A Generic Framework for Developing Monitoring Programs

In 2016, the Directorate for Cultural Heritage in Norway asked The Norwegian Institute for Cultural Heritage Research (NIKU) to develop a program for the long-term monitoring of climate change impacts to historic buildings. In order to develop the program, a multi-disciplinary team of experts was gathered and the work proceeded in a systematic way, which is presented in Figure 1. Based on our experiences, we suggest that this generic approach can be a valuable framework for the development of monitoring programs in other contexts (Figure 1).

The first step is to define and understand the system of interest or the target of the monitoring by:

- Understanding the historic building through the collection of data on location, type of immovable cultural heritage, type of material and state of preservation, and statement of significance, authenticity, and integrity to understand aspects to be safeguarded.
- Understanding the hazards, i.e., dangers and threats to the area including those induced by climate change, use of the building, existing policies, strategies, plans, and actions that are of relevance for preventive conservation and maintenance.
- Understanding the instruments of safeguarding, i.e., national law, legislation, local regulations, international conventions/charters, and, later in the project, to understand if these instruments have to be adapted or new ones have to be developed.

The second step is to gather a multidisciplinary team with specialized competence in building physics, monitoring, conservation, climate, different kinds of damage (biological, chemical, and mechanical), and climate change impact monitoring (Figure 1, second column, step 2). The combined skills of the group should be tailored for the system of interest, i.e., the target of the monitoring. By establishing a project team with the necessary competence, it is possible to quickly develop and implement the monitoring project, perform the analysis of the collected data, identify the effect of climate change on the historic fabric, and also to find the parts of the buildings that are most vulnerable to climate-related decay. The interdisciplinary expert team should be carefully chosen and, to ensure competence and continuity, it should preferably include younger members. Additionally, a second group of relevant stakeholders is involved at an early stage. This is composed of relevant public and private stakeholders that can take actions once monitoring reporting has been delivered. During this step, organizational, operational structures and procedures for further developing actions to safeguard and adapt historic buildings to climate change effects (e.g., through ordinary and extraordinary maintenance) have to be decided.

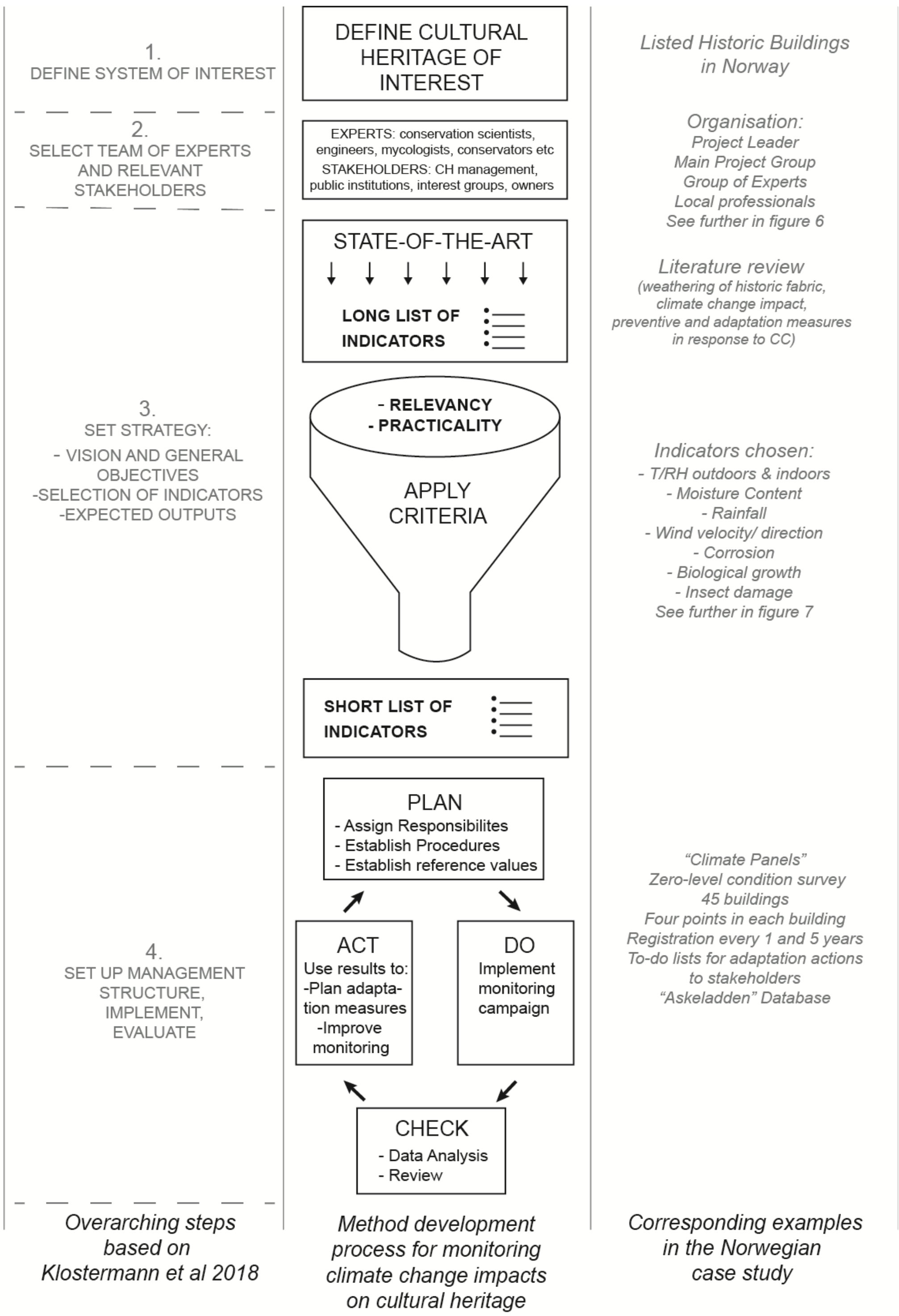

Figure 1. A generic framework for developing monitoring programs targeting specific cultural heritage objects. The first column shows the overarching steps (adapted from Klostermann et al., 2018), the second column shows the method development process for monitoring climate change impacts on cultural heritage, and the third column shows corresponding examples in the Norwegian case study.

The third step (Figure 1, second column, step 3) involves deciding the strategy and includes:

- The overall vision and general objectives of the monitoring: (1) understanding the field of actions (i.e., adaptation of cultural heritage to climate change effects by minimizing their negative impacts); (2) acquaintance with the state-of-the-art, i.e., identification of relevant issues to deal with (e.g., weathering of historic fabric, preventive and adaptation measures in response to climate change), and, consequently; (3) objectives to achieve and strategies (integrated approach).
- The understanding of how to achieve the goals, i.e., identifying the environmental variables, actions, instruments, and techniques (both existing and to be developed with a main focus on a non-destructive technique (NDT)) to accomplish the objectives of the long-term monitoring. These are the outputs achieved as the recognition of alterations ascribed to climate change when compared to the zero status registration.

Lessons learned from other fields such as agriculture and human health help to determine how to reach the objectives, e.g., the selection of domain-specific indicators for climate change impact. Clear objectives help to discern intermediate steps and/or important selection criteria for reaching the ultimate goal. Related to the objectives of a long-term monitoring program, it is important to distinguish between measurements and indicators: Measurements concern changes in physical, quantitative attributes while indicators are used to describe or project the performance of a system in a quantitative or qualitative way [21]. The initial step is to find a systematic method with which to identify useful indicators among those available in the literature and to include those indicators in a final monitoring plan. During our discussions in the project group, two selection criteria emerged as being the most important, which are relevancy and practical relevancy. For an indicator to be relevant for monitoring the impacts of climate change, it must be possible to determine if a change was caused by climate change or other factors. The indicator has to address specific and overall vulnerability and exposure related to the effects of climate change based on a starting condition level, i.e., a zero status registration. If the cause–effect relationship is too uncertain, there will be little or no possibility of discerning which changes were actually caused by climate change and which were caused by other factors. The involved uncertainties can be related to measurement errors (input to the model), deficiencies of the model itself, and the natural variability of the cause–effect relationship. Dose–response relationships are the easiest to model. However, climate-induced damage is often more complex involving synergisms and, hence, is more difficult to model [22]. Practicality. Given the time frame, available resources (financial and competence) and the availability of existing technologies, it is necessary to prioritize indicators that are possible to monitor in practice. Non-destructive techniques (NDT) are preferred for the detection of environmental conditions so as to avoid damage to the building structure. However, very few such techniques are routinely used in cultural heritage conservation as a number of barriers that are both technical and institutional and hinder their in situ implementation on a long-term basis.

The fourth step (Figure 1, second column, step 4) is setting up the management structure of the monitoring program. The proposed strategy is based on the "plan-do-check-act" cycle that employs long-term monitoring and its review to take adaptation actions in time. The four phases of this cycle have to meet the following requirements:

- *Plan*: Development and/or adaptation of organizational and operational structures and procedures clearly allocating responsibilities and tasks to be met (e.g., through an organigram that explains a responsible body/person and sets the individual goals for: (1) safeguarding the cultural heritage values, (2) the implementation, application, and revision of monitoring and data collection, and (3) assuring that actions are taken in time, according to monitoring results.
- *Do*: Implementation plan and execution phase of long-term monitoring. The implementation plan includes a sequence of actions (i.e., tasks and activities as systems for collection and storage of data, reporting and management, etc.), which have to be executed (e.g., who is doing what, what inputs are needed, what outputs are intended, etc.). Additionally, the collection of information concerning the assessment of the building or structure to define the so-called zero-level registration condition (step 1) has to be concluded before starting the monitoring (execution phase). This defined state will

be the base for the future assessments and registrations of the object that is to be monitored. In this phase, a close communication with the institution that is managing the historic buildings is needed.

- *Check*: Continuous monitoring and review (e.g., description of who is monitoring or evaluating what and how results will be used). This checking or review stage will strengthen the evidence base in time for the next cycle of reporting so that the historic building will be better served by the method/process itself.
- *Act*: Acting to adapt historic buildings to climate change effects on the basis of monitoring results. In the long-term perspective, the program will evaluate adaptive measures that have been proposed and eventually implemented by directly or indirectly monitoring them.

2.1.2. Suggested Monitoring Method

The suggested monitoring method is based on a zero-level condition survey (first step) focusing on possible climate-induced degradation processes, which is followed by a control survey every fifth year (fourth step and iteration of first step) depending on the category of the building. The condition survey is based on the European standard NS-EN 16096:2012 [23]—Conservation of cultural property—condition survey and report of built cultural heritage. The zero-level condition survey starts with the identification of the (1) building involving the site description, climate conditions, environment, construction, materials, age, and condition including the history of damages and the history of maintenance; (2) predicted future change involving temperature, relative humidity, solar radiation, wind, and precipitation; and the (3) risk for the climate involving induced disasters on the site such as floods, avalanches, and rockslides. The focus of the monitoring is the slow influence of the climate on the monitored cultural heritage.

Further condition surveys and documentation during the implementation of the long-term monitoring (fourth step) are dominated by climate logging combined with visual control and detailed photos. Climate logging is performed by the use of "climate panels."

2.1.2.1. The Climate Panels

"Climate panels" provide a standardized continuous record (registration every hour) of temperature (T), relative humidity (RH), and moisture content (MC) and information on biological risk. A climate panel mounts specimens or blocks and meters on a non-organic, lightweight sheet material. The following are mounted: (1) a T and RH logger (Materialfox from Scanntronik Mugrauer GmbH selected for the Norwegian monitoring program); (2) an MC logger (i.e., an electrical resistivity probe inserted into a specimen of the same material that the meter is calibrated for); and (3) a certain number of standardized specimens or small blocks used as test material to provide an early warning about conditions that favor the proliferation of microorganisms. All climate panels must have a set of standard blocks of a single type of material but may also have additional materials adapted to issues specific to the location.

Climate panels should be placed in carefully chosen parts of the building. It is possible to perform analyses of salts, bacteria, algae, and the identification of insects on the specimens. The specimens are evaluated each time a subsequent registration is made in the building through visual inspection by recording visible growth or other visual changes in the control material. Photography and sampling and analysis of the surface layer of the block closest to the logger are performed at the first follow-up and then are repeated for block 2 from the logger for the second follow-up, and more. Indirect measurements of the moisture ratio in adjacent blocks can be made through comparison between climate panels. Monitoring using climate panels makes it possible to define the damage from and symptoms of the moisture impact on building materials (e.g., progress of damage, new damage, and symptoms) in relation to the zero status registration mentioned above.

The climate panels should be placed approximately in the same positions in all the monitored buildings in order for the results to be comparable. An example of standardized placement is shown in Figures 2 and 3.

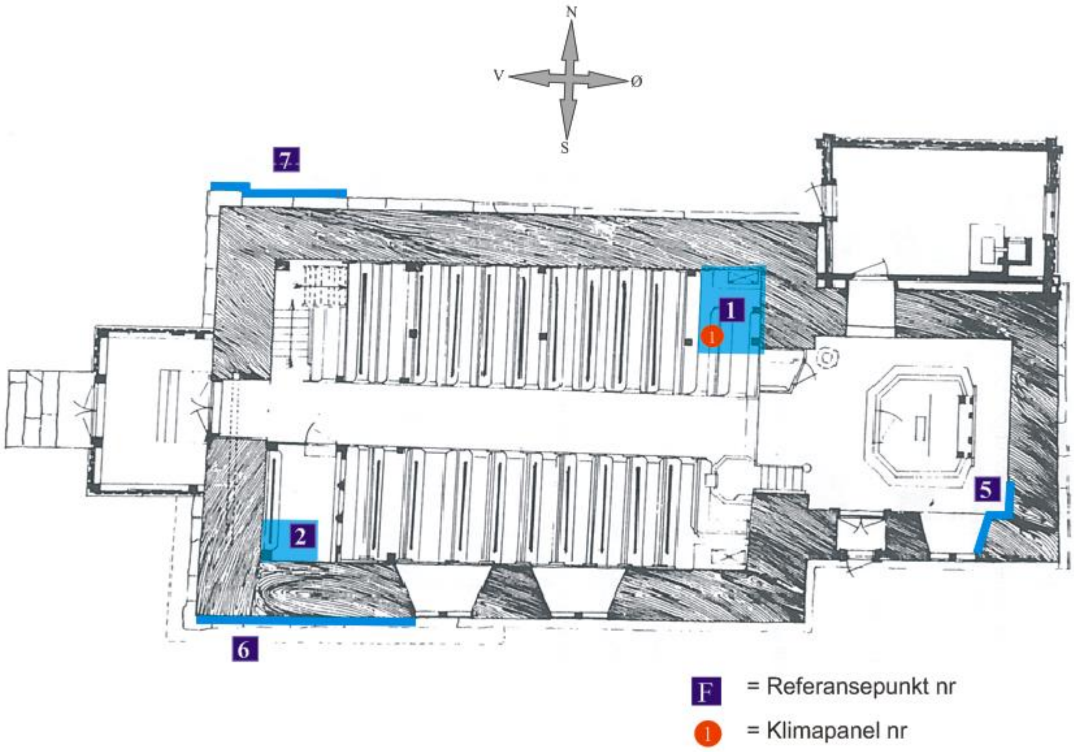

Figure 2. Positions of climate panels (red dot) and reference points (blue squares) in Skoger Old Church.

Figure 3. Climate panel. Photo: NIKU.

In the present study, four fixed reference points are chosen in each building and the climate panels are placed in two of these. These four fixed reference points are situated in the parts that are likely to be most and least threatened by moisture, which are the northeast and southwest corners, respectively, both on the ground level and at the highest levels in the buildings. The climate panels are placed in the northeast corners, which are likely to have the highest levels of moisture and, thereby, are also likely to be the most threatened.

2.1.2.2. The Reports

The results of the on-site surveys as well as the collected information from the logging equipment are presented as processed information in reports for each monitored building.

There is one report for the zero status registration (first step) and reports for each of the following control registrations (check phase in the fourth step). The expert group will perform the analysis and prepare the reports. The degree to which observed alterations at any of the selected reference points for each building or observations of a general change of the situation at the site are of a nature that will increase the risk for the building in the future climate will be reported. If needed, measures and further examinations will be proposed in a report (e.g., changes in the monitoring plan and implementation following the notion of adaptive monitoring and/or proposal of adaptation measures to apply on the building).

Additionally, if a set value in the monitoring is exceeded and indicates increased degradation between two surveys, a warning must be generated from the onsite local person involved in the project. A warning report will be produced. The observed deviation in the monitoring may be difficult to define and the onsite local person must have the ability to involve experts immediately if there is any uncertainty. The report will describe the problem and propose necessary measures or a possible change in the monitoring focus for the site in question. If the situation is critical, the expert team should be notified and a summary of the most important information with the raw data enclosed will be included in the warning report. The project's expert team is responsible for handling these situations and for the elaboration of the warning reports. If actions are needed, the manager of the building has the responsibility for implementing measures.

A huge amount of data is collected during a monitoring program. It is necessary to collect enough high-quality data for the aim while simultaneously obtaining a minimum of data. The challenge is to define exactly what data is needed for the monitoring. It is a demanding task to both find systems that, with necessary modifications, will run for a long period of time and find a way to make it possible to compare data for the duration of the monitoring period. Comprehensive reports for each building must be made with certain intervals during this long period. These may be used for comparison in case the access to the raw data becomes difficult or impossible.

It is necessary to use an official database that will be maintained in the future and which contains information on cultural heritage buildings. A system for storing the information and photos must be developed in cooperation with the owner of the database.

In principle, the aim of the reports and storage of data is to have a transparent system with a high grade of accessibility for as many data items as possible. The baseline requirement is that all levels of management should have access to the raw data. The owner of the project will own the information database and handle the formalities related to the system of accessibility and the system of transferring data to the managers and researchers.

3. Results

3.1. Implementation of the Method in a Monitoring Program in Norway and the First Results

3.1.1. Selection of Buildings

The selection of buildings was based on a set of criteria outlined in Figure 4. These criteria might be used on a general basis as part of the monitoring model.

Based on the abovementioned criteria, 45 buildings were chosen to be included in this study. As demanded by the Directorate for Cultural Heritage, 35 of these buildings dated to before 1537 and 10 of these buildings were medieval churches built in stone. The remaining 10 buildings are situated in the World Heritage sites of Bryggen in Bergen on the west coast of Norway and in Røros, which is an inland mining town east of Trondheim. The monitoring is planned to run for 30 to 50 years.

The selected buildings are geographically distributed over the country in various climatic zones and in different landscape sites and situations within the zones such as in valleys, mountainous areas, forests, or close to water. Buildings close to a weather station and with rainfall and/or temperature data already monitored were preferred.

The risk of damage was considered as the most important criterion and the exterior was valued as more important than the interior in terms of authenticity and original or old building elements. We avoided excessively complex buildings. The type, function, and use of buildings were determined to be less important criteria since the old buildings were mainly of the same type. Distance to other selected buildings was considered to be of high importance for the economy and the implementation of the monitoring project. Availability signifies accessibility to the building including an accommodating owner.

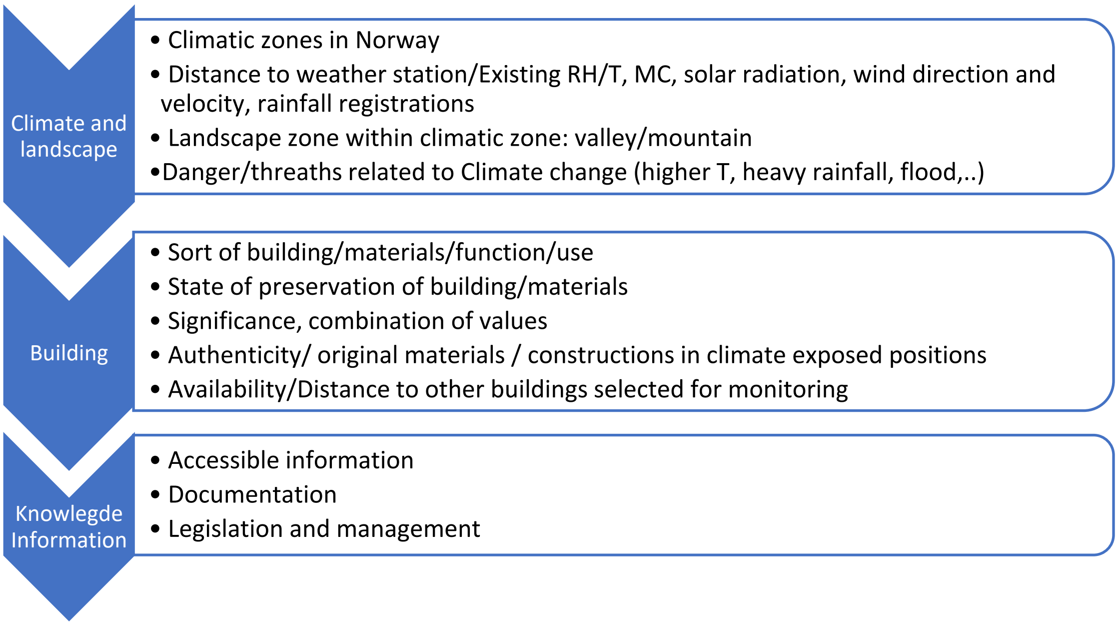

Figure 4. Criteria for the selection of buildings. RH = Relative Humidity, T = Temperature, and MC = Moisture Content.

Documented buildings and buildings that were well known to the project team were preferred.

We found that availability of buildings was crucial. Additionally, to secure a long-period contract for the monitoring, only cultural heritage sites owned or managed by the public should be selected for monitoring to ensure that they are available for the whole monitoring period.

The monitoring project was started in July 2017 with the following four buildings:

- Skoger Old Church, which is a stone church dating to around 1200 and is located in the inland region near Oslo.
- Raulandstua, which is a timber building dating to 1238, which has been hosted at the Oslo open-air museum since 1899.
- Garmo stave church, see Figure 5, which is a wooden building originally dating to early 1200 and is now hosted at the Maihaugen museum, Lillehammer, in the inland region north of Oslo. It was erected at the museum in 1921.
- Bugarden, which is a wooden 18th century building at the World Heritage Site of Bryggen (the Wharf) in Bergen on the west coast.

3.1.2. Organization

The organization includes both the expert team and onsite local persons, see Figure 6. The expert team started and implemented the monitoring and established the close and necessary communication with local persons. A control of the registration from the climate panel made after one year and the following control registrations (every fifth year) were made by the interdisciplinary team of experts.

Figure 5. Garmo Stave Church, Lillehammer. Photo: NIKU.

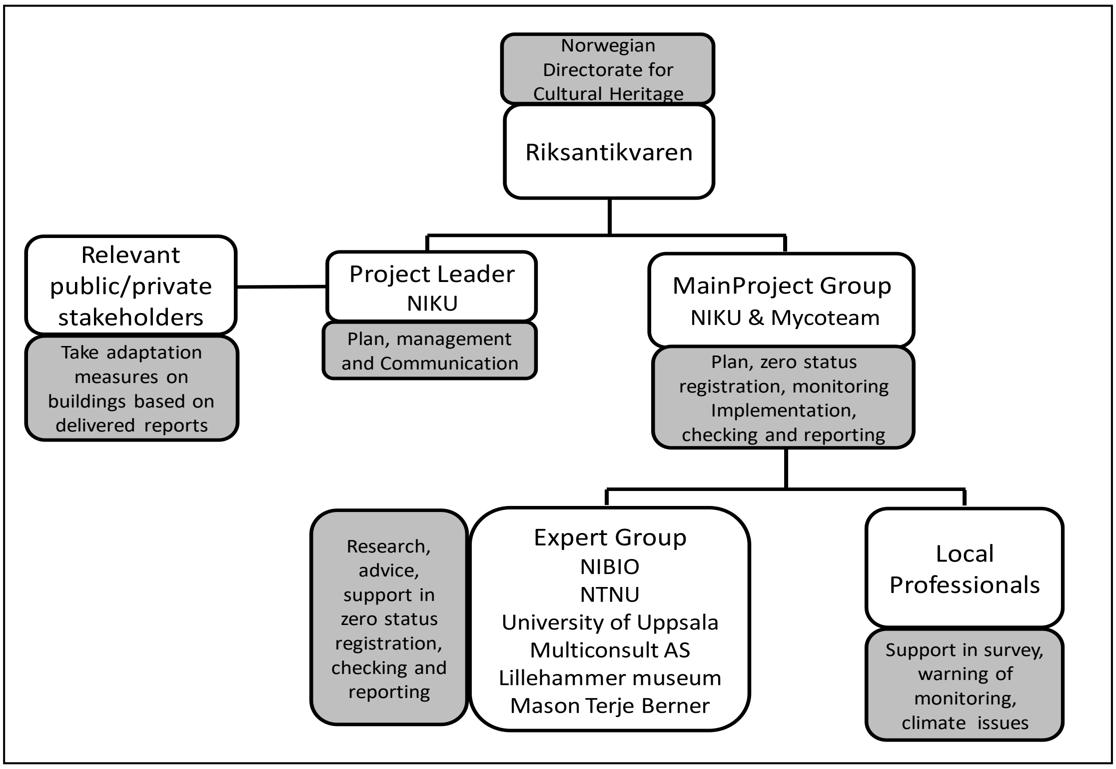

Figure 6. Organigram of the monitoring program: Environmental monitoring of the impact of climate change on protected buildings—Miljøovervåkning av konsekvensene av klimaendringene på fredete bygninger (2017–2026). Project Number SAKSNR 15/02185 funded by Riksantikvaren—Norwegian Directorate for Cultural Heritage. White Boxes: Responsible body/person. Grey Boxes: Set of tasks.

3.1.3. Choice of Indicators

Selected indicators used in the monitoring program are outdoor and indoor climate parameters (e.g., T and RH), weather variables (e.g., precipitation, wind direction, and wind velocity), moisture-related parameters in building materials (e.g., MC), visible damage on wood and masonry such as cracks and voids, biological decay of wood and surfaces such as the growth of micro-organisms, observation of insects, salt crystallization, frost damage in masonry, and the flaking of painted surfaces on wood and masonry (see Figure 7).

Sometimes the change of a single indicator against the zero-level registration cannot give a clear measure of the effect of climate change. However, using several indicators in combination can provide a better overview of the effect and the cause of changes. Although the proposed methodology provides measures and, therefore, quantitative information, it might be necessary to consider an indication of change and/or a new risk development to determine if an adaptation action has to be taken or not. The indicators presented in Figure 7 were chosen based on our monitoring objectives and available resources for monitoring. However, the proposed scheme can be easily adapted to changing needs and objectives.

Objective	**Indicator**	**indicators and risk levels control against the zero level registration**		**Verification date**	**CC scenarios for comparison**
		Warning code	**Explanation**		
Climate Change effect on historic buildings	T, RH, MC, rainfall,…, biological risk		Low (<<) Change of indicators and risk levels → No need of adaptation intervention(s)	Period: last 1,..,5 year(s)	https://www.climateforculture.eu/
			Medium Change of indicators and risk levels → need of adaptation intervention(s)	Last data collection and reporting: 01.08.2018	http://www.miljostatus.no/tema/klima/klimainorge/klimainorge-2100/
			High Change of indicators and risk levels → urgent and major adaptation interventions needed		

Figure 7. Setup of the indicators used in the long-term monitoring program to assess the impact of climate change on historic buildings.

3.1.4. The Zero-Level Condition Survey

For each building, former alteration and repair history were collected through an archival search, see Figure 8. Since damages often occur in the same parts of the buildings, the damage history is important. Studies of climate scenarios for the building sites and their surroundings were conducted as a background for the interdisciplinary zero-level condition survey (Figure 1, third column). A thorough survey was conducted in each building, which establishes the zero-level condition. During this survey, the most vulnerable parts of the buildings and their interiors were selected and reference points were established. The reference points include the four fixed points as well as possible supplementary points (see Section 2.1.2.1). Early warning reports for two of the buildings were immediately sent to the Directorate for Cultural Heritage

3.1.5. Information Storage and Access

It was decided together with the Directorate for Cultural Heritage that all information collected in the monitoring project would be added or linked to the official database of the Directorate for Cultural Heritage in Norway, which is named "Askeladden." This included: (1) The information from the "zero status survey" and photos for each building, (2) the raw data collected during the monitoring, and (3) the reports with the processed information. The system for storing the information in the database was developed in cooperation with the Directorate for Cultural Heritage. Once all the data has been stored in the database, the integration of a long-term monitoring program in a Cultural Heritage Integrated Management Plan (CHIMP) becomes possible through the implementation of the suggestion provided in the monitoring reports.

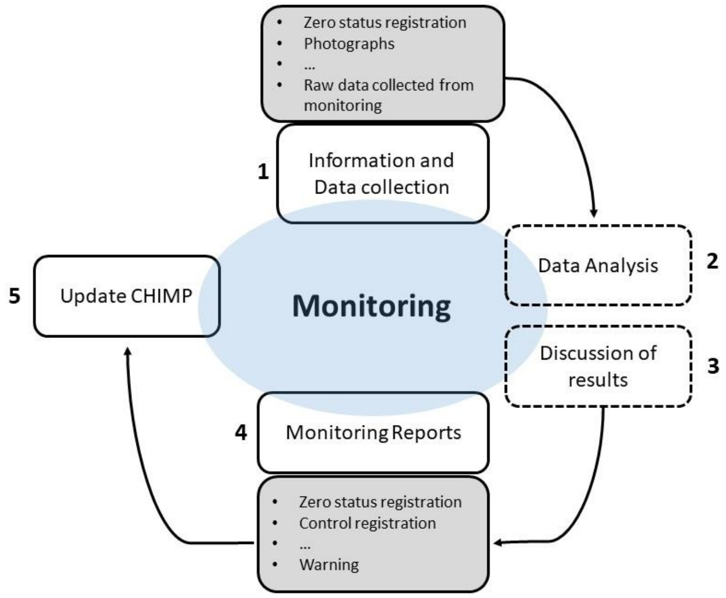

Figure 8. Incorporation of a long-term monitoring program in a Cultural Heritage Integrated Management Plan (CHIMP). Transparent boxes with solid border: information, data, and report publicly available in the official database of the Directorate for Cultural Heritage in Norway named "Askeladden." Boxes with dashed border: information available internally in the main project group. Gray boxes: examples of information, data, and reports within the monitoring program.

3.1.6. Future Plans for the Monitoring Project

In 2018, the project will include 10 additional buildings situated in Bergen in the northern part of the west coast and in Northern Norway. A thorough zero-level condition survey will be conducted in all of these buildings and the first year control will be performed on the four buildings that initiated the project in 2017.

Adding the experiences after half a year of monitoring, the expert group concluded that there is a need to focus on a solid systematic approach in the project. It has been recognized to be of great importance to document and mark photographs and log files in a well-established, systematic, and solid protocol to be able to correctly interpret results in the long term and to speed up corrective decisions concerning measures related to the monitoring.

4. Discussion and Conclusions

The development of an efficient and focused monitoring technique with results useful for the preventive conservation of cultural heritage depends, to a high degree, on a deep knowledge of the thresholds of decay that are acceptable or not acceptable to maintain the aesthetic, historic, and cultural values of aged and weathered materials. There is a need to define acceptable thresholds of several types of degradation processes through experience by conservators who work on real objects in situ as well as from experience gained during laboratory tests by heritage scientists working with imitation samples and with aging tests and/or simulations in climate chambers. However, during such laboratory work, it is important to involve to a high level an interdisciplinary reference group with competence in climate-related decay in buildings. Improved knowledge of degradation thresholds will allow conservators to intervene in time to mitigate the impacts of climate change on historic buildings by applying a preventive (early warning) intervention method.

More efficient monitoring could also be achieved by the use of refined and customized information technologies. For example, methods for uploading documents and monitoring data as well as by the systematic use of more detailed photos.

One of the main objectives of long-term monitoring is to calibrate and validate climate and building simulations aiming to assess future risks. In order to be able to use theoretically simulated climate conditions and degradation processes as a base for real monitoring in the future, it is necessary to further examine existing simulation programs, test them, and compare them with monitoring results. The results of the EU project Climate for Culture could be used for combining simulation results with existing monitoring results [24]. It will, thereby, be possible to both develop simulation models further and to establish more efficient monitoring programs. Additionally, by linking simulations and monitoring, it will be possible to better manage proactive restoration work. Through a closer connection between monitoring and adaptation, both risk assessments and the preservation of cultural heritage values will be improved, which is illustrated in Figure 9.

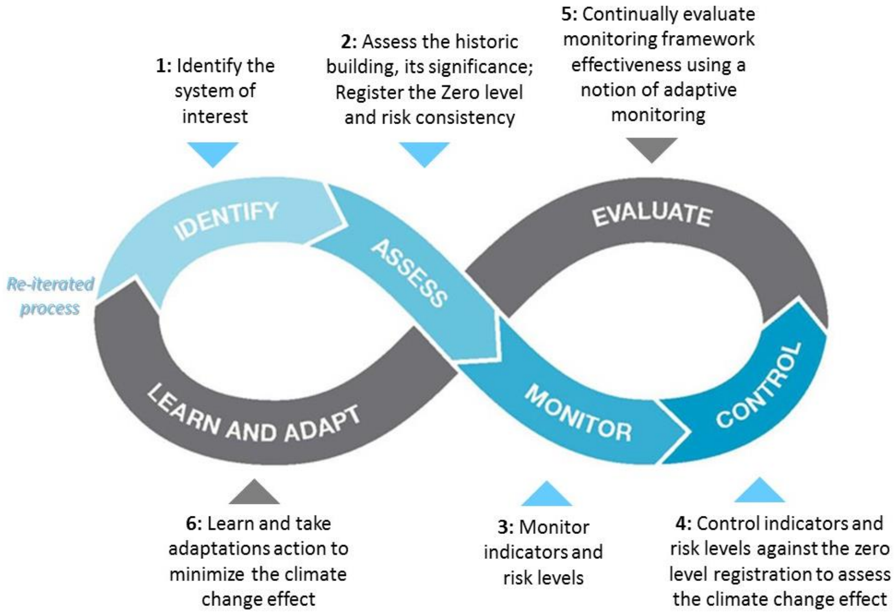

Figure 9. Through a closer connection between monitoring and adaptation, the risk assessment and preservation of cultural heritage values will improve.

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