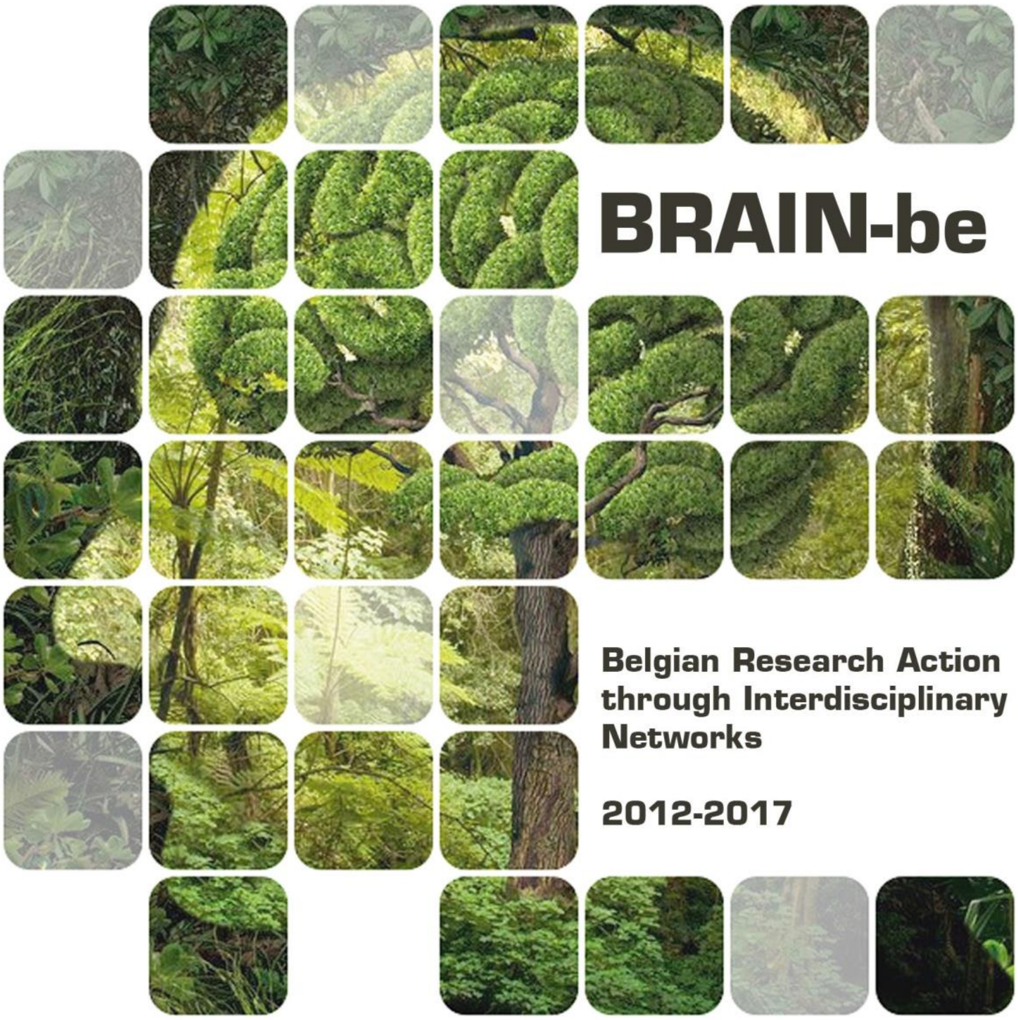

AIRCHECQ

Air Identification & Registration for Cultural Heritage: Enhancing Climate Quality

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AIRCHECQ

Air Identification & Registration for Cultural Heritage: Enhancing Climate Quality

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FINAL REPORT

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ABSTRACT

Context

The environmental conditions have a profound impact on heritage conservation: optimal conditions can significantly prolong the lifetime of heritage objects. The most common way to evaluate the environmental preservation conditions, is to monitor temperature, relative humidity, the intensity of visible light and UV radiation and visualize the trends using line graphs. However, the evaluation of the environmental appropriateness from such graphs is not straight forward.

Objectives

The project developed several methods and tools that allow heritage guardians to evaluate the indoor air quality. A work process that formalizes the inspection of rooms, a monitoring system that is also able to monitor the concentration of particulate matter and gaseous pollutants, and software that converts the measurements into indoor air quality assessments give heritage caretakers the possibility to make better choices about the most appropriate mitigation actions that are needed.

Conclusions

To convert measurements of environmental parameters into indoor air quality, a new conceptual framework was built. That framework allowed us to build a decision support system that guides heritage guardians in selecting mitigation actions to improve the indoor air quality and thus the preservation conditions of indoor collections in heritage buildings.

Keywords

Preventive conservation, Cultural heritage, Indoor air quality, Particulate & gaseous pollutants, Mitigation actions

1. INTRODUCTION

Cultural heritage is a fundamental source of individual and group identity, vitality and solidarity. It connects people with our past, asserts our similarities with and differences from another. Heritage is a shared and public good that should be protected against the threats of the 10 agents of deterioration (e.g. incorrect temperature and relative humidity, pollutants, light and radiation, etc.) (Michalski, 1990). Although we are not always aware of its importance, it is obvious when following the news. For example, the website www.standaard.be gives 288 results when searching on the keywords 'erfgoed' (i.e., heritage) and 'schade' (i.e., damage). Or it affects us when irresponsible conservation-restoration actions result in irreversible damage of priceless objects (e.g. the failed attempt to restore a fresco of Ecce Homo by an untrained amateur in Borja, Spain in 2012, shown in Fig.1, or the adhesion of the beard of Tutankhamen by the museum caretakers using improper glue in Cairo, Egypt in 2015). Its importance is even felt more when it is the victim of deliberate destruction and looting during conflicts (e.g., the destruction of the Stari Most Bridge in Mostar, Herzegovina during the Balkan War in 1993, Buddhas of Bamiyan dynamited in March 2001 by the Taliban shown in Fig. 2, Temple of Baalshamin in Palmyra blown up by ISIL in July 2015, etc.).

Fig. 1a: Fresco of Ecce Homo in Borja, Spain in 2012 before and after the so-called restoration.

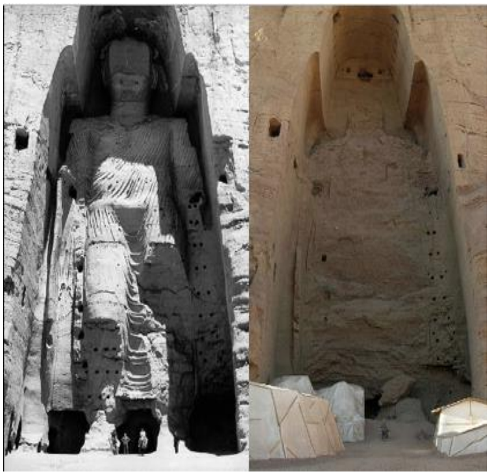


Fig. 1b: Buddhas of Bamiyan dynamited in March 2001 by the Taliban before and after its destruction.

It is the responsibility of the heritage guardian to preserve the patrimony we inherited from our ancestors and to pass it on to our children with a minimum of damage. This is a Titans work because the heritage sector is taking care of collections that consist of millions of objects. For example, the Royal Museum of the Armed Forces and Military History in Brussels is responsible for more than 300.000 objects, resulting in exhibition rooms that are fully packed. If we assume that each object of that collection requires a conservation-restoration treatment every 50 years (i.e. once every generation), it is almost impossible to give all objects a proper treatment due to lack of time or budget (16 objects per day including all weekends and holidays). Public budgets are limited, while high tourist influxes increase revenues but result at the same time in enhanced environmental and physical pressure. *Preventive conservation* (all terms in italic are defined in annex 1 at the end of the report) is considered as a solution to this problem. It entails all measures and actions aimed at avoiding and minimizing future deterioration or loss. The measures and actions are carried out within the surroundings of an object and are indirect. They do not interfere with the materials and structures of the items and do not modify their appearance. An example of a preventive conservation action is improving the environmental preservation conditions (light, humidity, pollution and pest control) to slow down the *degradation rate* of the entire collection.

The AIRCHECQ project does not consider the 'most appropriate preservation conditions' as a technical solution that eliminates all problems at once, but as a goal that should be strived for. That goal is reached by a chain of mitigation actions that reduces the probability of *hazards* to occur (or lower the impact of occurring hazards). The adaptation of preservation conditions by performing a sequence of actions is for that reason a continuous process where the average degradation rate v of a collection is systematically reduced towards zero. Mathematically, that goal can be described as the limit of the function $v(t)$ (i.e., the average degradation rate of the collection over time). As time approaches infinite ∞, $v(t)$ will reach 0 but never attain that value. That goal is illustrated in Fig. 2 as the end-point that must be reached.

$$\lim_{t\to\infty} v(t) = 0$$

At a management level, preventive conservation means the allocation of resources to realize a sequence of (low-cost) mitigation actions that are sufficiently good for the time being, interspersed with (high-cost) drastic mitigation actions. The sequence of mitigation actions must be considered as a specific path in a roadmap of many possibilities as is illustrated in Fig. 2. Each path contains moments where decisions must be made (e.g., select the most appropriate action). These moments are shown as nodes. Due to a lack of information, there is always some uncertainty about the decision taken. This means that the AIRCHECQ approach must be considered as a decision-making process under conditions of *uncertainty*. Such an approach is already considered in the heritage community by others (Waller, 2003). It is not completely known if the resources will be invested in the best possible mitigation action. In addition, investments are made in something that remains invisible (i.e., reducing future harm).

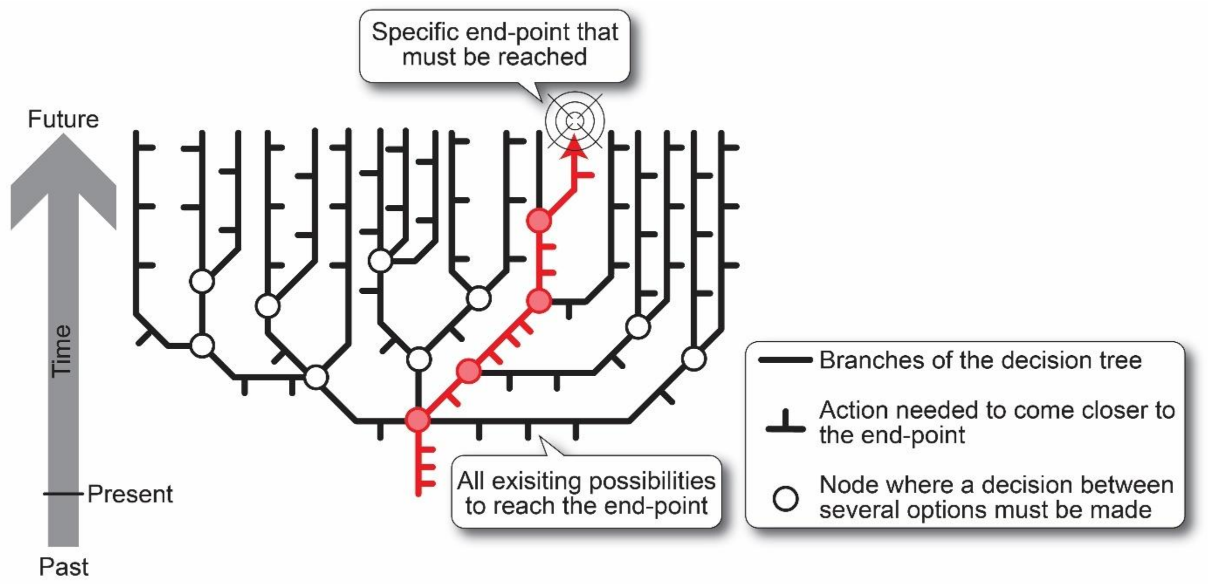


Fig. 2: AIRCHECQ approach of preventive conservation where a decision-making process is needed to find the most appropriate road in the numerous possibilities to achieve the end-point. The road map consists of decision nodes and actions.

The aim of the AIRCHECQ project was to assist heritage guardians in the implementation approach of preventive conservation as a *decision-making* process, focusing on environmental conditions. To support heritage caretakers in that approach, 3 practical tools with a Technology Readiness Level between 4 to 5 had to be developed. The tools are described in the list below and visualized in Fig. 3. The combination of tool 2 and 3 forms a *decision support system* (see annex 1 for its definition).

- **Workflow:** A workflow is developed that allows heritage guardians to consider preventive conservation as an ongoing decision-making problem where appropriate preservation conditions are strived for.
- **Monitoring unit:** A ready to use measurements box is developed with a minimal number of affordable measuring instruments, which can be lend to collection caretakers;
- **User-friendly software:** The monitoring unit is accompanied by a user-friendly software that is able to process the collected data stream, allowing laypeople to evaluate indoor air quality. The software also enables the processing of data collected with devices that heritage guardians use;

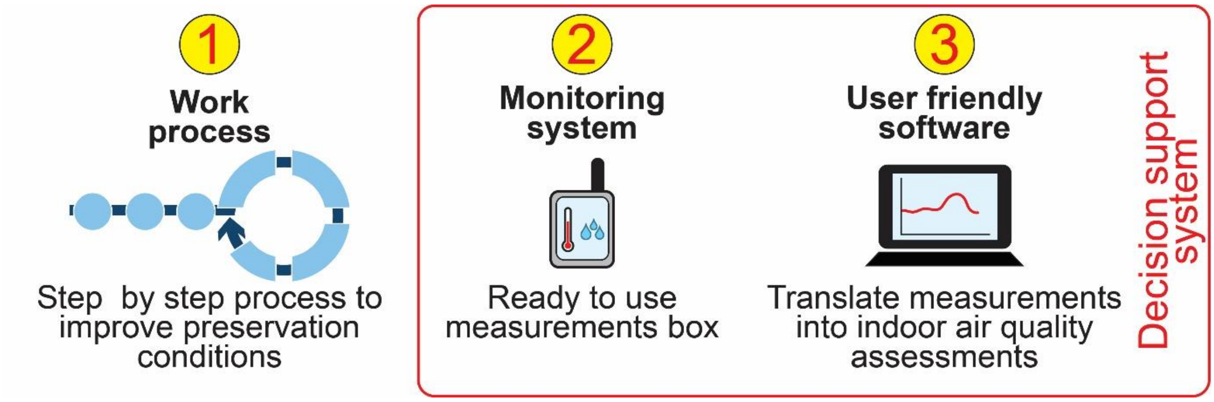


Fig. 3: Overview of the final deliverables of the AIRCHECQ project. The first 2 deliverables form together a decision support system. The work process describes how preventive conservation can be performed practically as a decision-making process.

2. STATE OF THE ART AND OBJECTIVES

To get an insight in the state of the art of *preventive conservation* it is necessary to describe the complexity of the problem first. The complexity will be illustrated by the many relations that exist between *hazards*, environmental parameters, degradation mechanisms and the loss in value. In addition, the numerous degradation mechanisms of materials occurring simultaneously can be grouped in 2 different categories: a continuous approach and a discrete approach. Then, the different methods will be described to collect information about preservations problems.

2.1. Complexity of the problem: numerous relationships

The complexity of the relationships between hazards, environmental parameters, degradation mechanisms (i.e., response of materials) and the loss in value of objects is illustrated in Fig. 4. The arrows between the elements in adjacent sets visualize what elements affect each other. The complexity of the problem is even worse than Fig. 4 suggests because the elements in the sets are only exemplary cases and not all relations are visualized. In the list below, the 4 sets are described in more detail.

- **Set A in Fig. 4:** Set A contains all the *hazards* (i.e., dangerous phenomena or conditions that might harm objects) to which a collection is exposed to. Several types of hazards can affect the same environmental parameters. For example, sun light, acclimatization systems and the presence of people influence the temperature inside a room;
- **Set B in Fig. 4:** This set contains all the environmental parameters that drive the degradation processes. They describe the *exposure* of a collection towards hazards. Due to many-to-one relationship between hazards and environmental parameters, it is not straight forward to identify hazards from environmental measurements. Set A and B contain valuable information about the probability that preservation conditions might lead to a harmful situation;
- **Set C in Fig. 4**: This set contains the responses of all heritage materials present in the collection. Since heritage collections consist usually of a large variety in materials in a

single room, a wide range of degradation mechanisms will occur simultaneously. All these degradation mechanisms are influenced in their own way by the environmental parameters in set B. Moreover, the response determines how fast the heritage collection will accumulate harm;

- **Set D in Fig. 4:** People attribute a certain appreciation to materials that endured degradation (e.g., the green patina of bronze statues is due to corrosion but is appreciated, the yellowed varnish on a painting is considered as disturbing). This appreciation is found in set D and is an interpretation of the response of materials in set C. Set C and D give valuable information about the impact of harmful situations on the collection.

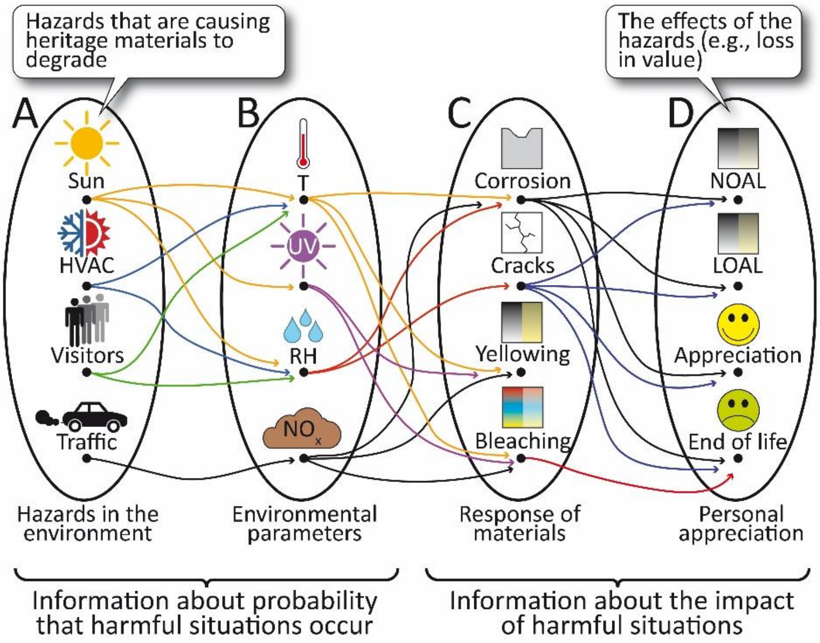


Fig. 4: The complex relationship between cause (i.e., the hazards in set A) and effect (i.e., loss in heritage value in set D).

The visual inspection of a collection (e.g., condition reports) gives an insight in the actual preservation state of a collection. It delivers information of set D and C. The goal of preventive conservation is to select the most appropriate decisions to minimize the hazards in set A. Fig. 4 shows that preventive conservation based on a tactile approach is a backward process where the consequences are analysed and with that information the causes of the problems are mitigated.

2.2. Complexity of the problem: continuous vs. discrete exposure to hazards

As shown in Fig. 5, a heritage collection can be exposed to hazards in 2 different ways. The most common *exposure* model to hazards is the one where the *degradation rate* of an object/collection is governed by environmental parameters. The aggressiveness of the environment is omnipresent at all moments but can vary over time. Sudden moments of enhanced aggressiveness can occur at random moments. In the other exposure model to hazards, the environment is described by a sequence of randomly occurring stressful moments that might lead to harm. Between the stochastic exposure of stressful moments, there is no accumulation of harm. The 2 exposure models are described below.

- **Stochastic exposure to hazards:** Collections are exposed to hazards during discrete and short periods of time. These occasions with random hazard intensity occur at random occasions and are interspersed by (longer) periods without any exposure. These occasions are denoted as *undesirable situations*. Some of these situations are characterized by such a small hazard intensity that a collection will not be affected by it. Other situations will have such a disastrous impact that we call them calamities. The severity of the exposure is described by the fraction of time to which a collection is exposed to hazards or the frequency of sporadically occurring exposures and the impact that each undesirable situation has on the collection;
- **Continuous exposure to hazards:** The *degradation rate* is a complex function of several environmental parameters (e.g., relative humidity, UV radiation). When the environmental conditions remain constant, the degradation rate will be nonzero but constant as well. However, at some moments the environmental conditions can be such that the degradation rate decreases of increases. With the continuous exposure model, the total accumulation of harm is estimated using the accumulated exposure dose (i.e., exposure level multiplied with the total length of the exposure time) or using the average exposure level.

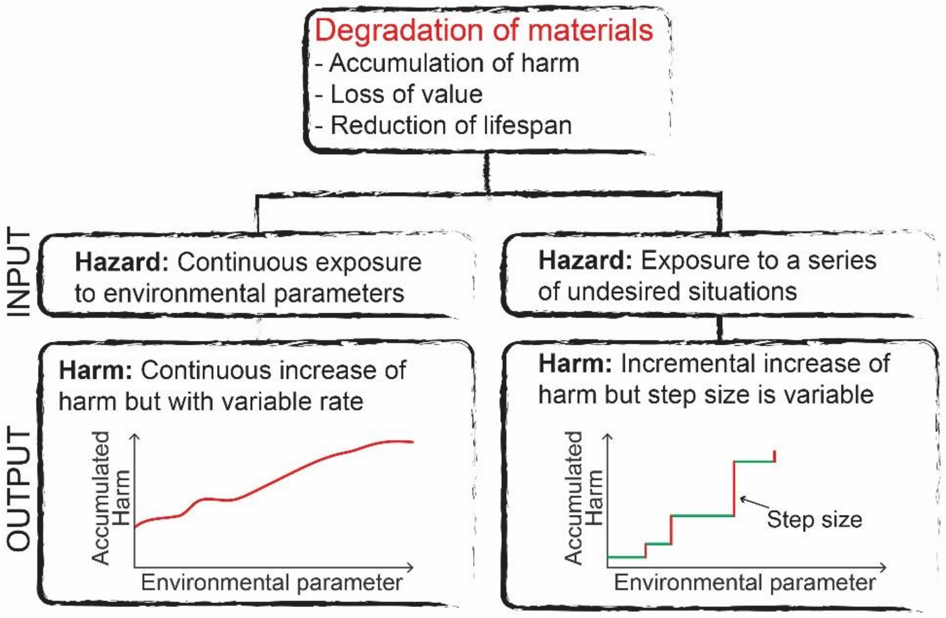


Fig. 5: The 2 different exposure models to describe the impact of the environment on the accumulation of harm by a collection.

The phenomena behind the 2 models in Fig. 5 cannot (always) be considered as independent processes. For example, the impact of relative humidity on the degradation rate of an object is usually estimated using a continuous exposure model. However, the random fluctuations in relative humidity that is often observed can also be approached as a sequence of randomly occurring moments where the hazard intensity is described by the relative humidity. Some of these moments have a low hazard intensity that do not contribute (much) to the accumulation of harm. At other occasions, the environmental conditions suddenly change due to a much higher hazard intensity. That intensity is accompanied with unacceptable *risk* for damage. In cases where an environmental parameter fluctuates over time, the continuous exposure can be described as a stochastic exposure as well. Some estimate the aggressiveness of the preservation conditions by the fraction of time where the hazard intensity is unacceptably high.

In the following example, both models need to be combined to estimate the *degradation rate* of a collection. For environmental parameters such as visible light and UVA-radiation, the impact of the exposure is typically considered by the continuous approach using the concept of exposure dose (e.g., radiation dose is the total amount of absorbed radiation energy within the duration of exposure). The impact of earth quakes is a typical example of stochastic exposure. In other cases, the degradation of heritage materials is best described by a combination of both models as is the case for relative humidity that is composed of randomly occurring peaks or valleys superposed on a slowly changing background. In such cases, it is not always clear what model should be used.

2.3. Complexity of the problem: interest in degradation rates vs. measuring environment

It is paradoxical that the heritage community has the habit to monitor only environmental parameters to determine the aggressiveness of the environment, while their main concern is the behaviour of their objects. In the best case, the degradation process of an object is monitored by analysing the preservation state (i.e., a distinction must be made between preservation state and degradation process) of a sequence of moments. To illustrate: shrinkage and expansion of wooden panels or statues should be avoided, discoloration due to photochemical reactions are undesired, while the blackening of silver objects is aesthetically displeasing. Below are several reasons that explain this paradox:

- Despite the presence of gradients in environmental conditions inside a room, it is much more homogeneous compared to the large variety of responses of all materials present in the same room. For that reason, the analysis of the preservation conditions requires less measurement devices;
- The number of objects in a room can be so large that it is nearly impossible to analyze them all. Analyzing a small number of objects is also problematic because heritage collections are usually so heterogeneous that the representativeness of the samples can be questioned;
- The heritage sector demands that interventions on heritage objects do not leave traces in the long term. Because of this limitation, the required information about the behaviour of

materials can hardly be measured in a direct way. For example, gluing strain gages is an irreversible action which is usually not allowed.

2.4. Problem solving: The role of intuitive and rational data collection

In the field of *decision-making*, it is generally accepted that information is collected through a dual-process. This dual-process approach starts from the idea that human judgements are influenced by both rational processes where data is collected in a controlled, voluntary and effortful way (e.g., measurements, inference, etc.) and intuitive processes where information is automatically and effortlessly recognised (e.g., visual inspection). Intuitive processes evolve with experience and learning and occur outside the conscious thought. Some methods such as risk analysis explicitly combine both processes. In that method the impact of former *incidents* on heritage collections is evaluated by visual inspections (i.e., an intuitive process) while the probability that the same incident will reoccur in the future is usually estimated with an elaborated inference from a substantial amount of information (i.e., a rational process). In the list below the role of both processes is described more in detail.

- **Intuitive process:** To solve practical preservation problems or to improve the preservation conditions of a heritage collection, heritage guardians usually rely on *visual cues* (i.e., visual features that attract the observer's attention to a particular area and that allow the observer to estimate a physical property) (Fleming, 2014). Such information can trigger the selection of a mitigation action (Henderson and Waller, 2016). Mitigation actions can also be selected using other kinds of sensory cues (e.g., close the curtain to avoid too much light, open the window because it is too warm).
    - **Visual inspection of collections:** The preservation state of objects can be estimated from visual cues such as cracks or discolorations. For that reason, regular visual inspections are considered as important in cultural heritage. The disadvantage of this method is that the *hazards* cannot be identified until there is visible damage.
    - **Visual analysis of graphs:** Visual cues are also used in the evaluation of the appropriateness of environmental conditions by the peaks and drops in temperature and relative humidity graphs.
- **Rational process:** In the heritage community, different kinds of measuring systems are installed to measure temperature and relative humidity. An overview of such systems is given in Fig. 6. In some cases, that information is supplemented with the intensity measurements of visible light and UV-A. Besides the access of the absolute value of certain environmental parameters, also the trends of these parameters are of interest.

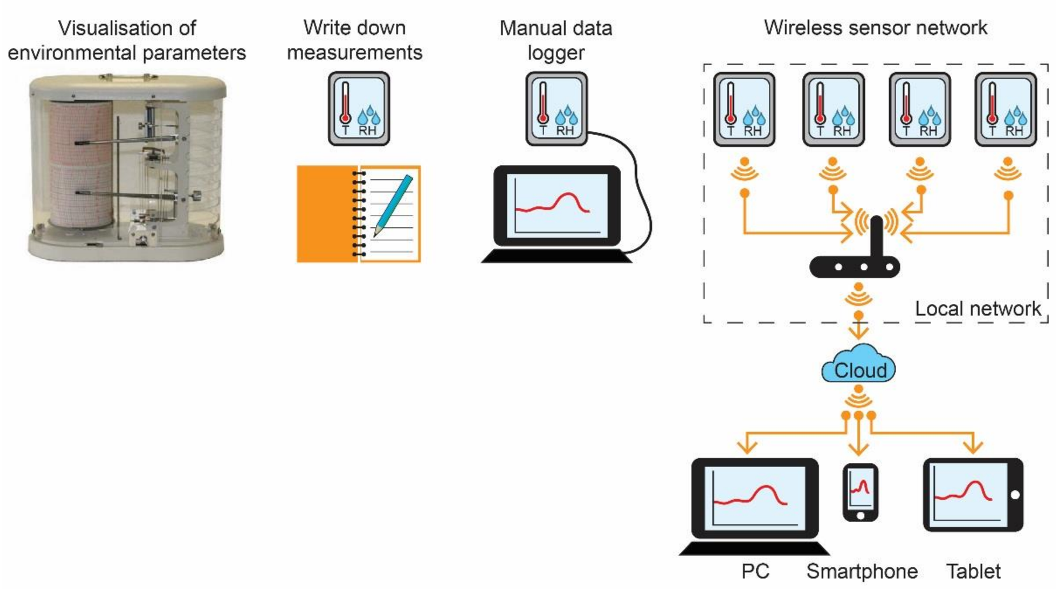


Fig. 6: Different methods that are used to monitor the temperature and relative humidity going from the thermo-hygrograph (completely left) to a network (completely right) where measurements are accessible in real time.

The AIRCHECQ project considers both data collection processes as important. The project has developed tools that help heritage guardians in decision-making by focussing on the rational process (i.e., data collection and data processing using final deliverables 2 and 3 in Fig. 3). The bridge between intuitive and rational approaches is assured by maximizing the intuitive access of huge amounts of measurements using visualization techniques.

2.5. Problem-solving: Time-averaged versus continuous measurements

The measurement of environmental parameters gives a good insight in the *exposure* of a heritage collection towards endangering *hazards* because their values and trends are affected by many hazards. The environmental parameters can be measured in 2 distinct ways (see description in list below).

- **Time-averaged measurements:** A measuring device determines the average value of an environmental parameter for a given period. An example of such a measurement is the analysis of chemical pollutants using diffusion tubes. Another example is the determination of the corrosion rate of metal coupons by analyzing the total amount of corrosion product formed within a period of 3 months. The disadvantage of this approach is that much information about trends are lost;
- **Continuous measurements:** There is a huge number of sensors that can be purchased on the markets that are able to sense the environment in real time. Some of them are extremely cheap (e.g., a motion sensor) while other ones have a certified calibration and costs several hundred euro. Their main advantage is that they can see trends.

The environmental trends give important information about the (partially) unknown and complex relationships between hazards (set A) and environmental parameters (set B). For that reason, the AIRCHECQ project focused on continuous measurements. Moreover, this approach does not require a labour-intensive post-analysis as is the case with diffusion tubes and the results can be available in real time.

2.6. Problem-solving: Different input-output models

To solve preservation problems, it would be useful to have a model that describes the relation between the *exposure* of collections to *hazards* and the accumulated damage of collections. The exposure to hazards is the reason why heritage collections accumulate harm. Therefore, exposure can be considered as the input of cause-effect relationships. In a simplistic approach, such cause-effect relationships are described by a linear function. (see Fig. 7). In that model, 2 critical parameters play a role:

- **Sensitivity:** This parameter describes how much a collection is affected by the exposure. The *sensitivity* is the slope of the linear function;
- **Resilience:** This parameter describes the ability of a collection to resist harm and change when exposed to hazards. *Resilience* is considered as a threshold value: apparent forces below that threshold do not result in harm, forces above that threshold result in permanent harm. That threshold can be interpreted as a yield point that distinguishes elastic deformation from plastic deformation as is the case in stress-strain curves.

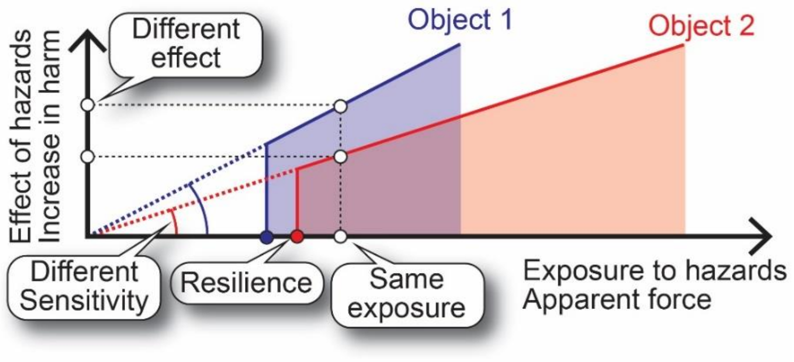


Fig. 7: The relationship between exposure and the effect on a collection and the effect of resilience and sensitivity. The coloured zones visualize the ranges where the linear relationships are valid.

It is a common practice to measure environmental parameters and from these measurements estimate the corresponding effect on materials. Therefore, the relationship between environmental parameters (i.e., input) and *degradation rate* (i.e., output) plays a crucial role in *preventive conservation*. The rather simplistic approach of that relationship as visualized in Fig. 7 can be approached in a more elaborated way using 4 different methods. Each approach is described in the list below and is illustrated in Fig. 8.

1. **Understand cause & effect relationships:** Degradation mechanisms need to be elucidated to understand the relationship between environmental parameters (i.e., input of the model shown in case 1 Fig. 8, set B in Fig. 4) and the degradation rate of a series of common heritage materials (i.e., the output of the model, set C in Fig. 4). Besides understanding the degradation mechanism, also the ability to estimate degradation rates is needed. The method to obtain that insight is based on decomposing the problem in many subproblems (e.g., using a large variation of experiments under well-controlled conditions by numerous scientists). Then, the overall behaviour of the mechanism is reconstructed by combining all these components. The mathematical description of how a material degrades can be considered as the contents inside the white box of case 1 in Fig. 8. However, all models are in principle wrong in the sense that they simplify reality. Despite the simplification of reality, models are useful when they give a good approximation of that reality. Despite the proceeding deepening of our understanding, the exact degradation mechanism for many materials is still insufficiently understood. There is still too much *uncertainty* on these relationships. For that reason, they do not give a reliable estimate of degradation rates. Therefore, degradation models are insufficiently accurate to be usable. In fact, the contents of the box is not white as shown in case 1 of Fig. 8, but rather grey. In addition, we cannot wait to protect our precious heritage against environmental aggressiveness until a fully understanding is achieved.
2. **Degradation mechanism as black box:** The relationships between input and output are unknown, but with (accelerated) degradation experiments under well-controlled conditions it is possible to measure the degradation rate (i.e., output) for given environmental conditions (i.e., input). The relationships between environmental parameters and the degradation rate are then described by a best-fitting mathematical function but without any knowledge of the internal workings of the box (i.e., *black box*, see case 2 in Fig. 8). These relationships describe the overall behaviour of the degradation mechanism without considering all the separate issues/subproblems of that mechanism. They enable the prioritization of the agents of deterioration and the definition of damage *thresholds* (Leissner et al., 2014, Strlic et al., 2015, Strlic et al., 2013). An example of such a dose-response function is the preservation metrics developed by the Image Permanence Institute (Nishimura, 2011). Unfortunately, dose–response functions are not available for all materials. Secondly, the degradation of a material is often influenced by the way it is integrated in the heritage object. Finally, the experimental conditions under which the functions are determined are not necessarily representative of natural conditions. Therefore, this approach is impractical for a generalized evaluation of the preservation conditions.
3. **Risk analysis approach:** Over the last two decades, risk assessments for collections have made their appearance in the heritage sector (Waller, 2003, Michalski and Pedersoli Jr., 2016, Pedersoli Jr. et al., 2016). Such assessments tackle the following questions (Brokerhof and Bülow, 2016): What might happen? How likely is that? What will the consequences be? Risk analysis is a backward approach. It starts with the analysis of past effects of hazards (Set C in Fig. 4). With the limited knowledge inside the box (i.e., for

that reason the box in Fig. 8, case 3 is grey) it is possible to identify some of the hazards that cause the harm (set A in Fig. 4). That information allows to make statements about the environmental conditions from the past (i.e., at what frequency *incidents* occurred). Since incidents from the past can reoccur in the future, it is possible to prioritize some *mitigation actions* in an informed way. However, such risk assessments are often time-consuming, require considerable expertise and the analysis gives only an insight for a given moment in time and not in the evolution over time (Ashley-Smith et al., 2013). In addition, this approach cannot be used to process the measurements of temperature, relative humidity and other environmental parameters.

4. **Use limited knowledge about mechanism:** There is a huge amount of literature concerning the degradation of historic materials. Unfortunately, that information is overwhelming, not well-structured, fragmented, insufficient and sometimes contradictory. Besides the complexity of the input-output relationship, the holes in our knowledge due to insufficient information, there is also insufficient time. We cannot wait to protect our heritage until the input-output relationships are well understood. An alternative approach is to simplify the problem and use expert intuition or gut feeling to estimate degradation rates. The simplified problem-solving methods usually ignore a great amount of existing information and deliberately avoid much computation rather than aiming for as much as possible of both. Such problem-solving strategies are known as *heuristics*. Although heuristics are usually associated with intuitive thinking, the AIRCHECQ project is using them in a rational way. The approach is illustrated in Fig. 8, case 4. The use of heuristics does not guarantee optimal, perfect, logical, or rational answers, but are enough for reaching an immediate goal. The AIRCHECQ project used 2 strategies:
    - **Simplify the problem:** The complex problem of estimating the degradation rate is replaced by a related but easier to answer question. In the AIRCHECQ project, the question about estimating the degradation rate of materials was replaced by the question when periods for enhanced *risk* of degradation occur;
    - **Simplify the task:** The complex task of estimating degradation rates from the degradation mechanism can be simplified by using rules of thumb that describe the overall behaviour of degradation processes in a simplified way. A *rule of thumb* is a broadly accurate guide or principle, based on practical experience rather than theory. It is possible to extract several simple *rules of thumb* from the literature. With these rules of thumb, periods for elevated *risk* for accelerated degradation can be identified.

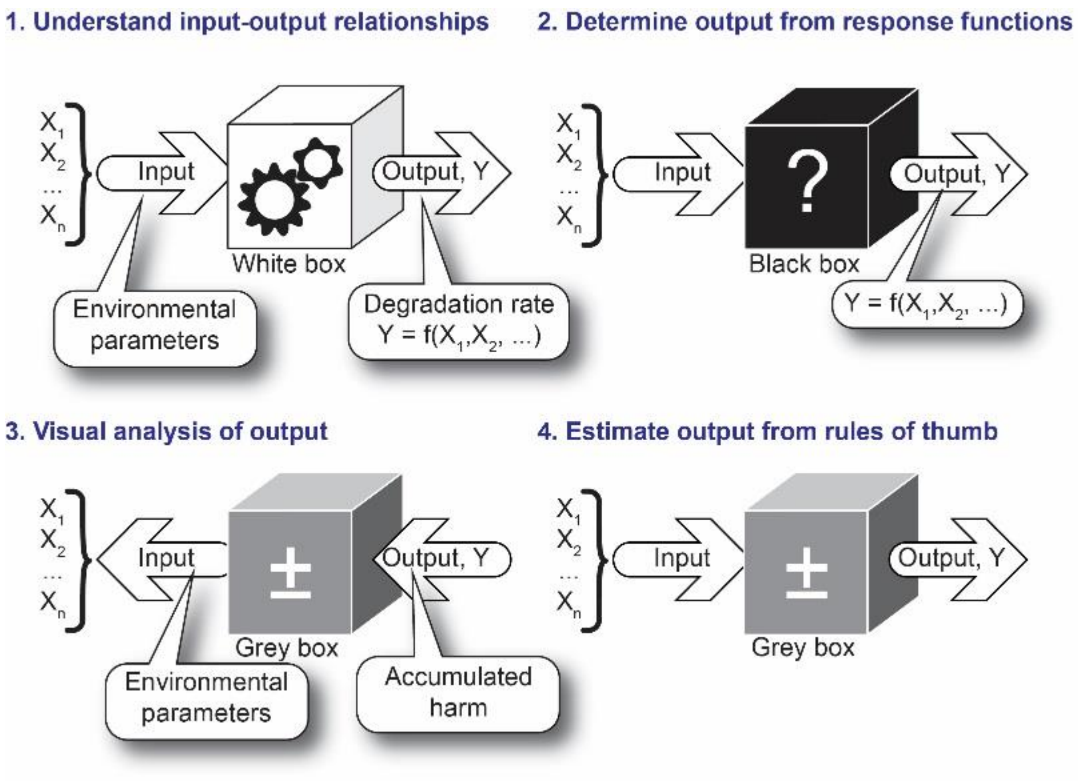


Fig. 8: Different approaches to estimate the degradation rate of materials.

The first 3 approaches in Fig. 8 summarizes the state-of-the-art. The academic community tends to focus on the elucidation of degradation mechanisms (case 1) or the elucidation of the overall degradation behaviour (case 2). The heritage community has a clear preference for case 3 because it is practical and sustains the preventive conservation approach as a decision-making problem. During the AIRCHECQ project, we have chosen to develop a new approach (i.e., case 4). That approach is described in the paragraph about methodology.

2.7. Problem solving: Solutions as a risk

Heritage guardians know that the selection of a mitigation action can be a *risk* because it is sometimes difficult to know in advance if it will have the desired effect. A decision that turns out badly is a loss of valuable resources or can even endanger the collection. People generally tend to avoid risk and loss and so do heritage guardians when they fear to make a wrong decision (i.e., risk aversion (Kahneman and Tversky, 1979)). It can tempt heritage guardians to postpone decision-making, unless they know that waiting is even worse.

3. METHODOLOGY

The design of the deliverables was refined during the numerous discussions with stakeholders. Stakeholders emphasized that it should help them in looking at data. According to them, decision-makers are easier convinced of the importance of mitigation actions when the environmental dangers are visualized in a single image instead of using many abstract numbers and graphs. Finally, a cheap, small and aesthetically pleasing data logger is preferred. These additional boundary conditions were considered during the project but could not all be realized during the course of the project.

One of the final deliverables of the project is the formalized work process shown in Fig. 9 (i.e., final deliverable 3). That work process is used to find weak spots in buildings and inappropriate environmental conditions that need to be improved. Another important final deliverable from the project is the monitoring unit (i.e., Final deliverable 1) that can measure several environmental parameters simultaneously. The data collected with that device is processed with a user-friendly software that converts the measurements in *indoor air quality* colour bars (i.e., Final deliverable 2). The colour bars can easily be read by laypeople. The monitoring unit and the software forms together a *decision support system* that visualizes the periods where preservation problems occur. In that way, the decision support system helps heritage guardians in the identification of *hazards* (i.e., the moments when they occur are known) that endanger their collection. The identified hazards define the list of possible mitigation actions from which an action must be chosen. Fig. 9 visualizes how the 3 final deliverables are interconnected with each other.

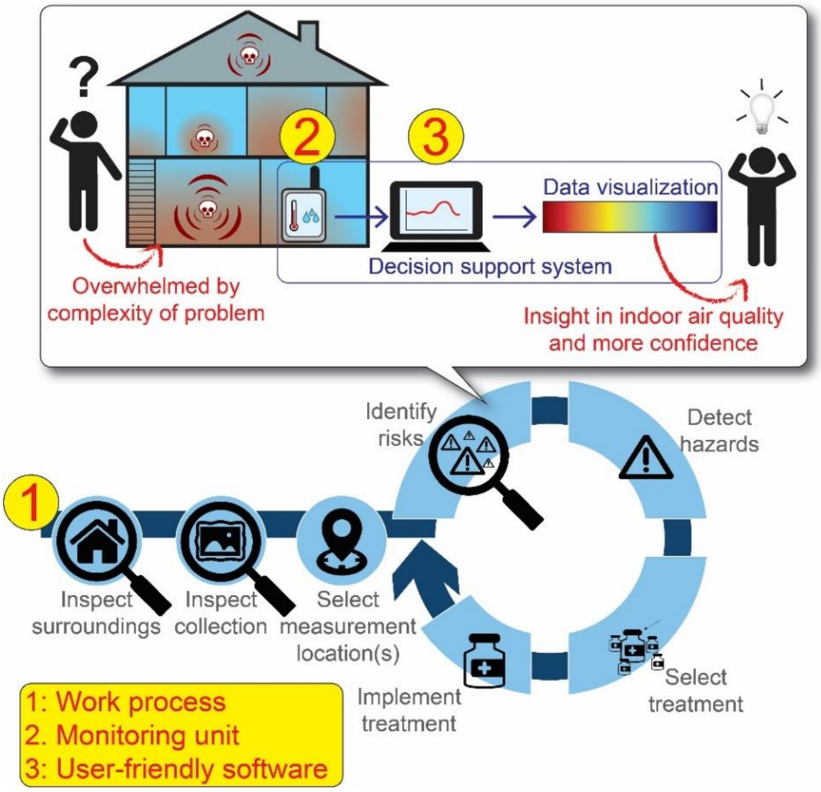


Fig. 9: Overview of the subsequent steps in the work process used to improve preservation conditions and the role of the monitoring unit and the software in that process.

In this paragraph, the 3 main deliverables of the AIRCHECQ project will be described in consecutive order. It includes the measurements that substantiate the methodology. These measurements do not have the intention to fully characterize a specific location in a museum, archive or church but were part of the development process of the methodology. In the next paragraph, the results of several case studies will be given. The paragraph about results entails the measurements obtained by applying the work process, the monitoring unit and/or the software on the specific case studies. The central problem of the case studies are preservation issues which can be answered/solved by the AIRCHECQ tools.

3.1. Deliverable 1: Data collection with the monitoring unit

3.1.1. Development of a measuring system

When it comes to indoor heritage collections, the overall environmental quality is ideally evaluated by considering not only physical parameters (e.g. temperature, relative humidity, intensity of visible light) but a much wider range of parameters. While several cheap and relatively easy-to-use commercial systems are commonly used to monitor physical parameters with high-time resolution (seconds to minutes), other parameters such as chemical pollutants (e.g., diffusive samplers for gas pollutants, impactors for PM sampling) are still analysed using discrete methods (days or weeks of sampling time). However, by studying only average concentrations of pollutants, a large part of the information on short-time variations and sudden decreases in the *indoor air quality* (IAQ) are inaccessible. Due to this lack of information, it is hard to estimate the real *risk* to which heritage materials are exposed to. This hampers the recognition of *hazards* behind unacceptable IAQ values and impedes the deployment of adequate mitigation actions.

Small, simple to use and low-cost sensors represent the future of IAQ monitoring. New technologies allow important steps forward in the development of always smaller and more affordable sensors for the monitoring of a larger range of parameters such as PM, gaseous pollutants, wind speed, motion, etc. Even though these solutions are usually not appositely designed for the application in museums and conservation environments, the size and cost factors make them extremely appealing. To explore the possibilities of such sensors, it was decided to use a multipurpose data logger (DataTaker DT85, Thermo Fischer scientific, Australia) to which an extensive combination of off-the-shelf sensors is connected. Fig. 10 gives an overview of the architecture of the monitoring system. The architecture consists of a consecutive series of components as described in the list below:

1. **Measurement nodes:** The measuring chain starts with the measurement nodes (left in Fig. 10). Two types of measurement nodes can be used: (1) battery operated sensors installed at diverse locations that transmit their data wirelessly to a base station (e.g., sensors from the company Wisensys) that is coupled to the data logger, and (2) several wired sensors located close to each other. Only wired sensors can be used that generate a voltage, current or resistance as a signal. In some cases, sensors also need to be connected to a specific power supply (5V, 12 V, 24 V, etc.). In other cases, the sensor needs to be implemented in a Wheatstone bridge. All these additional wiring is put inside metal enclosures to obtain a stable signal. A major issue at this level is the complexity of the wiring between sensors, power supply and data logger. In addition, the wiring should be sufficiently stable and at the same time it should allow changes in the setup to adapt the measuring system to specific measuring conditions;
2. **Data acquisition system:** Most sensors generate a voltage, a change in resistance or a current that is proportional to the measured signal. The data logger can measure the electric signal of all sensors simultaneously. One option is that the sensors are read out at a fixed frequency (e.g., every 15 minutes). The option exists to measure for example every second and to calculate the average value of a fixed time interval of for example 15 minutes (i.e., a way to reduce noise) or to determine the maximum value (i.e., for air speed this is the best measure). An alternative measuring method is *event*-based data acquisition, where data acquisition is started after the detection of an event (e.g., temperature exceeds a *threshold* value). During the AIRCHECQ project we used the continuous data acquisition generating times series.
3. **Data transfer:** Data can be downloaded wirelessly by connecting the data logger to a 4G router. With this option, the data can regularly be uploaded and checked. This option is useful when the location of the measuring system cannot be visited regularly.
4. **Central base station:** All uploaded data is brought together in a single data matrix using Excel. The data matrix consists of many measuring points (matrix rows) that is collected every 15 minutes. Each measuring point consists of several measurements obtained

from each sensor (matrix columns are associated to a specific sensor). In addition, each measuring point is labelled with a timestamp. The data of some sensors need to be post-processed (e.g., convert signal in a quantity using a calibration function, reduce noise by using a moving average, etc.). Since the columns contain information about both absolute values and trends, that information is best visualized using graphs.

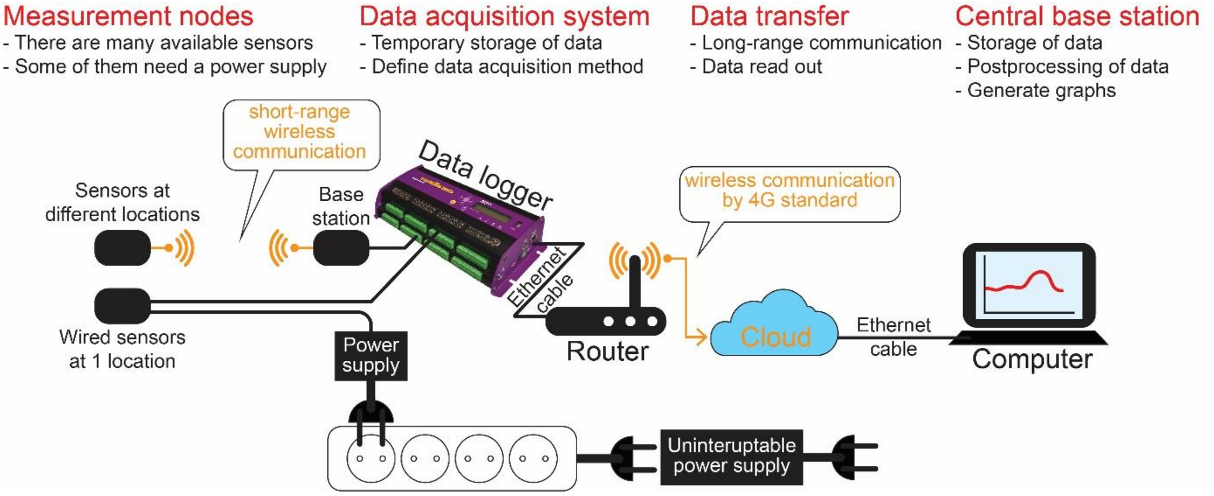


Fig. 10: Architecture of the monitoring unit.

When measuring only temperature and relative humidity with commonly used monitoring systems (as the ones in Fig. 6), many relevant parameters that affect the *degradation rate* of a collection remain invisible. Consequently, the environmental dangers might be underestimated. For example, housekeeping or moving actions in a museum environment may cause a sudden rise in particulate matter (PM). NO_2 and black carbon concentrations may significantly increase inside buildings due to traffic rush hours. Current sensor technology makes it possible to supplement the conventional information (temperature, relative humidity, the intensity of visible light and UVA radiation) with additional environmental parameters such as particulate matter and reactive gases. Since we are interested in the impact of the environment on materials, it would be interesting to monitor directly the material behaviour as well. For this, in-house developed sensors for the shrinkage and expansion behaviour of wood surfaces, as well as sensors for metal corrosion rates were incorporated in the monitoring system. Additional sensors were used to monitor hazard related parameters such as motion or CO_2 (i.e., human activity around heritage objects can be hazardous). Although CO_2 is an environmental parameter, it is not considered as a parameter that affects the degradation rates of materials. However, it is a valuable source of information about what happens in the surroundings of heritage objects. The monitoring unit was able to measure the 3 types of parameters simultaneously using the following sensors:

- **Environmental parameters:** Data of temperature (T), relative humidity (RH) and CO_2 were collected with a GMW90 (Vaisala, Finland). The intensity of visible and UVA radiation was monitored with the upward positioned sensors SKL310 and SKU421, respectively (Skye Instruments, UK). Air speed was measured with a HD403TS omni-directional hotwire sensor (Delta Ohm, Soest, The Netherlands). Concentrations of NO_2 and O_3 were collected with the NO2-A43F and OX-A431 sensors of Alphasense (Essex, UK). Particulate matter was collected with a DC1100 Pro Air Quality Monitor (Dylos Corporation, CA, USA). The measured concentration in number of particles per m^3 has been converted into $\mu g\ m^{-3}$ using an empirical formula provided by the supplier.
- **Material behaviour:** The behavior of two materials was monitored as well. The shrinkage and swelling of the surface of a cube of 16th century oak with a volume of 10 dm^3 was monitored by adhering a PFLW-30-11 strain gauge on the wood using the corresponding PS adhesive (TML, Tokyo). The wood originates from a beam of a historic house and was dated by means of dendrochronology. The beam was not in its original position anymore but kept in the basement of the house. A small piece was sacrificed to be used as a sensor. The metal corrosion sensor is an atmospheric electrical resistance (ER) probe Model 610 consisting of Ag with a thickness of 250 nm (Cosasco Corrosion Monitoring and Chemical Management Systems, Santa Fe Springs, CA, USA). The resistance of this sensitive probe increases with progressing corrosion (Dubus and Prosek, 2012). The wood and silver sensors were directly attached to the data logger using a Wheatstone bridge.
- **Hazard related parameters:** The CO_2 concentration was measured by the GMW90 (Vaisala, Finland) sensor. Human activity was measured with a passive infrared motion sensor with a detection range of 10 m (Panasonic Electric Works, Osaka, Japan).

The monitoring system as shown in Fig. 10 with all the sensors described in the list above requires a complicated wiring. The many wires hamper the setup of the monitoring unit in a specific location. Therefore, the system was built in an open rack to assure transportability and to guarantee contact between the sensors and their environment. Sensors and metal boxes containing electrical components were attached to the rack using Velcro tape so that customization remains possible. The wires were immobilized with Colson cable clamps. The components with a fixed position (e.g.; the data logger) were attached to the metal rack using screws. The rack allowed the transportability of the complete system without dismantling and rebuilding the system.

3.1.2. Validation of the measurement device

Current technology provides many types of low-cost sensors that can generate information with a high temporal resolution. Some of these sensors (e.g., for temperature, relative humidity, visible and UVA radiation) are well-calibrated and do produce reliable information. However, many other sensors are provided with poor quantitative specifications (e.g. unclear effect of temperature or relative humidity on pollution sensors, cross-sensitivity of gas pollution sensors, unclear calibration graphs, etc.). This is the case for sensors that analyse particulate matter (PM) and gaseous pollutants analysis. The independent testing of low-cost PM and gas sensors both in controlled laboratory conditions and in real life environments is a crucial step towards the application to their full potential. A large number of studies tackled this issue in the past few years, but the questions about the reliability of these sensors for the application in different types of environments have only been partially answered.

To fully understand the advantages and limitations of mid-price PM and gas sensors, 2 optical particle counters and 3 gas sensors were tested during a 7-months long monitoring campaign in the St. Martin's church in Aalst, Belgium. These measurements were compared with reference equipment. An overview of the measurement campaign with mid-price sensors and reference equipment can be found in Table I.

TABLE I: Overview of the measuring devices used in a 7-months long monitoring campaign in the St. Martin's church in Aalst, Belgium (between December 2017 and July 2018). Given the relatively high cost of the Radiello® samplers, this analysis was only conducted over a period of 6 weeks (21/12/2017–6/02/2018).

	Mid-price sensors	Reference analyses
PM	• The optical particle counter Dylos DC1100-Pro distinguishes particles in two size channels: particles larger than 0.5 μm and particles larger than 2.5 μm. • Optical particle counter Shinyei PPD20V. This sensor detects particles larger than 0.5 μm.	• Well-calibrated Lighthouse Handheld 3016-IAQ particle counter. It can resolve particles in the range of 0.3 μm – 10 μm into 6 particle size channels (>0.3 μm, >0.5 μm, >1 μm, >2.5 μm, >5 μm, >10 μm).
Gas	• Gas sensors NO2-A43F (Alphasense) for NO_2 • Gas sensor OX-A431 (Alphasense) for O_3 • Gas sensor PID-AH2 (Alphasense) for the total concentration of volatile organic compounds (VOCs)	• Average weekly gas concentration by means of Radiello® passive samplers for NO_2 • Radiello® analysis of O_3 • Radiello® analysis of VOCs with a focus on 7 volatile compounds that are typical for different VOC sources inside and outside the church: o Wooden furniture: αpinene, acetic and formic acid; o Traffic: toluene; o Polyethylene plastic used for temporary protection of the church interior: 2-ethyl-1-hexanol; o Industry: ethanol and ethylacetate.

a) PM sensors

The two low-cost PM sensors tested in this study showed a generally accurate response. These positive results translate into a great potential for the application of these sensors in the IAQ monitoring of churches and historical buildings in general. However, the low-cost sensors have also some limitations and this should be considered when a specific sensor is selected. Positive and negative characteristics of the sensors considered are summarized in Table II. The characteristics in bold are discussed in the list below. In conclusion, the combined use of Dylos and Shinyei represents the best solution for the monitoring of PM particles number concentration in an historical building potentially subject to intense PM *events*. The deviations from the linear response at high concentrations observed with Shinyei can be corrected with Dylos, while at the same time recognizing possible time delays in the Dylos response can be corrected with Shinyei.

- **Accuracy:** Concerning the absolute PM concentration, Dylos presents a linear correlation with the Lighthouse data with an angular coefficient significantly close to unity. The average ratio between the Dylos and Lighthouse instruments (Dylos signal: Lighthouse signal) of 0.71 ± 0.26 reflects the high similarity between the results of the two particle counters.
- **Sensitivity:** The values registered by Shinyei are much lower than the reference values. The signal of the Shinyei of ca. 700 counts/m^3 (i.e., this agrees with the analog output of 3 V) corresponds with a PM concentration of 4.0 – 5.0 x 10^7 particles/m^3. The huge difference in *sensitivity* is related to a low proportionality coefficient linking the measured signal in voltage and the number of airborne particles. According to the manufacturer, the 2 properties are directly proportional, but the proportionality coefficient is not further expressed. The Shinyei signal is not directly expressed in PM concentration and needs a cross calibration with a well-calibrated monitor such as the Dylos to obtain information on the absolute PM concentrations;
- **Saturation:** The tendency of Shinyei to systematically underestimate the real concentration for high PM levels is the consequence of a saturation of the counter. This means that above a certain PM concentration, individual particles cannot be distinguished. This drawback of the instrumental design is mentioned by the manufacturer itself, indicating a nominal upper limit of the linearity range of 3 to 5 x 10^7 particles/m^3. Up to this concentration, the Shinyei shows a good linear correlation with the reference data. If detecting the presence and the magnitude of intense PM events is the aim of a measuring campaign, relying on Shinyei PPD20V alone could lead to significant underestimations of the severity of the most intense PM events.
- **Sensitivity problems in high PM environments:** The Lighthouse Handheld 3016-IAQ counter (an instrument of 4000 euro and too expensive to be used for routine PM monitoring) is used as a reference instrument. The drawback of that system is that at high PM concentrations, even for short periods of time, the internal HEPA filter tends to get saturated in a matter of a few weeks. This leads to a decrease in the true sampling rate of the instrument, resulting in an underestimation of the PM concentration close to 50% after only 3 weeks and reaching 90% approximately 3 months from the starting of the measurement. By changing the internal filter the ideal response is restored, but any intense PM event can trigger again an exponential decrease in sensitivity with time. This result suggests that the reference instrument should not be used for periods longer than 2-3 weeks in environments characterized by high-PM events, even short in time (few hours). The relatively low-cost solutions (< 500 euro) did not show any loss of sensitivity problems over the 7 months of sampling, overcoming the limits of the more expensive Lighthouse unit.
- **Particle size selectivity:** The Shinyei PPD20V has a nominal cut-off size of 1 μm. However, the sensor clearly measures smaller particles as well. There was a better correlation with the >0.5 µm reference channel than with the >1 µm reference channel. The Dylos 1100-Pro measures all particles larger than 0.5 μm and in a second channel

all particles larger than 2.5 μm. It showed an extremely good linear correlation with the reference counter for both the size channels ($R^2 = 0.89$ for particles > 0.5 µm, $R^2 = 0.90$ for particles > 2.5 µm), as well as average signal ratios (i.e., signal of Dylos instrument divided by the Lighthouse signal) significantly close to the unity (small fraction: 0.71 ± 0.26; large fraction: 0.72 ± 0.25).

- **Irregular time shift of the signal:** The Shinyei PPD20V did not show any time shift in its signal compared to the Lighthouse 3016-IAQ. For the Dylos 1100-Pro, an irregular shift of 6 h 45 min ± 45 min was observed when compared with both Lighthouse and Shinyei. It was not possible to identify any clear correlation between the size of the delay and any of the experimental properties measured. Even if the data can be corrected for the average time shift, which could just depend on a mistake in the settings of the internal watch of the monitor or some problems during the saving of the data, the irregular changes in the time shift cannot be accounted for. This could constitute a problem when a high time resolution is needed in order to understand the causes behind a specific PM event.
- **Influence of T and RH on the signal:** The convective flow that the Shinyei sensor exploit to draw particles into the scattering chamber, is supposed to be influenced by the ambient temperature, being dependent on the temperature gradient. Most likely, the temperature changes observed in the church (6-28 ˚C) are not extreme enough to cause a noticeable effect.
- **Conversion into μg m^{-3}**: Different mathematical assumptions in the transformation of PM from particles/m^3 into μg/m^3 concerning the mass, shape (i.e., a sphere), density and optical properties of the measured particles leads to significant mass differences even when the starting particle number data are similar. The counters separate particles into size channels based on their optical properties, and therefore based on the "optical" diameter. This property does not necessarily coincide with the aerodynamic diameter. Counters such as Dylos and Lighthouse are supposed to obtain direct PM mass data (μg/m^3) by assuming an average density of particulate matter (assumed to be 1.5 g/mL; PM sensor of Alphasense assumes a density of 1.65 g/mL). Extreme caution should be exercised when using PM mass data directly obtained from optical particle counters. However, Dylos provides some suggestions about appropriate PM concentration expressed in both counts and in mass.

Table II: Summary of the advantages and disadvantages of the PM sensors considered in this study. The information in bold is directly derived from the comparative study.

Sensor type	Advantages	Disadvantages
Dylos DC1100-Pro	- Low-cost (≈ 500 euro) - Relatively small dimension (18x11x8 cm) - 2 different size channels - Can be connected to a data logger - **No obvious influence of T and RH on the response**	- **Irregular time delay in the response** - **Slight underestimation of PM concentrations (71% ± 26% of the real value)**
Shinyei PPD20V	- Low-cost (≈ 100 euro) - Small dimension (8x6x2 cm) - Can be connected to a data logger - Immediate response (no experimental time delay) - **Below concentrations of $5.0*10^7$ particles response is linear with concentration of Dylos for particles larger than 0.5 μm/m^3** - **No obvious influence of T and RH on the response**	- Approximate cut-off size (<1 μm) - No size discrimination - **Deviation from linearity at high PM concentrations (underestimation)** - **Need for a cross-calibration with a well calibrated monitor to obtain absolute PM concentrations**
Lighthouse 3016-IAQ	- Relatively small dimension (22x13x6 cm) - 6 different size channels - Accurately calibrated according to ISO regulations (100% counting efficiency for particles >0.45 μm)	- High-cost (≈ 4000 euro) - Need to manually save the data (3000 memory slots) - **Sensitivity drift in high PM environments**

b) Gas sensors

There is a large amount of gas sensors on the market that can be used to monitor air quality. Although some sensors are provided with calibration certificate, it is not clear what their performance is in indoor situations and how accurate the measurements are. The 3 low-cost gas sensors considered in this work showed very different results: from the accurate response of NO2-A43F to the total lack of detectable signal for PID-AH2. What all these sensors have in common, is that the measured signals are close to the detection limit (See Table III). The contribution to random noise is relatively high. Due to an accuracy problem, the conversion of the small signals resulted in some situations in negative concentrations. In addition, Alphasense is proposing several formulas to calculate the concentrations. Some of these formulas contain errors as well. The positive and negative characteristics emerged from the testing of these sensors are summarized in Table IV. In conclusion, contrarily to what seen for the PM sensors considered, more laboratory and field testing will be necessary before being able to exploit these gas sensors to their full potential in cultural heritage applications.

- **NO_2 concentrations:** In detail, the NO2-A43F NO_2 sensor by Alphasense showed promising linear response when compared with reference Radiello data ($R^2=0.92$, slope=1.1). The correlation observed, together with the relatively low influence of random noise on the instrumental output, are nonetheless very positive results regarding the reliability and average weekly accuracy of the Alphasense NO_2 sensor.
- **O3 concentrations:** The low environmental concentrations of O_3 caused problems both to the OX-A431 Alphasense sensor and to the Radiello passive samplers. In the first case a high influence of random noise in terms of short time variations was observed, together with a general underestimation of the real concentration for low O_3 levels (negative output). In the case of Radiello, high levels of standard deviation were observed for most of the data points. This situation resulted into a worse, both still promising, linear correlation between sensor output and reference concentrations ($R^2=0.60$, slope=0.69).
- **TVOC concentrations:** The raw output of the PID-AH2 Alphasense sensor for the analysis of total VOCs appeared to be dominated by the presence of random noise. No meaningful signal could be isolated. The extremely low environmental concentrations of VOCs in the church (below the experimental LOD of the reference method in most of the cases) are likely responsible for this poor performance.

TABLE III: Overview of several pollutant concentrations inside and outside the church of Aalst. Week 1: 21/12/2017-30/12/2017; Week 2: 30/12/2017-06/01/2018; Week 3: 08/01/2018-15/01/2018; Week 4: 15/01/2018-23/01/2018; Week 5: 23/01/2018-30/01/2018; Week 6: 30/01/2018-06/02/2018. RSD: relative standard deviation. LOD: limit of detection. Red: two out of three samples <LOD; blue: one out of three samples <LOD.

			Average conc. (µg m^{-3}) – RSD (%)									
Week			**O_3**	**NO_2**	**SO_2**	**Formic acid**	**Acetic acid**	**Ethanol**	**Ethyl acetate**	**Toluene**	**α-pinene**	**2-ethyl-1-hexanol**
Plastic removal	**1**	**IN**	<LOD	8.19 - 7	<LOD	<LOD	<LOD	<LOD	<LOD	0.52 - 17	0.16 - 21	1.09 - 14
		OUT	24.07 - 9	8.52 - 10	<LOD	<LOD	<LOD	<LOD	0.41	0.89 – 19	<LOD	0.70 - 13
	2	**IN**	11.00 - 21	6.54 - 6	<LOD	<LOD	<LOD	<LOD	<LOD	0.30 - 8	<LOD	0.22 - 13
		OUT	49.96 - 3	4.30 - 21	<LOD	<LOD	<LOD	0.78	0.38 - 27	0.67 - 8	<LOD	<LOD
Back-ground	**3**	**IN**	<LOD	12.60 – 7	<LOD	<LOD	<LOD	<LOD	0.72	1.76 – 8	0.37 – 8	<LOD
		OUT	8.81 – 13	12.43 – 24	9.49 – 4	<LOD	<LOD	2.06 – 15	1.21 – 4	2.16 – 1	<LOD	<LOD
	4	**IN**	8.30 – 20	12.48 – 8	<LOD	<LOD	<LOD	<LOD	<LOD	0.70 – 19	<LOD	<LOD
		OUT	39.97 – 6	13.45 – 1	<LOD	<LOD	<LOD	0.67 – 24	0.36 – 10	0.89 – 4	<LOD	<LOD
Heating	**5**	**IN**	<LOD	13.00 – 7	<LOD	8.57	35.14 – 18	0.77	0.85	1.01 – 50		<LOD
		OUT	32.42 – 4	11.67 – 13	<LOD	<LOD	<LOD	0.65 – 8	0.36 – 7	0.96 – 5	<LOD	<LOD
	6	**IN**	5.68	26.19 – 6	<LOD	13.00	34.76 – 22	2.08 – 9	0.34 – 11	1.03 – 35	0.32 – 8	<LOD
		OUT	21.01 – 15	15.21 – 17	3.37 – 10	9.88 - 13	39.70 - 17	8.95 – 4	0.71 – 3	1.24 – 9	<LOD	<LOD
LOD (µg m^{-3})			**4.70**	**2.30**	**3.20**	**3.71**	**9.58**	**0.67**	**0.31**	**0.20**	**0.10**	**0.12**

Table IV: Summary of the advantages and disadvantages of the methods for the study of gaseous pollutants. In bold the information directly derived from the comparative study.

GASEOUS POLLUTANTS	**Advantages**	**Disadvantages**
NO2-A43F (NO_2)	- Low-cost (≈ 150 euro) - Small dimension (2Φ2 cm) - Can be connected to a data logger - **Good linear response and accuracy with NO_2 weekly average concentrations**	- **No clear drawback in these experimental conditions**
OX-A431 (O_3)	- Low-cost (≈ 150 euro) - Small dimension (2Φ2 cm) - Can be connected to a data logger - **Approximately linear response even at low O_3 concentrations (weekly average)**	- **High noise/signal ratio in these experimental conditions (low environmental O_3 concentration)** - **Underestimation of the real concentration for low PM levels (negative output)**
PID-AH2 (TVOCs)	- Low-cost (≈ 400 euro) - Small dimension (2Φ2 cm) - Can be connected to a data logger	- **No visible signal in these experimental conditions (concentration of TVOCs was too close to detection limit)**
RADIELLO®	- Low cost (≈ 300 euro for a package of 20) - Small tube (8x8x6 cm) - Widely tested and employed - Accurate and precise	- Long sampling time (days/weeks) - Before use, cartridges must be stored in a fridge - Labour intensive processing in well-equipped lab

3.2. Deliverable 2: Algorithms that make sense of data

Despite the importance of *indoor air quality* (IAQ) for heritage conservation, its assessment is a complex and challenging task. Experienced heritage guardians can perform very effective assessments of the IAQ through their senses. However, this intuitive perception is very personal and results in different or contradictory opinions between stakeholders (Slovic, 1987, Weber, 2006, Schanze, 2006). Moreover, intuitive *risk perception* is not always in agreement with a rational analysis of risk: apathy for genuine risks or panic for small risks might occur (Slovic, 1987). Therefore, the first step to an objective IAQ assessment requires the acquisition of environmental information, which implies registering and managing a considerable amount of data. However, the absolute values and trends of the monitored parameters visualized with graphs only give an indirect impression of that IAQ. In the context of the AIRCHECQ project it became clear that such information is perceived by many heritage guardians as either too technical and difficult to interpret, or as meaningless and of no value. The complexity of the analysis of environmental measurements explains why too often data are collected but never analysed, especially when there are no obvious signs of alarming situations.

In the following paragraphs, 6 methods will be described (see list below) that were used to determine the *environmental appropriateness*. These methods can help heritage guardians in selecting the most appropriate mitigation actions from collected data. In the following paragraphs, each method will be described in detail:

1. **Visualize data using graphs:** A time series generated by a sensor can be visualized using a line graph;
2. **Analyse peaks and drops in graphs:** The presence of peaks and drops can be assessed using a risk analysis approach;
3. **Analyse peaks and drops in different frequency ranges:** Every time series can be decomposed in low-, mid- and high-frequency fluctuations using moving averages. Then the peaks and drops of every frequency range can be studied separately;
4. **The use of an IAQ-index based on existing norms and guidelines:** Determine the indoor air quality (IAQ) by comparing the collected data with guidelines that are relevant for heritage materials (there are also guidelines for human comfort such as Fanger's comfort model ISO 7730);
5. **The use of an IAQ-index based on material specific criteria (Weighted Thresholds):** Calculate the IAQ-index by converting the measurements of a fixed set of key risk indicators into the level of risk that a marker is generating for a specific material or object type. The conversions are realized by material specific conversion functions. The importance of the key risk indicators in the degradation rate of a specific material is considered using weights;
6. **The use of data mining related techniques (Data Mining):** Estimate the environmental appropriateness while avoiding the use of guidelines.

3.2.1. Visualizing data using line graphs

Each column in the data matrix can be visualized as a line graph. In such a graph, the coordinates of the subsequent measurements are connected with a line. It visualizes both the absolute values and the trends of the environmental parameters and give an insight in (1) when *hazards* are particularly dangerous, and (2) how dangerous these hazards are. The information in such graphs can be enhanced by adding yardsticks that denote the acceptable range as defined by some guidelines. Data of several parameters (e.g., temperature and relative humidity) can be shown in a single graph. However, when too many parameters are shown in the same graph, data overload will make them hard to read. Some heritage guardians only visualize the data of 1 week to avoid data overload and to visualize subtle details.

The example in Fig. 11 visualizes several monitored parameters. All parameters except for temperature and relative humidity appear to have some relatively constant background level (e.g., a perfect dark situation for visible light, average CO_2 concentration on earth of around 400 ppm) with a superposition of numerous sharp peaks and/or drops. For temperature and relative humidity, peaks and drops are more difficult to identify. This is mainly due to the fact that the fluctuations of ambient temperature and relative humidity cannot be described as a deviation from a baseline.

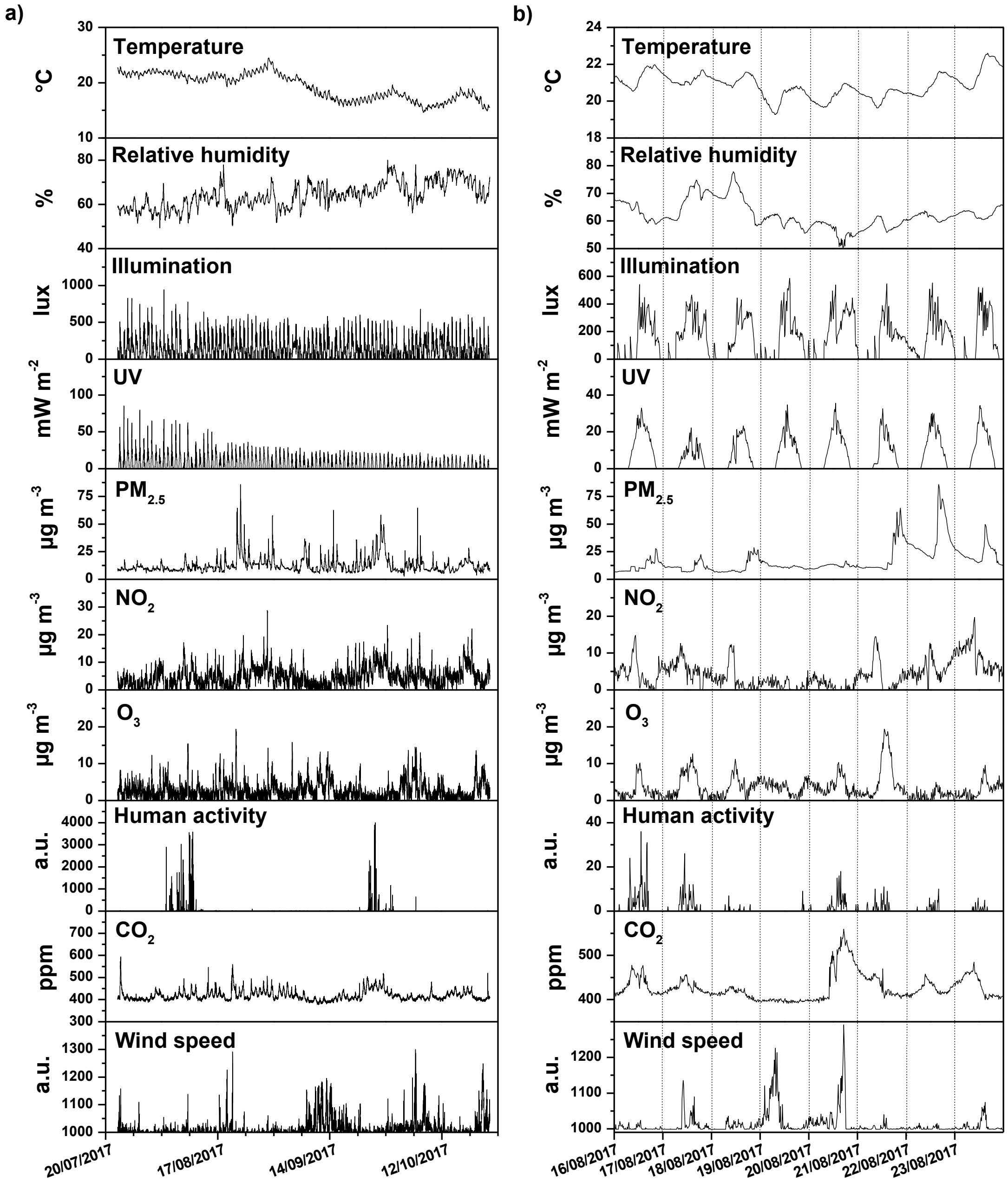


Fig. 11: (a) Plots of environmental data over time collected in the Saint Martin church in Aalst from a period of 3 months (between 23/07/2017 and 23/10/2017); (b) One-week detail (between Wednesday 16/08/2017 and Wednesday 23/08/2017).

3.2.2. In depth analysis of peaks and drops in line graphs using risk analysis

Although the graphs in Fig. 11 visualize a considerable amount of information, it is not always clear how they should be read to evaluate the indoor air quality. This means that such graphs are meaningful but not very actionable. A simple way to analyse such graphs is using the following *rule of thumb*: The moments at which peaks and drops occur in the graphs coincide with the periods that the collection endures exposure to *hazards* at elevated intensity. The exact moments at which the peaks and drops occur is a useful tool in the recognition process of hazards that threaten the collection. That approach relies on a risk analysis method. The *level of* *risk* is a measure for the potential loss in value that will occur in the future. *Risk* is defined as a multiplication of the following parameters:

- **Probability that the same hazard will reoccur in the future:** It is assumed that a specific type of *incident* that occurred in the past will reoccur in the future at the same frequency. That frequency is usually estimated by an elaborated inference from a substantial amount of historical information (i.e., a rational process).
- **Impact of hazards on the collection in the past:** The accumulated harm of a heritage collection is the result of incidents that occurred in the past. The impact of these incidents is usually estimated by a thorough visual inspection (i.e., an intuitive process). It gives an insight in the value loss of a heritage collection (see set D of Fig. 4);

The parameters probability and impact that define *risk* cannot be evaluated from measurements obtained by monitoring campaigns. If we want to apply risk assessment on such measurements, another approach is needed. That new approach considers the world that surrounds us as a sequence/chain of undesired situations beyond the control of humans that occurs at random moments with a random intensity. For such an environment, the hazards that are responsible for the occurrence for risk can be analysed with the parameters described below.

- **Exposure:** Only when an object or a collection is exposed to a hazard, there is a risk that harm may occur to some of the objects. Therefore, *exposure* is the link between hazard and risk. The monitoring of environmental parameters gives an insight in the exposure of a collection to hazards. It describes how much time a collection is exposed to hazards and at which moments in time the exposure occurs.
- **Intensity of hazards:** The monitoring of environmental parameters also gives an insight in the intensity of the hazards. We can state that the probability that the current preservation conditions will lead to harm is related to the intensity of the hazard. That probability can be estimated with the following *rule of thumb*: The more extreme peaks and drops are, the higher the probability that harm will occur. That rule is an oversimplification of reality and can lead to errors also known as a *bias* (e.g., constant but high relative humidity or high gas concentrations inside a closed box) but works well in many other situations.

In this new approach, the term '*risk*' is used because an undesirable situation can lead to several possible outcomes (some of them increase the harm of the collection) and because it is unknown in advance which outcome will occur. Some possible outcomes are situations with an elevated threat although it did not result in harm, or situations where the collection acquire damage. The more certain we are that an undesirable situation leads to a harmful outcome or to substantial harm (i.e., high impact), the more we consider that risk as unacceptable. The term 'acceptable risk' denotes a normal exposure where the probability for the occurrence of harm is at an acceptable level (rare *incidents* or incidents with a small impact).

The higher the peaks or the lower the drops, the more intense the hazard is. From that intensity, the increase of harm of a specific collection can be estimated. However, the relationship between hazard intensity and the increase in accumulated harm is only partly understood. Therefore, environmental measurements can only suggest if harm will occur or if a substantial amount of harm will occur. For that reason, the estimation of the occurrence of harm from environmental measurements remains *uncertain*. In some cases, the probability for the occurrence of harm is high (i.e., unacceptable risk) while in other cases that probability is low (i.e., acceptable risk). The classification of risk in 2 categories with a transition zone between these 2 categories is mainly based on a comparison of the hazard intensity with material specific guidelines. The list below distinguishes 3 types of undesired situations.

- **Undesirable situation with acceptable risk:** Reportable period where at least 1 environmental parameter shows an elevated hazard intensity, though the risk for accelerated accumulation of harm remains low because the intensity of the undesirable situation remains below the warning line. In that case, the risk for the occurrence of harm is acceptable. It is possible that the same hazard can reoccur in the future with much higher hazard intensity;
- **Transition zone:** Reportable period where at least 1 environmental parameter falls within the transition zone between acceptable (i.e., warning line) and unacceptable hazard intensity (i.e., alarm line) and where the probability accumulation of harm is significant. In this transition zone, there is a higher possibility that the hazard intensity can lead to damage;
- **Undesirable situation with unacceptable risk:** Reportable period where the hazard intensity is unacceptably high so that the probability that harm will occur to at least 1 object is high. At least 1 environmental parameter exceeds the alarm *threshold* value and a situation of unacceptable risk occurs.

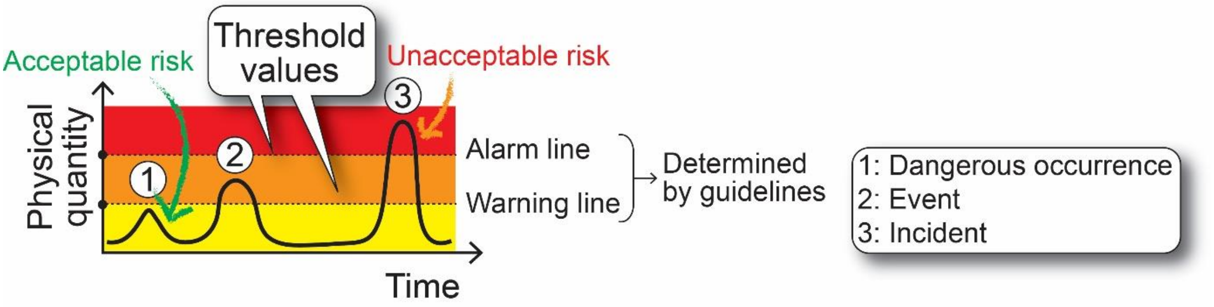


Fig. 12: The comparison of the height of peaks with threshold values.

This risk analysis approach can be applied on information obtained by the monitoring of environmental data when risk is defined in the following way: **(1) identifying the moments that a collection is currently exposed to undesired situations, and (2) estimating the current hazard intensities as determined from the height of the peaks and drops**. This approach uses current risks and not the risk of harm within the next 100 years. Since the same *hazards* causing current risk can result in much larger risks in the future, it is recommended to take mitigation actions so that these hazards cannot affect the heritage collection. This approach suggests that heritage guardians should analyse the graphs as the ones in Fig. 11 by focussing on the analysis of peaks and drops.

Several simple and quick risk analyses based on monitoring campaigns of environmental parameters rely on the calculation of the percentage of the collected data that fall within specific guidelines. For example, the 'performance index' is defined as the percentage of time in which a measured parameter such as relative humidity lies within the required (tolerance) range (Corgnati et al., 2009). A similar index is the time-weighted preservation index (TWPI) developed by the Image Permanence Institute. It is a single value that evaluates the total cumulative effect over time of fluctuating temperature and relative humidity conditions based on the rate of chemical deterioration in collections (Nishimura, 2011, Reilly et al., 1995). Others use the ASHRAE guideline to evaluate the hazard intensity of the environmental conditions by calculating the percentage of the collected data that corresponds with the different ASHRAE climate classes (Martens, 2012, Bucur et al., 2017, Klein et al., 2017). Although these methods might lead to an overestimation of the *indoor air quality* for the following reasons:

- It is possible that drastic changes in the environment only occur for a short period of time (e.g., switching on the heating system, sudden failure of the climate system, etc.). Such changes result in peaks and drops that only cover a negligible fraction of the total measured period. However, they can be responsible for most of the harm. This means that the analysis of *exposure* or hazard intensity only are not enough to evaluate the overall preservation conditions as is suggested by the mentioned indexes;
- One should keep in mind that rarely occurring *hazards* might fall outside the measuring period and will not contribute to the apparent indoor environmental quality;
- With monitoring campaigns that consider only temperature and humidity many fluctuations remain invisible although the invisible fluctuations might contribute to the total harm of the collection.

3.2.3. Peak analysis in different frequency ranges

The previous section applied risk analysis to the peaks and drops that are visible in graphs. This method works well when the peaks and drops are well separated. However, the situation becomes much more complicated when fluctuations with different widths or time-scales are superposed on top of each other e.g., seasonal fluctuations, fluctuations due to good and bad weather, fluctuations of few hours due to an *event*, day-night fluctuations, etc. In addition, depending on the objects' response time, certain frequency fluctuations are more threatening compared to others. The low frequency fluctuations are often slow enough to allow stress relaxation in the objects (ASHRAE, 2011). For that reason, they are not considered as an important *risk*. This is also reflected in standard EN15757:2010. The mid-frequency fluctuations should be considered as dangerous for objects with response times in the range of days to week. For example, wooden cupboards with open doors have a response time of around 6 days (Ankersmit and Stappers, 2017). High-frequency fluctuations could be a considerable risk for objects with a fast response time, such as a sheet of paper which reacts in the order of minutes (Ankersmit and Stappers, 2017). However, some objects such as large wooden objects respond too slowly so that they do not adapt to fast environmental changes.

The low-, mid- and high-frequency fluctuations can be isolated using moving averages. The isolation of the different frequencies simplifies the recognition process of the hazards causing the peaks and drops. This approach is especially useful when the graphs are complicated and when 'data overload' hampers the visual analysis.

- **Low-frequency fluctuations**: Fluctuations that occur at long time scales (i.e., several months) are mainly due to seasonal cycles and are isolated by applying a central 30-day moving average on the raw data stream, considering 15 days before and after the data point of interest (NBN, 2010).
- **Mid-frequency fluctuations:** Fluctuations that occur at a time-scale of several days to weeks are isolated by subtracting the seasonal trend from the raw data. From this subtraction, high-frequency fluctuations (e.g., day-night fluctuations) are suppressed using a central 24-hour moving average. The 24-hour moving average is calculated by considering a symmetrical window of 12 hours before and after the data point considered (Leyva Pernia et al., 2018).
- **High-frequency fluctuations:** Fluctuations that occur at short time-scales (i.e., a matter of hours) are isolated by subtracting the seasonal and mid-frequency fluctuations from the raw data.

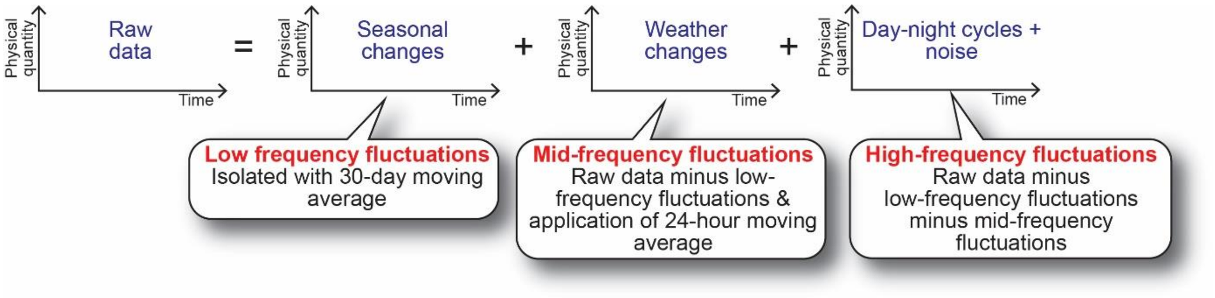


Fig. 13: Method used to decompose the raw data into trends in 3 different frequency ranges.

3.2.4. IAQ-index based on guidelines

The most obvious method to analyse *indoor air quality* is to visualize the trends in the data stream using line graphs as is the case in Fig. 11. Such graphs give valuable information concerning (1) the precise moments that a collection is exposed to a hazard (i.e., knowing these periods helps to recognition process of *hazards*), (2) the hazard intensity by comparing the height of the peaks and drops with target values as mentioned in guidelines, and (3) the hazard type because some hazards generate peaks and drops with a particular shape. Unfortunately, the graphs are not able to visualize the level of *risk* in a direct way; it only gives an impression. This means that heritage guardians do not get an insight in the overall *quality* of the preservation conditions. Therefore, it would be useful to convert the environmental parameters into more meaningful information such as *indoor air quality*.

In some cases, it is possible to visualize the distinction between acceptable and unacceptable risk by adding yardsticks to the line graphs. However, most guidelines, norms and standards use the simultaneous behaviour of temperature, relative humidity and their fluctuation to estimate the level of risk. In addition, the guidelines give a textual relationship between the level of risk (i.e., environmental states) and the interdependent relationships of the absolute value and their variations of several environmental parameters. These textual relationships must be formalized into conditional statements such as such as IF ($45\% <= RH <= 60\%$) AND ($18°C <= T <= 20°C$) THEN ... to evaluate a measuring point. A sequence of such conditional statements can be combined into a decision tree classifier. A *decision tree classifier* is an organized series of carefully crafted questions expressed as logical expressions (i.e., the answer it either true or false) about the preservation conditions. Each time an answer is received, a follow-up question is asked until the proper indoor air quality category is reached. The questions are used to classify a measuring point into one of the predefined categories (good indoor air quality, bad indoor air quality, etc.). Several rules are used to attribute a level of risk R to the quality categories. During this attribution, the states described in the list below is considered. The indoor air quality (IAQ)-index is defined as $IAQ = 1 - R$. The principle of such an algorithm is visualized in Fig. 14. The decision tree consists of internal nodes (i.e., black dots) where questions will split the data until the leaf nodes (i.e., a quality category) is reached. The major advantage of this approach is that the decision tree classifier can be applied to every measuring point in the data stream so that the IAQ over time can be visualized. In addition, the assessments are reproducible so that different moments in time can easily be compared with each other.

- **Environmental state with acceptable risk:** An informed decision to take a particular risk such as preservation conditions that are good enough for the time being and where one agrees to set risk equal to zero. The risk R for such a state is set to zero (IAQ = 1).**;**
- **Environmental state with unacceptable risk:** A state with a high chance that harm will occur such as accelerated degradation is associated to the maximum risk of $R = 1$ (IAQ = 0);
- **A transition zone between both states:** The risk between the state with acceptable risk and the state with unacceptable risk are to extremes of a continuous scale. In some guidelines, norms and standards some states with a risk between 0 and 1 are defined.

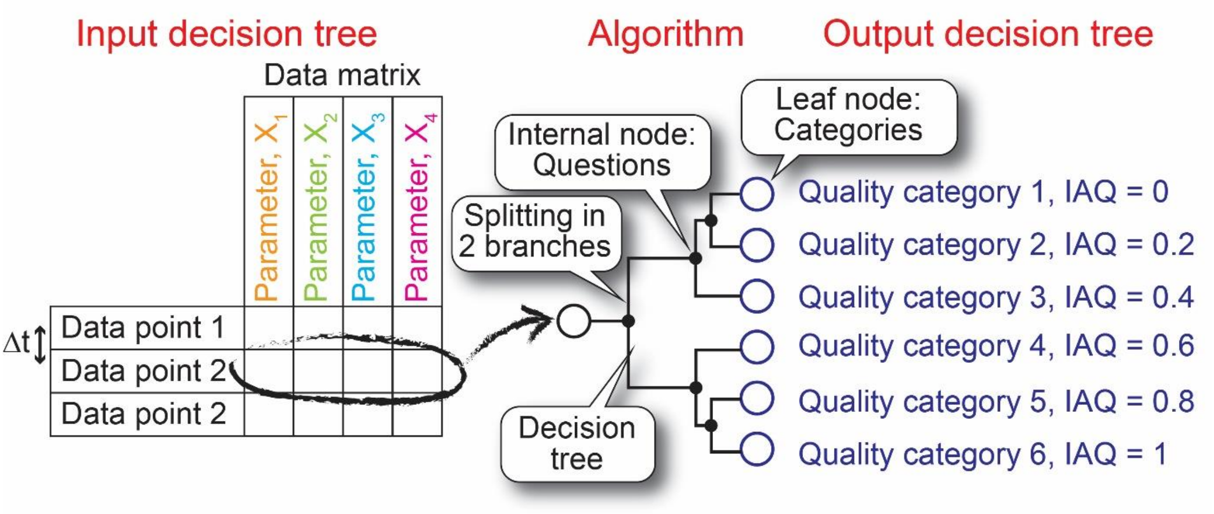


Fig. 14: Attribution of an IAQ-index using a decision tree. The decision tree is based on a single guideline.

Several standards such as the Thomson guidelines or the ASHRAE have been translated into a decision tree classifier algorithm as shown in Fig. 14. In principle, the descriptions in the guidelines, norms and standards contain all the required information to define the conditional statements that are associated with the internal nodes. However, even for the fairly easy example of the Thomson guideline there are some interpretation issues that need to be solved. Of all translated standards, the ASHRAE was the most complicated one. That standard describes the relationship of 6 quality categories (classes AA, A with subdivisions AS and A, B, C, and D where AA has the lowest level of *risk* and D the highest level of risk) and the environmental parameters temperature and relative humidity. In the cases where more categories are described it is possible to implement a more detailed analysis since the transition from higher risk situations to lower risk can be traced in multiple steps. An alternative approach is to combine several guidelines in the same algorithm. This is shown in Fig. 15. In that example temperature and relative humidity is evaluated using the Bizot guidelines while visible light and UVA radiation for sensitive material is evaluated using the CIE guidelines (CIE, 2004): 50 lux and 10 μW lm^{-1}. To combine the result of both guidelines, the worst IAQ-outcome determines the overall quality.

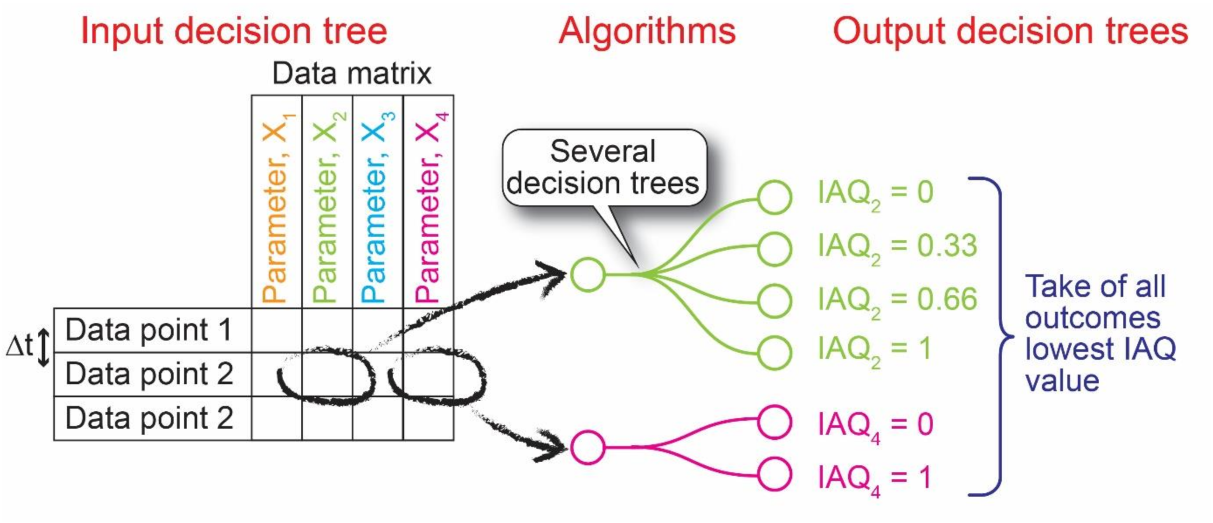


Fig. 15: Attribution of an IAQ-index using a decision tree. The decision tree combines several guidelines into one algorithm.

The decision trees in Fig. 14 and 15 only consider a limited number of IAQ-values. An alternative approach is that the decision tree decides in which category an environmental is located (see Fig. 16a), but that the IAQ-index within that category is calculated using linear interpolation (see Fig. 16b). Such interpolation is also used to calculate the IAQ-index for the transition zone between acceptable and unacceptable risk in the AIRCHECQ method (see Fig. 18).

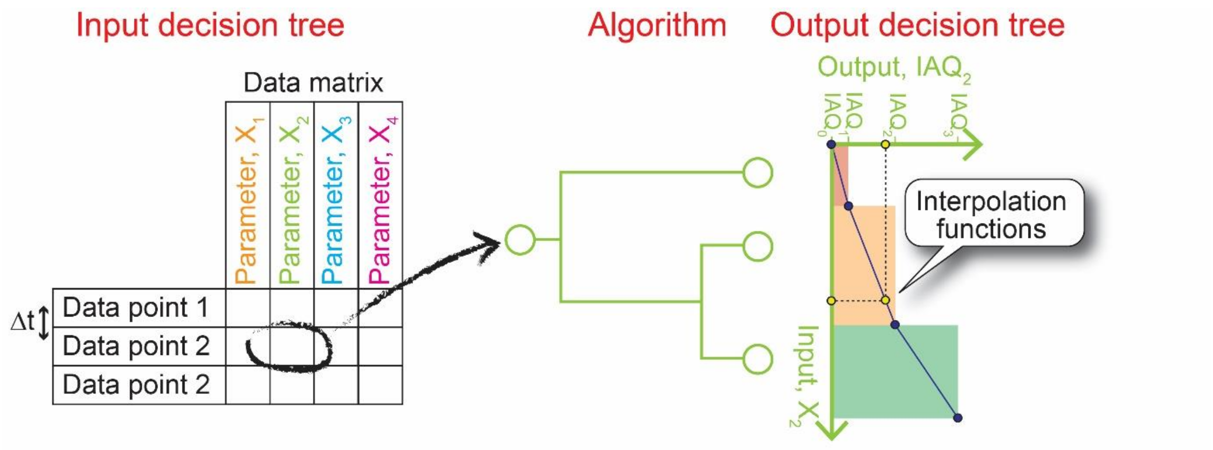


Fig. 16a: Attribution of an IAQ-index to a specific environmental parameter using a decision tree. The IAQ-value within a category is calculated using linear interpolation.

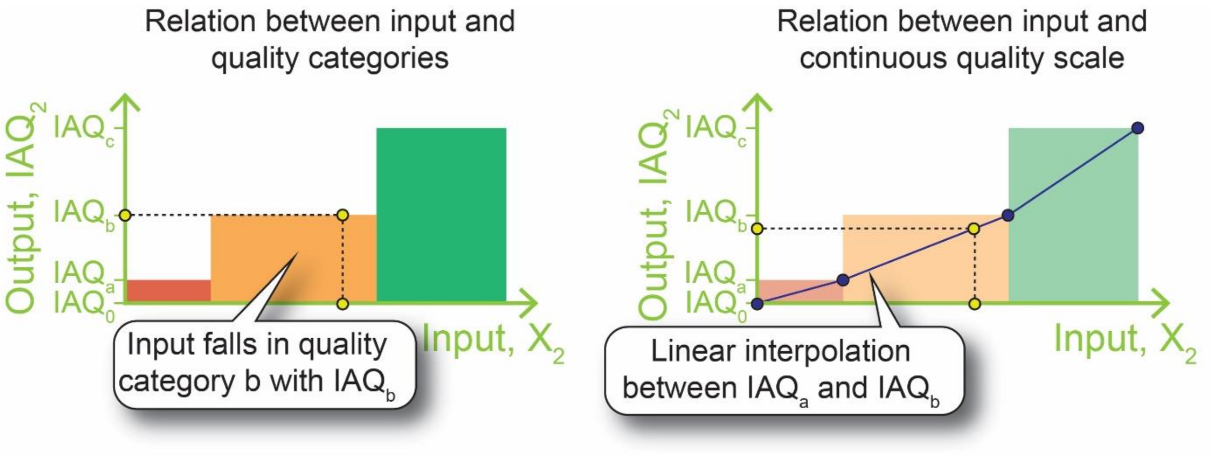


Fig. 16b: Comparison with the attribution of an IAQ-value to a given input using categories and the IAQ-calculation using linear interpolation between the IAQ-values of the consecutive categories

3.2.5. The AIRCHECQ method

The previous paragraph described how existing guidelines, norms and standards are converted into decision tree classifiers. The decision trees determine *indoor air quality* assessments from environmental measurements in a quantitative and reproducible way. Unfortunately, the expertise/knowledge described in such guidelines are hard to combine into an overarching conceptual framework because of the following reasons:

- Some guidelines consider the absolute value and variations in temperature and relative humidity but omit other parameters such as pollutant gases and particulate matter. As a result, not all critical environmental parameters are considered;
- Application of different guidelines to the same dataset does not yield in consistent assessments. In addition, there is no clear correlation between the assessments performed by newer and older guidelines, which would be expected if guidelines improved continuously over time. As a result, it is not always clear why certain guidelines are preferred;
- The interrelationships between environmental parameters used in guidelines might consider synergetic effects but they are too complex and too different from each other to extract general principles. When considering the complex combination of materials in heritage objects, we suspect a much higher number of synergetic effects than are considered today. However, considering all these synergetic effects would make the model complicated and can even introduce larger errors than a simplified model that do not consider synergetic effects;
- Some guidelines require a minimum of at least one year of data as an input before assessments can be made. Such guidelines cannot be used in the development of *early warning systems*;
- A guideline is usually valid for a specific material, object type or collection but can often not be used for all materials or object types in a single room. It is not always clear which combination of guidelines should be used.

During the AIRCHECQ project, a general assessment method was designed that solved all the mentioned limitations. The AIRCHECQ-assessment is based on a larger variety of environmental parameters than the common guidelines, norms and standards. Because all environmental parameters are evaluated in an independent way, it is possible to combine the knowledge of a larger number of guidelines and publications and create a consistent background knowledge to evaluate data streams. In addition, the general algorithm considers the sensitivity of materials towards environmental parameters. This means that the same algorithm can estimate the level risk for a large set of materials, objects or collections. The following paragraphs will describe that algorithm.

a) The concept of Key Risk Indicators (KRI)

From the huge amount of literature concerning the degradation of historic materials, it is possible to identify a large number of parameters that affect *degradation rate*s. However, the relation between environmental parameters and degradation rates is too complex to estimate the level of *risk* that threatens a collection. Therefore, we simplified that reality by using a first heuristic: the degradation rate of any material is, to a large extent, driven by a limited number of environmental parameters.

The small set of environmental parameters that dominate the degradation rate of all (historic) materials can be considered as *markers* (i.e., distinguishing and easily measurable features that give an objective indication of the preservation conditions in which a collection resides). Well-known examples of markers are temperature, relative humidity, illuminance and UV-radiation. This means that the markers describe the level of risk as caused by a multitude of *hazards* threatening a collection. For that reason, the markers can be used to introduce the concept of *key risk indicators* (KRIs) (Immaneni et al., 2004, Taylor and Davies, 2003, Scarlat et al., 2012). KRIs are independent parameters that estimate the threat that certain preservation conditions may harm the collection. This list in Fig. 17 gives an overview of the 13 most critical KRIs (i.e., type of threat): too high relative humidity (RH) from the perspective of the material, too high relative humidity ($> 75\%$) allowing the formation of mold on material surfaces, too low RH, too large RH fluctuations, too high temperature (T), too low T, too large T fluctuations, too high illumination, too high UV-radiation, too high concentration of oxidizing gases (O_3, NO_x, SO_2), too high concentrations of organic gases (acetic acid, formic acid, formaldehyde), too high concentrations of reduced sulfur compounds (H_2S, carbonyl sulfide (OCS)) and too high concentrations of dust ($PM_{2.5}$, PM_{10}, deposited dust). This set of parameters can be grouped in 4 categories that correspond to the following agents of deterioration: incorrect temperature, incorrect relative humidity, radiation and pollution.

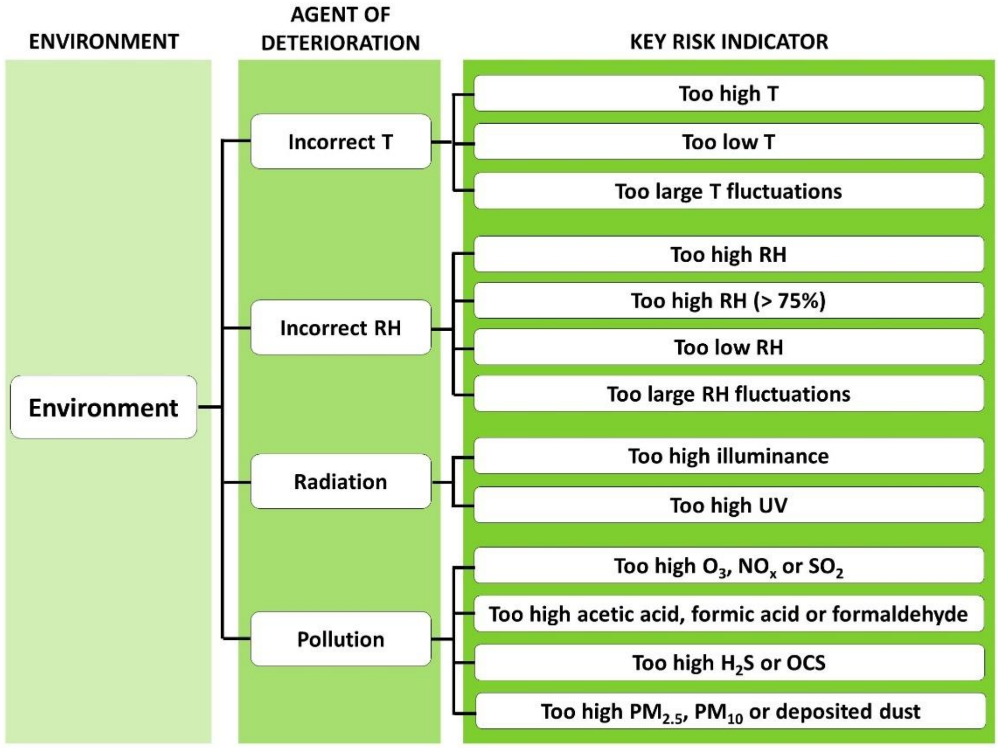


Fig. 17: Schematic overview of the different levels by which the environmental appropriateness for heritage conservation are evaluated on. Abbreviations: RH, relative humidity; T, temperature; OCS, carbonyl sulfide.

b) Quantifying the KRIs

KRIs are evaluated by comparing the value of a marker with the corresponding alarming situation. The alarming situation is defined by a *threshold* value that distinguishes acceptable *risk* (i.e., risk acceptance* is an informed decision to take a particular risk such as preservation conditions that are good enough for the time being) and unacceptable risk leading to enhanced *degradation rates*. Since the model is using environmental parameters to estimate the risk that *hazards* endangers a collection (see Model 4 in Fig. 8), the threshold values are statements about the *exposure*.

To simplify the estimation of the KRIs for specific environmental conditions, the question, “How fast do materials degrade?”, is replaced by the question, “How large is the risk for enhanced degradation?”. Although the answers of both questions contain similarities, they are not identical. For example, it is a complex matter to calculate the rate at which climate-induced damage accumulates in wooden objects from measurements of relative humidity and temperature (Kozlowski, 2007, Jakiela et al., 2007, Bratasz et al., 2012). However, we know that these parameters cannot be too low, too high or with excessive fluctuations without enhancing the risk of damage. This means that the level of risk as described by a KRI can be estimated by comparing the measurement of a marker with target values or ranges of acceptable values as can be found in the literature, guidelines and standards.

The KRIs are quantified by converting their corresponding markers into a level of risk that is described by a value between 0 and 1—the higher that value, the higher the risk. The conversion functions distinguishes exposures with acceptable risk (risk $R = 0$), exposures with unacceptable risk ($R = 1$) and transition zones in between. From an extensive literature study, four types of conversion functions have been identified. They are described in the list below and visualized in Fig. 18. Since the shapes of the conversion functions are predefined, the exact definitions of the conversion functions are dependent on just a few nodes (i.e., the red dots in Fig. 18, upper part). The position of the nodes coincides with published target values and is material-dependent. There is sufficient literature on *thresholds*, but their exact values are sometimes under discussion. During the AIRCHECQ project, one expert defined the values of the nodes and tested the results for consistency. The concept of calculating the level of risk with simplified conversion functions can be considered as another *rule of thumb*.

- **Conversion Function 1:** This function describes the impact of the KRIs having a too high/too low RH or a too high/too low T. For example, for most hygroscopic materials, a mid-range RH has an acceptable level of risk that damage may occur, while RH-values outside this recommended range are associated with unacceptable risks. Materials for which a too low RH does not matter, such as metals, the first node is set at position (0,0).
- **Conversion Function 2:** The fluctuation of a marker (e.g., RH or T) is defined as the maximum value minus the minimum value within a period of 24 h. Objects can usually withstand small fluctuations without damage. Therefore, until a certain magnitude of fluctuation, the level of risk for enhanced degradation is zero. The larger the peak-to-peak value becomes, the higher the risk is. From a certain peak-to-peak value, the risk for enhanced damage is so high that the level of risk is considered to be unacceptable ($R = 1$).
- **Conversion Function 3:** This function describes the risk for enhanced degradation that is caused by the intensity of visible light and UVA radiation. At lower radiation levels, there is an acceptable risk for degradation, but that risk increases at higher intensities. At a certain intensity, enhanced degradation is almost certain to occur, and the risk becomes 1.
- **Conversion Function 4:** This function describes the risk of all pollutant-related KRIs, i.e., oxidizing gases, organic gases, reduced sulfur compounds and dust. Although the exact influence of the pollutant concentration on the degradation of many materials is not known in detail, it is known that the lower the concentration is, the smaller the impact is (i.e., the ALARA principle, As Low As Reasonably Achievable, is a *rule of thumb*). A total of four nodes is used to define the conversion function, since well-accepted standards

often mention a lower and a higher 'range' of *threshold* levels (e.g., reference (ASHRAE, 2011)).

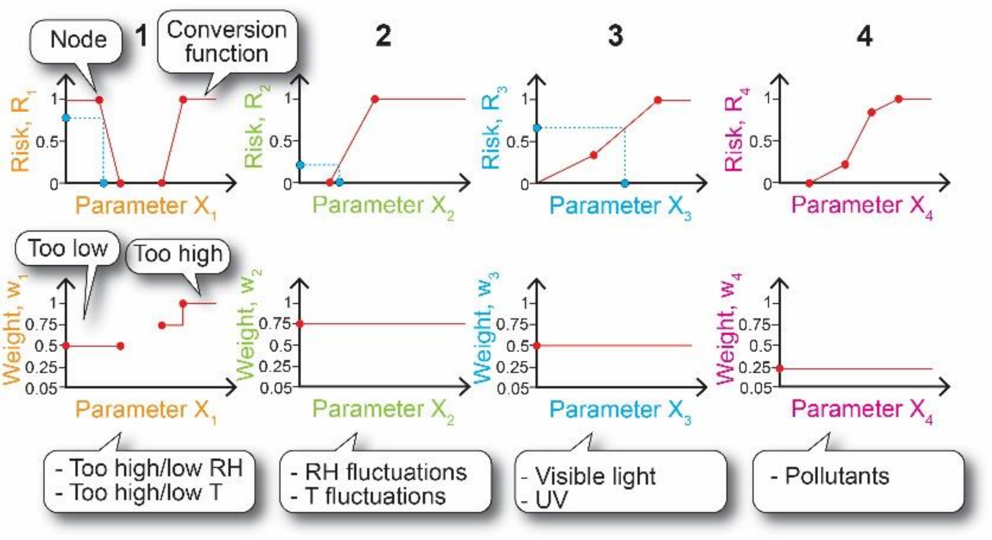


Fig. 18: Conversion functions to calculate the level of risk that a marker is generating for a specific material or object type (upper part) and the way a weight is attributed to a *key risk indicator* (KRI) (lower part).

c) Risk profile of a material

The first *rule of thumb* on which this method relies is that the *degradation rate* of historic materials is driven by a limited number of markers. However, the same marker does not have the same effect on the degradation rates of different materials. For example, the same amount of radiation endangers very sensitive materials, such as paper and textiles and affects oil paintings to some extent, while metals are almost insensitive to it. On the other hand, when considering all KRIs on a single material, pollutants have, for example, a larger impact on metals than temperature. Therefore, the third rule of thumb states that weighting factors can be used (1) to rank the importance of the 13 KRIs for each material or object type, and (2) to rank the *sensitivity* of material/object types per KRI. A matrix was set up to elaborate the third principle.

- The matrix rows list 35 commonly occurring heritage materials and object types. Table V gives an overview of these materials and object types. They are considered to be representative for most heritage collections and cover materials and object types for which sufficient information on degradation can be found in literature.
- The matrix columns list the 13 KRIs as shown in Fig. 17.

TABLE V: Overview of the commonly occurring materials and object types that represent most cultural heritage collections. They are classified in 14 main classes with the assignment of subclasses if relevant.

Material/Object Type	Subclasses
General collection*	
Paintings	Wood | Canvas | Copper
Paper	Cotton and rag paper | Groundwood containing paper | Lignin-free paper
Wood	Restrained | Unrestrained
Textile	Vegetable fibers | Wool/hair | Unrestrained silk | Restrained silk | Weighted silk | Synthetic fibers
Metal	Silver | Copper | Lead | Iron
Leather and parchment	Restrained | Unrestrained
Glass	General | Crizzling
Ceramic	Terracotta/earthenware | Stoneware/porcelain
Stone	Limestone | Gypsum | Alabaster | Marble
Ivory/bone/antler/horn	
Feather/insects/stuffed animals	
Photographs	Albumen | Collodion | Gelatin
Plastics	

* The material/object type ‘general collection’ offers an option that is material unspecific as a generic approach. If a sensitive object is present in the collection, one should opt to continue with this specific material.

First, the importance levels of the 13 KRIs are ranked per material/object type (horizontal matrix direction). The impact of KRIs on the degradation is described by one of the numerical scores: 0.05 (negligible), 0.25 (low), 0.5 (moderate), 0.75 (high) and 1 (extremely high). By using only 5 categories, disagreements between experts have a small effect on the final ranking because most disagreements are subtler that the rather broad categories that are imposed by our approach. For a given material, the same score can be attributed to several KRIs.

The matrix was built with the following method. For each material/object the rankings of the KRIs (i.e., matrix rows) were established on an extensive literature study, information from previous projects (MEMORI, 2013) and personal experience. Then, for each KRI the material/object *sensitivity* (i.e., matrix columns) was implemented by adapting the scores. During that process, the score of a KRI for a specific material/object can change, but the order of KRI importance within a material/object (i.e., matrix row) cannot change.

The weighting factors in the matrix describe the importance of each KRI. For this reason, the weight is independent of the marker value. Therefore, one weighting factor is assigned to each type of conversion function (Fig. 18, lower part). The only exception is conversion function 1, because it combines two KRIs and they need to be weighted independently. Moreover, for the KRI ‘too high RH’, an additional weighting factor is attributed when crossing an RH of 75%

because this might cause mold growth on the material surface. This KRI is only valid for mold-sensitive materials. In the range where the *risk* is zero, the weight is not defined because $w_i \times R_i$ remains zero.

For each material/object type, a spider graph can be plotted to visualize the relative KRI-importance. Each graph can be considered to be a *risk profile* for a given material/object type. The total area of the spider graph indicates the average sensitivity of the material/object to the overall preservation conditions. The differences in total area demonstrate that not all materials degrade at the same rate. Fig. 19 gives an example for paintings, making the distinction between paintings on wood, canvas and copper.

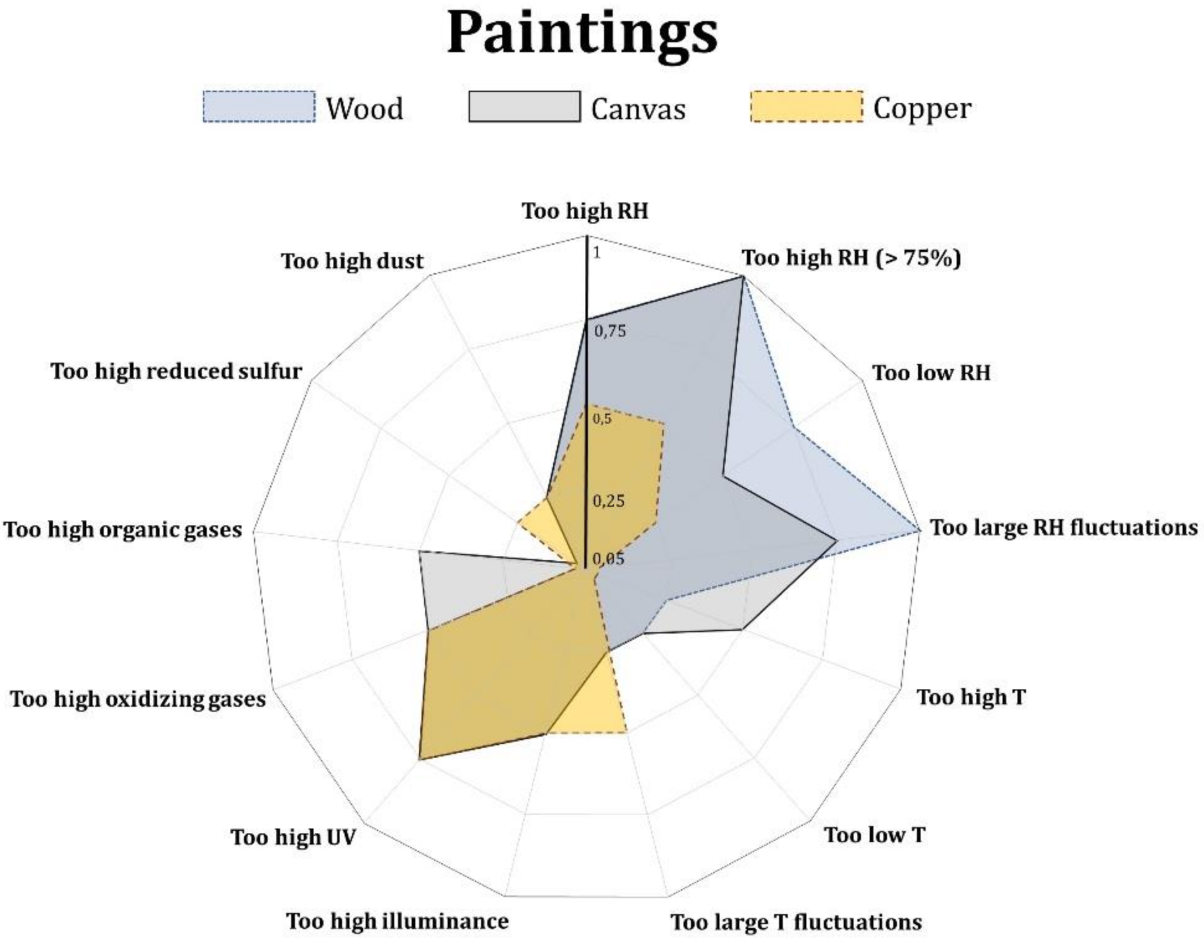


Fig. 19: Spider plot with 13 dimensions to visualize the KRI importance for paintings on wood, canvas and copper. Five categories describe the impact on the degradation: negligible (0.05), low (0.25), moderate (0.5), high (0.75) and extremely high (1).

d) Combining all KRI into an overall Indoor Air Quality (IAQ) index

The preservation conditions are not determined by a series of marker-specific risks but by one overall *risk*. The IAQ index is related to that global risk. To calculate the index, the heritage guardian must first select which material/object type he wants to determine the indoor air quality from a list of options. Then, the IAQ index is calculated with an algorithm that follows six subsequent steps (Fig. 20), as follows:

1. The heritage guardian preprocesses the monitored environmental data to create a consistent data matrix to be uploaded. The matrix should be based on data of simultaneous measurements of markers at fixed time intervals.
2. Before using the algorithm, the heritage guardian is obliged to select the materials or object types for which he wants to know the IAQ index from a list of materials/objects. Based on that selection, the algorithm identifies which conversion functions are needed to calculate the level of risk for each KRI, R_i.
3. The algorithm now identifies the relative importance of the KRI based on the weighting factors, w_i. The levels of risk for the KRIs, R_i, are subsequently multiplied by the respective weighting factor, w_i.
4. The overall risk for a specific data point, R_{max}, is controlled by the highest weight-corrected marker-specific risk (i.e., max [$w_1 \times R_1$, $w_2 \times R_2$, ...]).
5. Since risk is associated with the probability of occurrence of damage due to the preservation conditions, the probability that no damage will occur (i.e., the *safety* of the environment) is given by $1 - R_{max}$. This magnitude is defined as the overall IAQ index. The numerical value of this index varies from 0 to 1. The higher the index, the better the preservation conditions. The maximum value of the IAQ index is determined by the w_i of the marker that sets R_{max}. The algorithm is repeated for each data point, resulting in a time series of IAQ indexes. If needed, a marker-specific IAQ index can be evaluated as well, defined as $1 - R_i$. This marker-specific index does not consider the weighting factors.
6. The behavior of the IAQ-index over time can be visualized in line charts. Another visualization can be done by assigning a specific color to each IAQ value using a color map. This results in color bars that depict the IAQ index over time, allowing intuitive and user-friendly interpretation.

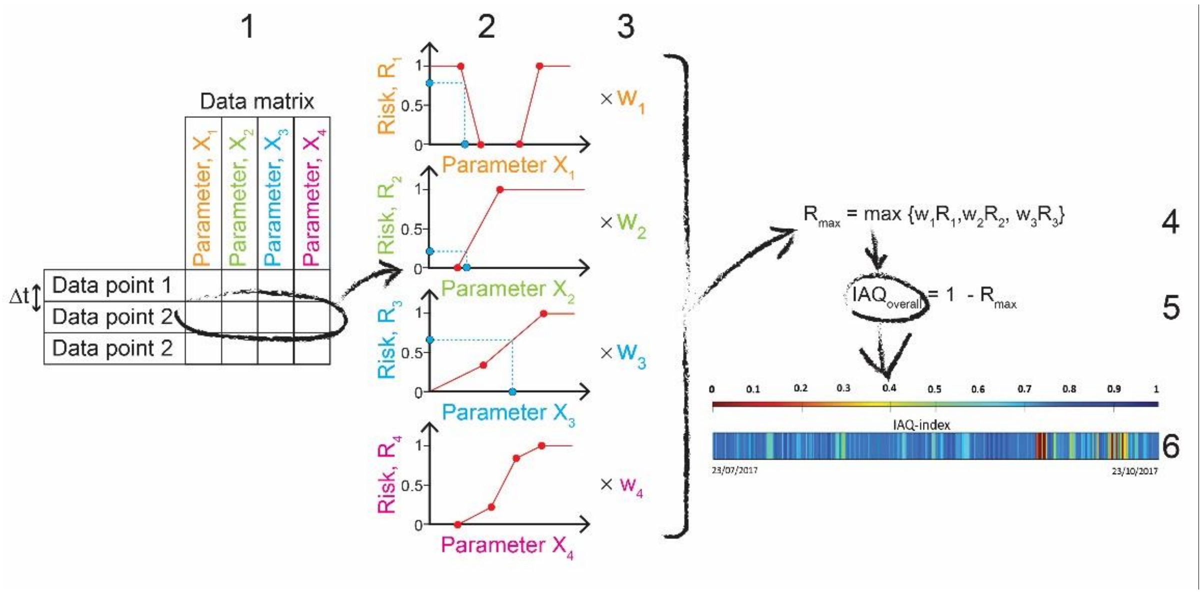


Fig. 20: Schematic visualisation of the steps considered by the indoor air quality (IAQ) index algorithm.

e) Visualization of the indoor air quality

In the line graphs of Fig. 21, the overall IAQ-index for a *general collection* (i.e., a mixed collection with all objects in relatively good condition and no objects that are remarkably more sensitive to a specific parameter) clearly fluctuates over time. That information has been enhanced by applying a coloured background in the line graph to enhance the contrast between appropriate (green), warning (orange) and alarm (red). Compared to graphs showing the absolute values and trends of environmental parameters, the graphs in Fig. 21 visualize directly the level of risk to which a collection is exposed to.

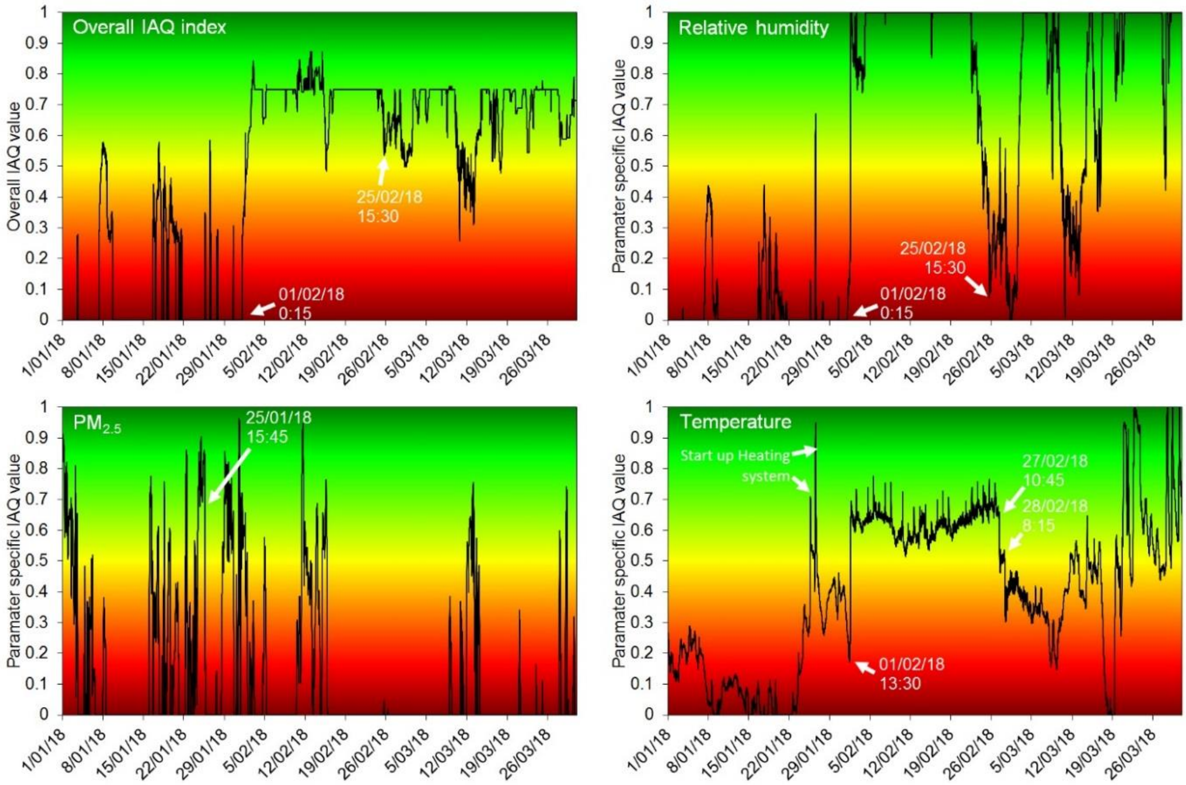


Fig. 21: Visualization of the overall IAQ-index for the church of Aalst and several parameter specific IAQ-values by means of line graphs. The IAQ-index has been calculated for a general collection. The 2 spikes in the temperature related IAQ-value in the graph bottom right at 25/1/2018 and 26/1/2018 are due to the first test with the heating system.

The graphical representation of the IAQ-index as shown in Fig. 21 is good enough for scientific purposes. It is able to show the essence (i.e., the trend of indoor air quality) without being distracted by too much details. However, the way how the data is organized and presented cannot be considered as user-friendly to laypeople (e.g., some decision makers have no scientific background). In addition, the aspects that are important in decision making (e.g., relative change, easy comparison of periods, the precise occurrence of periods of enhanced levels of *risk*) are not highlighted in these graphs. Therefore, the graphs in Fig. 21 do not meet the information needs of decision makers. For that reason, it was decided to convert line graphs into more intuitive colour bars. The more intuitive visualization of the IAQ-index uses a colour map to associate IAQ-values to colours. We use 2 predefined colour maps: (1) reverse Jet colour map from the software package MatLab R2017a) and (2) a custom colour map. Both colour maps are defined in Fig. 22. Each map comprises a range of 100 different colours, individually assigned to discrete values of the IAQ-index with a resolution of 0.01. For both colour maps, the colour red is assigned to the lowest IAQ values since it is intuitively coupled to danger (Pravossoudovitch, 2014). By associating the IAQ-index of each data point to a vertical coloured line, the time series is converted to a colour bar.

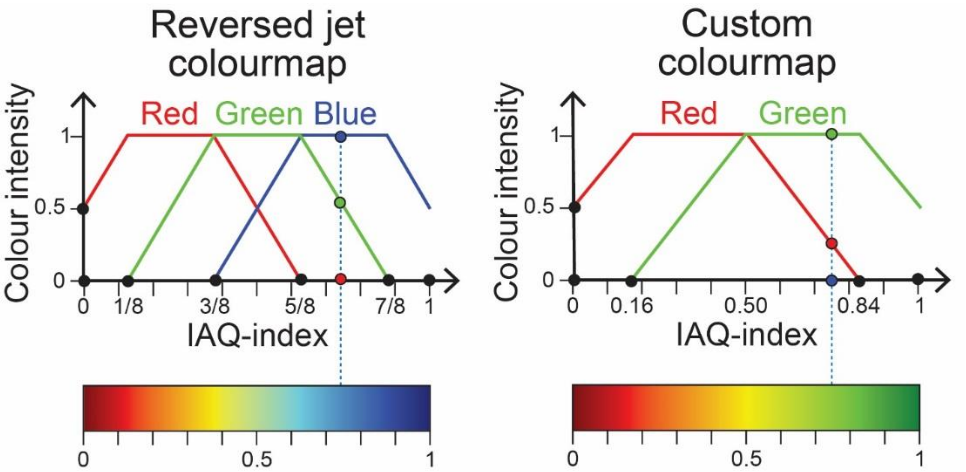


Fig. 22: Relation between colour and IAQ-index as defined by the colourmaps Reverse Jet and a custom-made colour that is based on the range of red – yellow – green.

By converting the IAQ-index in colour bars (see Fig. 23 and 24), the aspects that are important to decision makers and heritage guardians become much more salient. As a result, the same IAQ information as show in Fig. 21 also becomes relevant and useful to them (McNie, 2007). After explaining the meaning of the colour scale, heritage guardians can intuitively read the colour bars. The advantage of the reverse Jet colour map is that more chromatic variation between periods can be shown. The advantage of the custom colour map is that the colour codes ‘green-yellow-red’ are easily linked with the meanings ‘safe-warning-danger’. From a survey of c. 35 students at Conservation Studies (University of Antwerp) , the custom-made colour had a larger preference due to the more intuitive connotation of the colours. Increasing the readability of indoor air quality assessments in an intuitive way reduces the *uncertainty* because there is less room for misinterpretations. Although the AIRCHECQ project has a focus on the rational processes where data is collected in a controlled, voluntary and effortful way (e.g., measurements, inference, etc.), the bridge with intuitive processes has been assured by means of the intuitive reading of the colour bars.

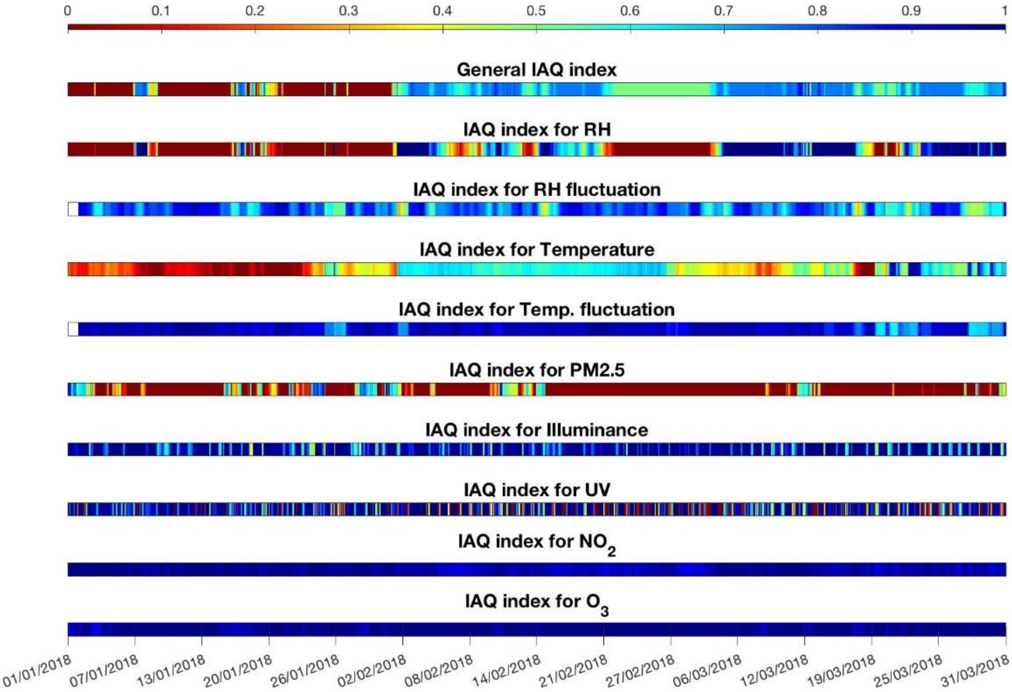


Fig. 23: Visualization of the evolution of the IAQ-index for a general collection over time using a colour bar based on the colour map Reverse Jet. The top bar is the overall IAQ-index; the ones below are the parameter specific IAQ-values. The colour bars contain the same information as the line raphs shown in Fig. 21

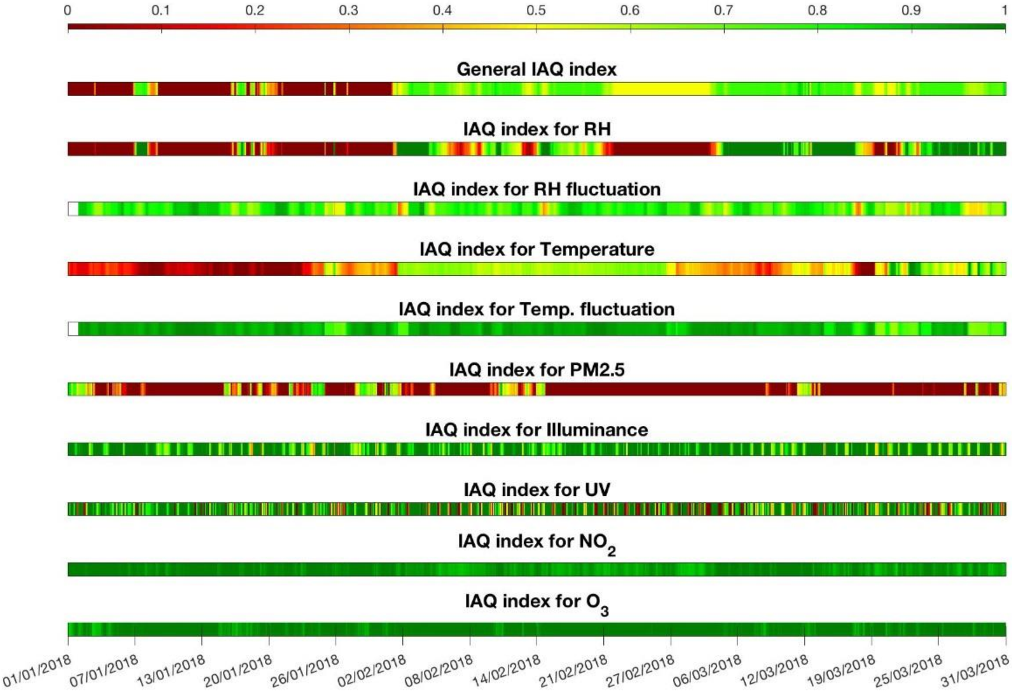


Fig. 24: Visualization of the evolution of the IAQ-index for a general collection over time using the custom-made colour map. The top bar is the overall IAQ-index; the ones below are the parameter specific IAQ-values. The colour bars show the same information as the ones in Fig. 21 and 23.

The colour bars give a direct insight in the absolute values and trends in indoor air quality. For that reason, periods of enhanced levels of risk can easily be identified. With the marker specific IAQ values underneath the colour bar of the overall IAQ index (top bar), it is possible to identify the markers that causes the sudden change in the level of risk. Once period and responsible environmental are known, it becomes much easier to track down the responsible hazard. Since hazards can reoccur in the future with a possible increased level of risk, it is advised that mitigation actions are performed to avoid or reduce the identified hazards reoccurring in the future. This means that identified undesirable situations contain valuable information and should not be neglected, even when they have not caused any noticeable *harm* so far. The overall IAQ index can be used to detect periods of elevated risk. By looking at the marker specific IAQ indexes or the original line graphs, the causes of risk can be identified. By mitigating these risks, even small ones, the general preservation conditions improve, and material degradation slows.

The colour bars contain also information to estimate the impact of mitigation actions on the overall indoor air quality. For example, to quantify the direct improvement of the start-up of the heating system in the church of Aalst, we considered the average IAQ index of one week before and one week after the heating system became operational. The moment where the heating system came into operation is visualized in the colour bars of Fig. 25 by a vertical line. By considering such a short period in time, we focused on the short-term impact of this mitigation action, and eliminated other influences (e.g., seasonal change) and undesired situations as much as possible. The ΔAQ between the weeks before and after the commissioning of the heating system equaled 0.6, 0.5 and 0.0 for canvas painting, restrained wood and copper, respectively. This suggests that the impact of mitigation actions for a given material can be quantified.

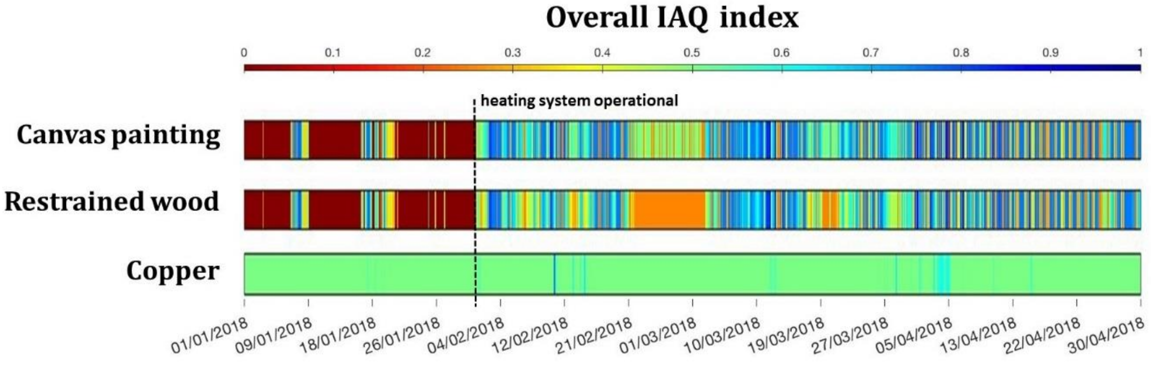


Fig. 25: Overall IAQ indexes for canvas painting, restrained wood and copper over a period of 4 months for the church of Aalst. The dashed line indicates the moment at which the heating system came into operation.

3.2.6. Indoor air quality assessment without guidelines

The main reason why the AIRCHECQ algorithm is user-friendly is because it can directly visualize *indoor air quality* for a large set of materials using the same algortihm. The line graphs visualizing the absolute values and trends of environmental parameters only give an indirect impression of that quality. For example, a concentration of 10 μg/m^3 NO_2 remains for laypeople just an abstract number with no clear indication of the precise level of risk. For heritage guardians, information about indoor air quality is more relevant than the actual values of environmental parameters. The huge amount of data from several monitored environmental parameters can be overwhelming for specialists with limited experience in data science. The user-friendly software visualizes such data in a compressed way using colour bars showing the overall IAQ-index. This approach is nothing else than a data reduction technique so that heritage experts get a grasp on the collected data. The colour bars also facilitates discussions about preservation conditions among heritage guardians. In addition, the algorithm combines a large amount of scientific information into one conceptual framework and the results of that expertise is made available in an intuitive way. For that reason, it helps heritage guardians in making decisions about how to improve preservation conditions. This means that the monitoring system in combination with the user-friendly software should be considered as a *decision support system*. The decision support system generates actionable data: it enables heritage guardians to actively look for problems and search for solutions.

Traditional assessments rely on the comparison of measured environmental parameters with their corresponding acceptable values. Unfortunately, *threshold* values distinguishing acceptable from unacceptable *risk* are not precisely known, and they depend on variables such as material type, preservation state, etc. The threshold values are for that reason *uncertain quantities*. The *uncertainty* behind the selection of the threshold values will affect the assessments determined from the environmental measurements.

Given the preceding, we propose a complementary approach to aid indoor air assessment for heritage conservation based on the implementation of Big-Data related techniques, such as data mining and data analytics. The goal of these techniques is to extract relevant knowledge from data streams without using any guideline. In our specific context we focus on interesting patterns or atypical behaviours. A filtering method is used for recognizing moments with unacceptable risk in the absence of standards or guidelines. The identification of periods of unacceptable risk is based on 3 *heuristics* as described below. It should be remarked that the method works when the overall situation is acceptable interspersed with moments of elevated risks. It is not able to recognize situations of permanent threats.

1. **High frequency fluctuations will not necessarily affect all objects, since the response time of the piece must be shorter than the fluctuation to have a potential impact on its conservation state.** Therefore, short-time fluctuations are removed from the measurements by applying a moving average inside a 24-hour window;
2. **A stable climate is more favorable for the preservation of heritage collections, especially in the case of temperature and relative humidity acting over hygroscopic materials.** For temperature and relative humidity, the relevant fluctuations can be found above or below the mean value. Small hazard intensities or fluctuations within the range of one standard deviation around the average ($\bar{x} \pm s$) are considered as acceptable risks and are filtered out. For situations outside that range, the deviation from that range

is calculated using $x_i - [\bar{x} \pm s]$. As a result, only the hazard intensities of unacceptable risks remain.

3. **Light exposure and the concentration of pollutants should remain as low as reasonably achievable to minimize the risk of material degradation.** For these parameters, only the fluctuations above the mean would be noteworthy, but can be processed in the same way as temperature and relative humidity.

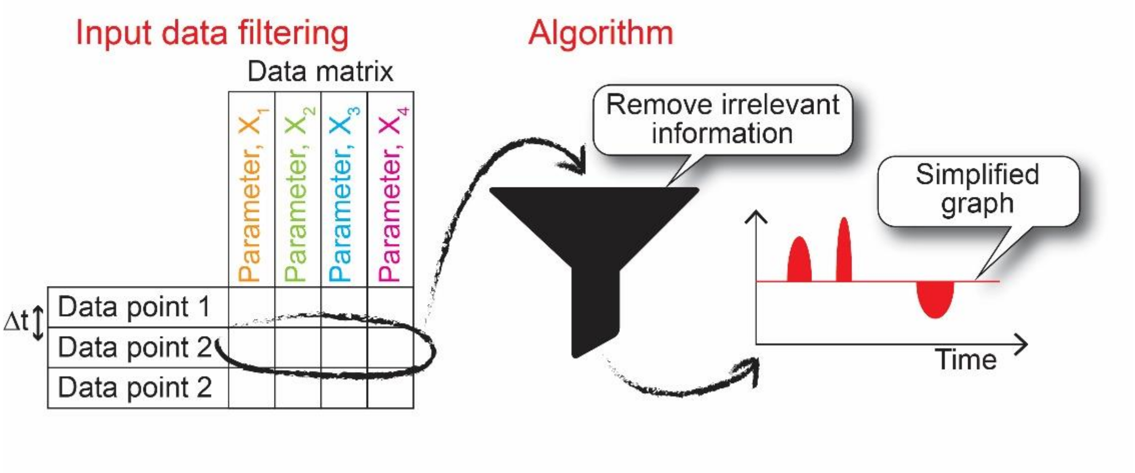


Fig. 26: Principle of data filtering to obtain data that are easier to read.

3.2.7. Reliability and limitations of heuristics

Several methods rely on the use of *heuristics* (i.e., method 4 in Fig. 8). Despite these advantages of this approach, one can question the reliability of the results obtained. One of the main reasons of this doubt is the oversimplification of the relationships between environmental parameters and degradation rates. The algorithms developed are also prone to personal/human decisions (e.g., selection of the reference material that defines indoor air quality, selection and interpretation of standards and guidelines, definition of weighting factors, etc.). In what follows, several arguments are given why heuristics are sufficiently reliable.

- **The concept of the standardized evaluator:** Despite the heuristics and personal choices made during the development of the algorithms, the algorithms themselves are a standardized procedure that leads to the reproducible and quantitative judgement of the IAQ. The IAQ-scale is not absolute, but this is not necessarily a problem. Science knows several relative scales (e.g., standard reduction potential where the standard reduction potential of hydrogen is set to zero, standard enthalpy of formation where the enthalpy of an element in its standard state is set to zero, etc.). Thus, the standardized evaluator generates reproducible and quantitative evaluations, but the scale is not absolute. The relative IAQ-scale allows the comparison of risks from different periods.
- **Proceeding deepening of our understanding:** Due to improved knowledge and expertise, green-thinking, and less energy-intensive preventive measures, standards and guidelines for temperature and humidity tend to become more relaxed (Atkinson, 2014). It is also expected that more accurate *thresholds* will become available for pollution levels. Therefore, the

algorithms should be kept up-to-date. Once revised, data from the past can be recalculated and re-evaluated considering the updated threshold values. Despite the changes in the 'standardized evaluator' (i.e., the algorithm) it remains possible to compare the IAQ with data collected from the past.

- **Advantage of a simplified approach:** The principles on which some algorithms are based are an oversimplification of the complex reality. Synergetic effects between environmental parameters are not considered. Therefore, periods of elevated risk can somewhat be underestimated. In many cases the simplification of reality into some rules of thumb work well enough to compare consecutive periods.
- **Considering more knowledge does not always result in a better mode:** More complex models based on a myriad of (partially understood) interactions between environmental parameters and historical materials might sound as a better alternative but the trade-off for the increasing accuracy is a reduction in clarity. In addition, the complexity of the model (e.g., overfitting of data, considering accidental patterns, the *uncertainty* of the real world, etc.) can introduce a larger amount of errors. For that reason, simple heuristics that ignore information can outperform more sophisticated inference strategies.

Despite the advantages of *heuristics*, there are also some points of concern that should be considered. Although the IAQ indexes give good insight into the periods with elevated *risk*, the initial question, "How fast do materials degrade?", is not answered. However, the IAQ algorithms supports the formulation of that answer by estimating the enhanced risk for degradation. This already helps heritage guardians to make decisions. However, in some cases the heuristics result in systematic errors, also known as a *bias*.

- **Missing information:** It is important to have measurements of all relevant key risk indicators for a given material/object type. Current technology does not yet allow continuous measurement of all relevant markers with low-cost devices. However, with fast-evolving technology, it is expected that more sensors with better detection limits will become available. In the meantime, the algorithm can be applied, but one should be aware of the possible overestimation of the IAQ due to missing information of a relevant marker.
- **Restricted options for material choice:** The IAQ-algorithms offer evaluations for different materials, objects types or collections. When using an IAQ index calculator, one should be aware that within each material/object type, variations in sensitivity exist depending on the applied techniques, material combinations, material purity, etc. These variations are one of the reasons why objects of art should be considered as unique objects. Also, the conservation state is important, since deterioration rates may vary during ageing (NBN, 2010), and conservation–restoration treatments can suddenly change the fragility of an object. Such refinements are not considered in the algorithms because they treat materials and objects at a statistical level (i.e., average materials and objects with an average behaviour).

- **Restricted visualization:** The visualization of the overall IAQ index using colour bars is intuitive and thus accessible to lay people but they omit a considerable amount of information that might be needed to select the most appropriate decision. The visualization method could be found that combines all available information in a simple way. Therefore, the analysis of the colour bars should always be supplemented with the line graphs of environmental parameters.
- **Effect of personal choices:** The intuition of the developer of the algorithm affects the definition of the standardized evaluator.

3.2.8. Deliverable 3: Work process

Risk management is the systematic application of management policies, procedures and practices to the tasks of analysing, evaluating, controlling and monitoring *risk*. Risk management should always take place in a structured, systematic process, for the purpose of being a continual part of management. For that reason, the analysis of risk-related aspects occur in subsequent steps and these steps form a fixed work process. In *preventive conservation*, risk management processes are based on the analysis of the past effects of *hazards* by means of visual inspection. Such analyses help heritage guardians in selecting the most appropriate mitigation treatment. The problem of the currently used approaches is that they are not able to use all available information sources such as the monitoring of environmental parameters.

To use more information sources, the AIRCHECQ work process shown in Fig. 27 approaches risk management in a different way. The work process analyses several markers that give an insight in the overall level of risk. It approaches preventive conservation as an iterative process where indoor air quality evolves to an ideal situation as a consequence of a series of smaller and/or larger mitigation actions. The work process consists of a linear and a circular part:

- **Linear part of the workshop:** The linear part analyses the risk related markers that remain stable for longer periods of time such as the efficiency of the protection shield surrounding a heritage collection and the sensitivity of the collection towards hazard *exposure*. At longer time scales, these markers do evolve: (1) the sensitivity of an object can be modified during a conservation-restoration process, or (2) the protection efficiency of one of the layers of enclosure can be improved during refurbishments. This means that the linear step should be repeated after drastic changes of the preservation conditions. The linear representation only suggests that such analysis should not be performed frequently. The linear part of the work process ends in a decision point. That decision point consists in choosing the most appropriate measuring location from a series of alternative locations in a building;
- **Circular part of the workshop:** Several risk related markers such as the exposure and the hazard types in the risk management process change much faster. For that reason, they

are analysed within a closed loop. Also the circle contains a decision point: the selection of the most appropriate mitigation action from a series of alternatives.

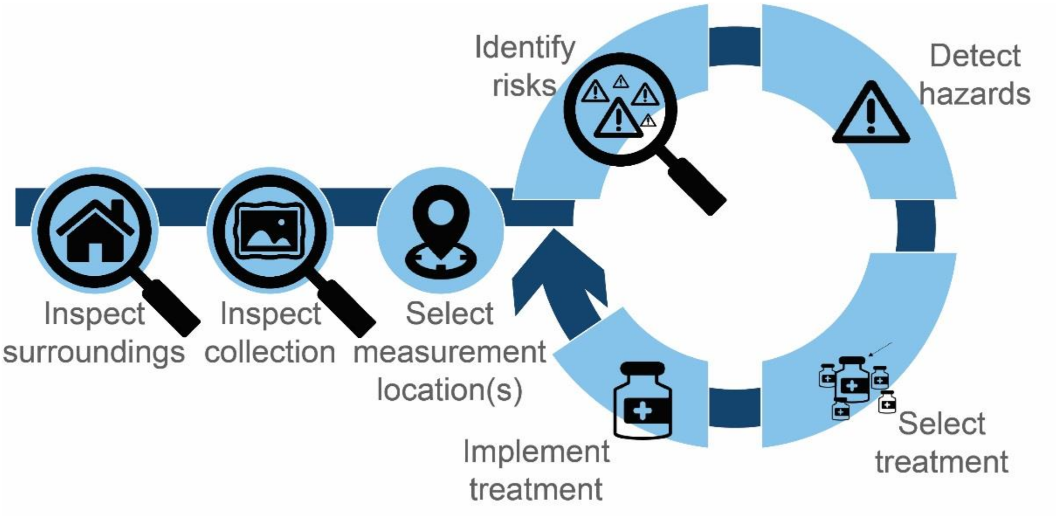


Fig. 27: Overview of the work process used to continuously improve the preservation conditions of a heritage collection. The process consists of a linear part that is only performed occasionally and a circular part that is performed in a cyclic way.

In what follows, each step of the work process in Fig. 27 will be described in detail. The description includes the markers *vulnerability*, sensitivity, exposure and intensity of the hazard that allow an estimation of the current risk and that can be calculated using the measurement of environmental parameters.

- **Inspect surroundings:** In this step, information is collected about the 6 layers of enclosure (i.e., region > site > building > room > fitting > support) that form a protection shield around the collection (Pedersoli Jr. et al., 2016). The layers of enclosure can be layers of protection (e.g., protecting a collection against outdoor climate) but they can also contain sources of danger (e.g., a leaking roof, failure of the climatization system). The information is mainly obtained by visual inspection. Supplementary information is obtained with mobile inspection equipment such as a handheld thermometer, air speed measuring device or a thermographic camera. This information is needed to evaluate the efficiency of the surroundings to protect a collection against hazards. The opposite of the protection efficiency is the *vulnerability* of the surroundings. Vulnerability is not directly used in the indoor air quality assessments but is used to determine the measuring locations;
- **Inspect collection:** The indoor air quality assessments are always related to a specific material, object or collection type. For that reason, insight is needed about the collection, specific objects or materials that receives special attention, the preservation state and if the climatization system is optimized for the preservation conditions of a specific material/object type. This information is needed to estimate the *sensitivity* of the collection towards hazards.;

- **Select measurement locations:** The linear part of the work process ends with this step. During this decision point, the most appropriate measuring locations for the monitoring systems must be selected to obtain meaningful information. For this, the number of measuring devices, the weak points in the layers of enclosure and the sensitivity of specific objects within the collection must be considered. It should be remarked that the air quality in the selected measuring location is not a point in a room but rather a vector;
- **Identify risks:** The measuring systems follow up several environmental parameters and, in some cases, also the real time behaviour of materials. Using the assessment techniques described in the previous paragraphs, it is possible to detect the moments that that the collection is exposed to elevated levels of risk. Besides the *exposure*, the ongoing measurements also give an insight in the intensity of the hazards. This means that the occurrence of unacceptable risks can be detected as well.
- **Detect hazards:** Once the moments of elevated levels of risk are known, it is possible to check if there is a correlation with some actions that occurred in the rooms. Logbooks and personnel can be consulted in a targeted way. This approach simplifies the identification process of hazards. People can respond in different ways to risks. Fig. 28 shows some typical undesired responses towards risk and risk communication;
- **Select treatment:** Once that a hazard has been identified, a dedicated list of possible mitigation actions can be made. This step is the decision point of the cyclic part of the work process and the most appropriate mitigation actions must be selected from the list of possibilities. An important bottle neck in the decision-making process is to convince decision makers to use the scarce resources to invest in 'invisible' mitigation actions that only have an effect on the long turn. In such cumbersome lobby work, the visualization of indoor air quality performed in the step 'Identify risks' can be used as an objective argument to sustain (intuitive) decisions;
- **Implement treatment:** Finally, the selected mitigation action is implemented and the effect on the environmental conditions can be evaluated by comparing the measurements just before and after the implementation of the mitigation measures.

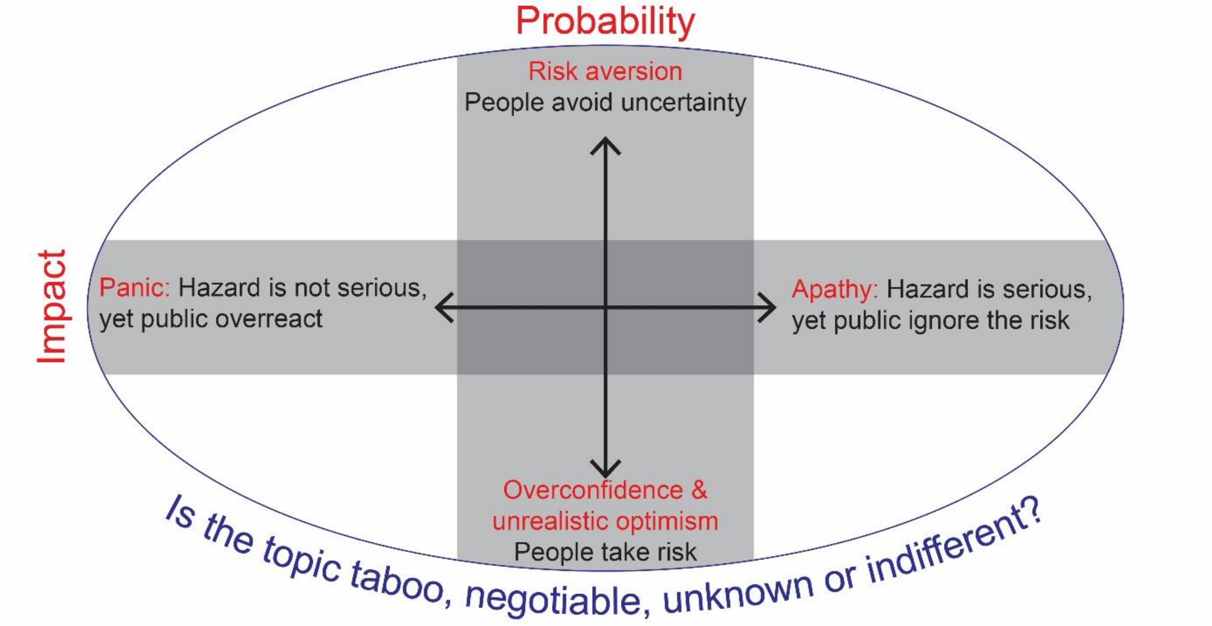


Fig. 28: Some undesired human responses to risk and risk communication within an organization and to a larger public on the level of topic, probability and impact. Risk perception is the stakeholder's view on risk.

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

The previous section gave a detailed description about the methodology that was developed during the AIRCHECQ project. That section contained all the measurements that was needed to substantiate the methodology. In this section, the focus is on the application of the methodologies to analyse the preservation conditions in specific locations. In the following paragraphs, the results of several case studies are summarized. The case studies are shortened versions of some publications.

4.1. Analysis of hazards in a 15th century chapel in Antwerp

Heritage-related standards and guidelines recommend stable climate conditions, since these extend the life of heritage collections. As a result, numerous museums and other heritage institutions implement (expensive) mitigation measures to achieve stable conditions. Despite such measures, fluctuations in temperature and relative humidity are often still observed. This case study demonstrates that the analysis of low-, mid- and high-frequency fluctuations in temperature and humidity graphs helps in identifying a large number of hazards. The method is applied on a 22-month monitoring campaign performed in a chapel in the center of Antwerp (Belgium) where the climate conditions are controlled with an HVAC-system. The low-, mid- and high-frequency fluctuations are treated in separate sections. The data processing following standard EN15757:2010 is discussed in the mid-frequency section.

4.1.1. Low-frequency fluctuations: seasonal trends

Fig. 29 gives an overview of the measured indoor temperature and relative humidity for the 22-month measuring period. The black line represents the raw data. The red and blue lines are the moving 30-day averages of the temperature and RH, respectively, and visualize the seasonal trend in the datasets. These trends are considered as low-frequency fluctuations because they cover periods of several months. The isolation of the seasonal trend is to some extent influenced by some large peaks and drops, especially in the RH. Therefore, the separation is not perfect but sufficient to give more insight in the overall climate behavior inside the chapel. Following observations are made:

- **Temperature:** In all seasons, except the summer season, the temperature is around 18°C. This is the set point of the HVAC-installation. In summer, the average indoor temperature is higher than 18°C. This is due to the combination of elevated outdoor temperatures and the climate control system that is not able to cool down the chapel. Therefore, the seasonal trend shows two clear peaks during the spring and summer months, while the rest of the year the temperature is relatively stable around 18°C.
- **Relative humidity:** The seasonal trend of the relative humidity shows more fluctuations compared to the seasonal trend in temperature. This is due to the interference between mid-frequency fluctuations and the seasonal trend. In general, summer periods are marked by a higher relative humidity (i.e., between 60% and 70%) compared to the other seasons (i.e., between 40% and 50%).

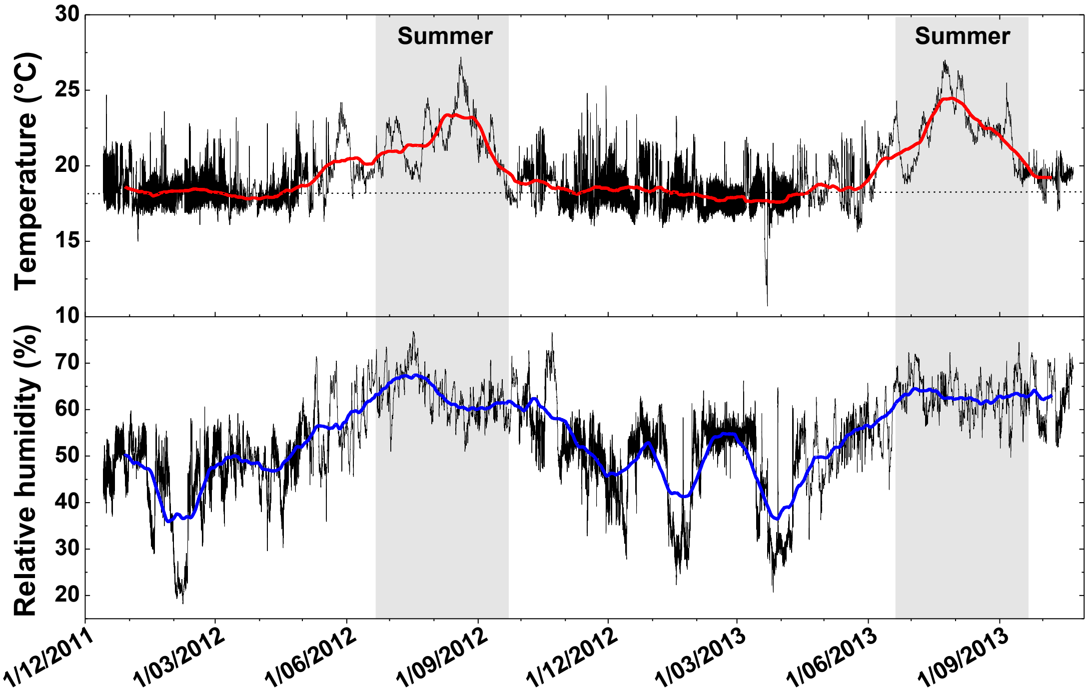


Fig. 29: Overview of the dataset of temperature and relative humidity from 13/12/2011 till 20/10/2013. The black line represents the raw data. The red and blue line are the 30-day moving averages of temperature and relative humidity, respectively.

4.1.2. Mid-frequency fluctuations: weather changes

The most important mid-frequency peaks and drops seem to be governed by the outdoor climate. Therefore, the change in weather is suspected to be an important hazard. Fig. 30 gives an overview of the raw data from which the seasonal trend has been subtracted and where high frequency fluctuations have been removed using a 24-hour moving average. The remaining fluctuations are caused by *hazards* that cause fluctuations with a width of more than one day. The standard deviation for the T and RH mid-frequency fluctuations are 1 and 5, respectively. The mid-frequency fluctuations of the indoor data are compared with the outdoor data. Sunshine duration data are plotted with outdoor temperature, since it is expected to mainly influence the temperature. Sunshine can warm up the chapel through the windows. Rainfall, on the other hand, is plotted with the RH. The arrows in Fig. 30 indicate several indoor peaks that are clearly related to outdoor peaks. The most important mid-frequency fluctuations are discussed in the list below:

- **Temperature peaks in the summer periods:** Outdoor temperature peaks often correspond to periods of high sunshine duration. Due to a high correlation between indoor and outdoor temperature during the summer period, these warm periods result in indoor temperature peaks. Indoor-outdoor peak correlations are mainly observed in spring and summer periods, since the rest of the year, mid-frequency temperature fluctuations are suppressed due to the artificial heating of the chapel.
- **Sudden drop in relative humidity at the beginning of February 2012:** One of the largest drops in RH can be noticed between January 27, 2012 and February 10, 2012 with a width of 14 days. Within one week, the RH dropped almost 35%, which corresponds to an average daily decrease of 5%. In this period, the RH reaches a minimum of 18.2%. During this period, the outdoor temperatures go below the freezing point with a minimum of -14°C on February 4. The additional heating of incoming outdoor air resulted in a strong decrease in indoor relative humidity. It is clear that the humidification module did not function at that time. Similar drops can be seen in January 2012, February 2013 and March 2013. These drops are to be considered as a severe *risk* to the historic furniture inside the chapel.
- **Limited influence of rainfall on the indoor relative humidity:** Intuitively one would expect an increase in indoor relative humidity when people enter the church with wet clothes. However, no clear relation was observed between rainfall and indoor relative humidity. This suggests that the influence of wet clothes on the chapel's RH is limited. The indoor relative humidity seems to a large extent dominated by the outdoor absolute humidity and not by rainfall.

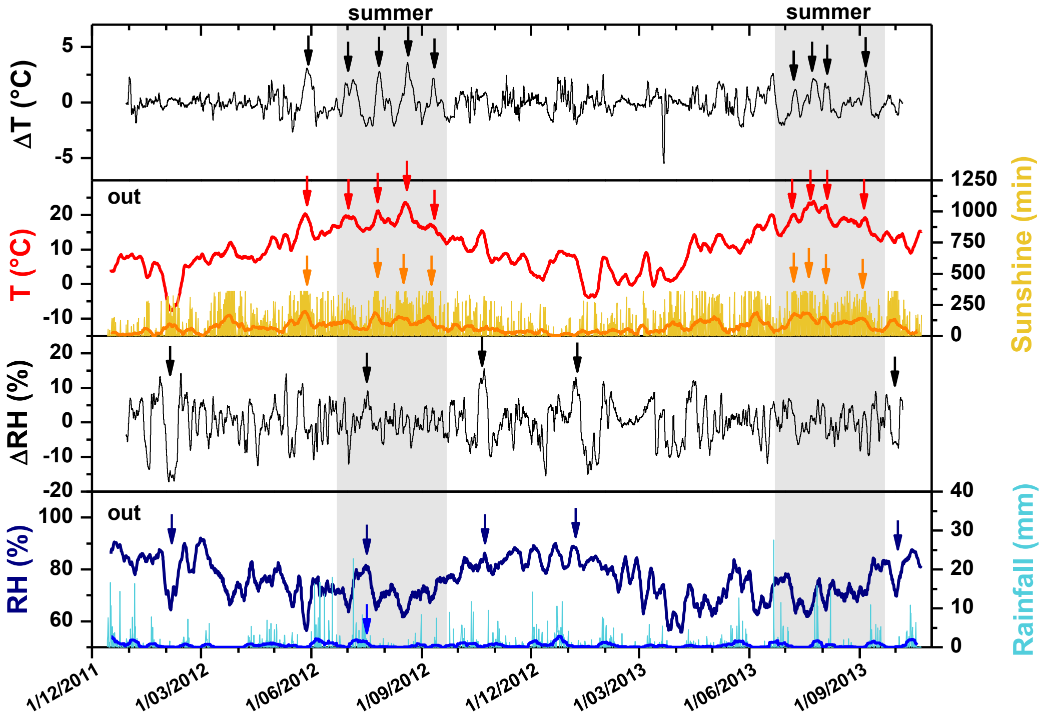


Fig. 30: Mid-frequency fluctuations (black), determined by subtracting the seasonal trend from the data set for indoor climatic conditions, and subsequently applying a 24-hour moving average. The indoor data are compared with outdoor data for temperature (red), relative humidity (dark blue), sunshine duration (orange) and quantity of rainfall (blue). Summer periods are marked in grey. Remarkable peak correspondences between outdoor and indoor data are marked with arrows.

4.1.3. High-frequency fluctuations

The remaining high-frequency fluctuations are sudden changes that occur in a matter of hours. Fig. 31 gives an overview of the raw data from which the seasonal trend and mid-frequency fluctuations have been subtracted. The remaining signal is more constant but clearly shows high frequency fluctuations. The temperature and relative humidity fluctuations are characterized by a standard deviation of 0.7 and 2, respectively. The high-frequency fluctuations are clearly lower in height during the summer periods.

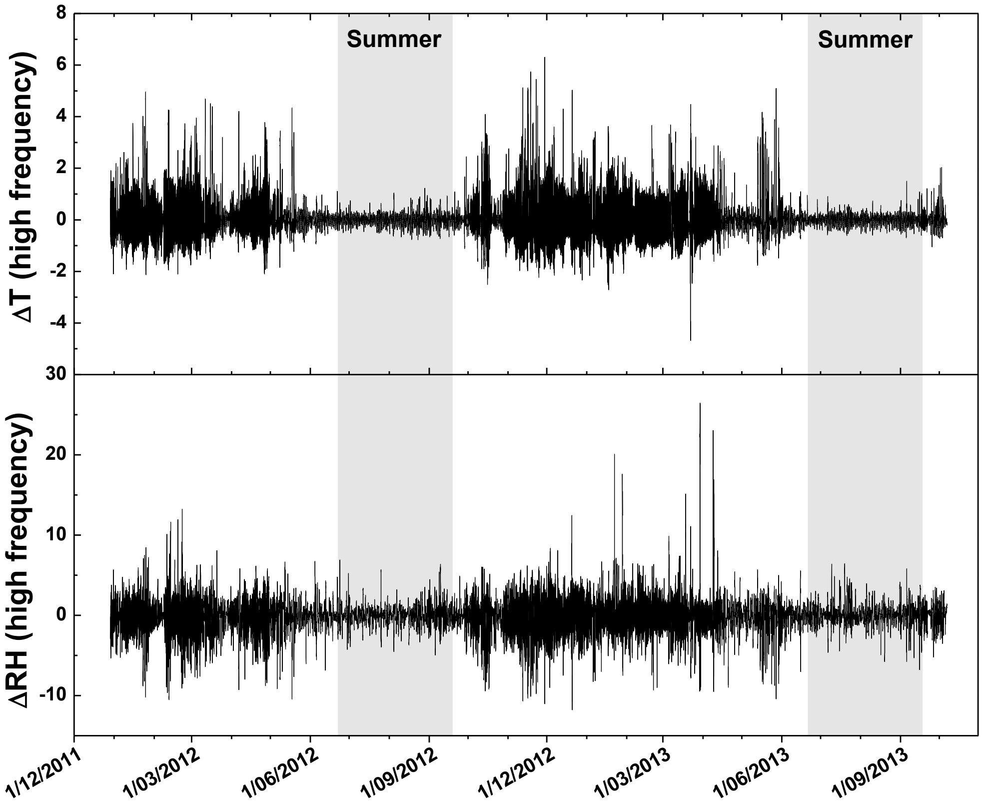


Fig. 31: Overview of the dataset of temperature and relative humidity from 13/12/2011 till 20/10/2013 from which the season trends and mid-frequency fluctuations have been subtracted. Grey filled areas mark the summer periods.

To identify the hazards of the high-frequency fluctuations, a 7-day detail of the dataset has been selected from Fig. 31, one in winter and one in summer (Fig. 32). In the winter periods, a fast fluctuating signal appears for both temperature and relative humidity. In the summer periods, the pattern is totally different. Both periods are discussed below:

- **Winter period:** A fast fluctuating signal appears for both temperature and relative humidity. This is related to the fast response of the climate control installation in order to maintain the chapel's temperature at 18°C. The RH shows a reverse fast fluctuating pattern. At several moments, the chapel's temperature is deliberately increased to around 21-23°C for a public event, for periods of around 3 hours. This results in a clear decrease in RH with ca. 10% in the same 3-hour period. After the event, the indoor temperature is cooled down again to 18°C. The cooling is expected to be a result from the mixture of warm indoor air with cold outdoor air, while the heating system is temporarily switched off. With a constant amount of moisture in the air, the relative humidity increases when temperature drops, with even an overcompensation in RH.
- **Summer period:** A high-frequency cycle in temperature and relative humidity can be noticed with peak-to-peak values that are clearly smaller than those in winter period. In the one-week period shown, 7 day-night cycles for temperature can be noticed. For relative humidity, more peaks are present. Some of these peaks are clearly anti-correlated with the temperature peaks, while others are correlated, or show a totally different pattern. This

means that the RH-peaks are not completely governed by day-night cycles but should also be influenced by weather changes or *events* in the chapel.

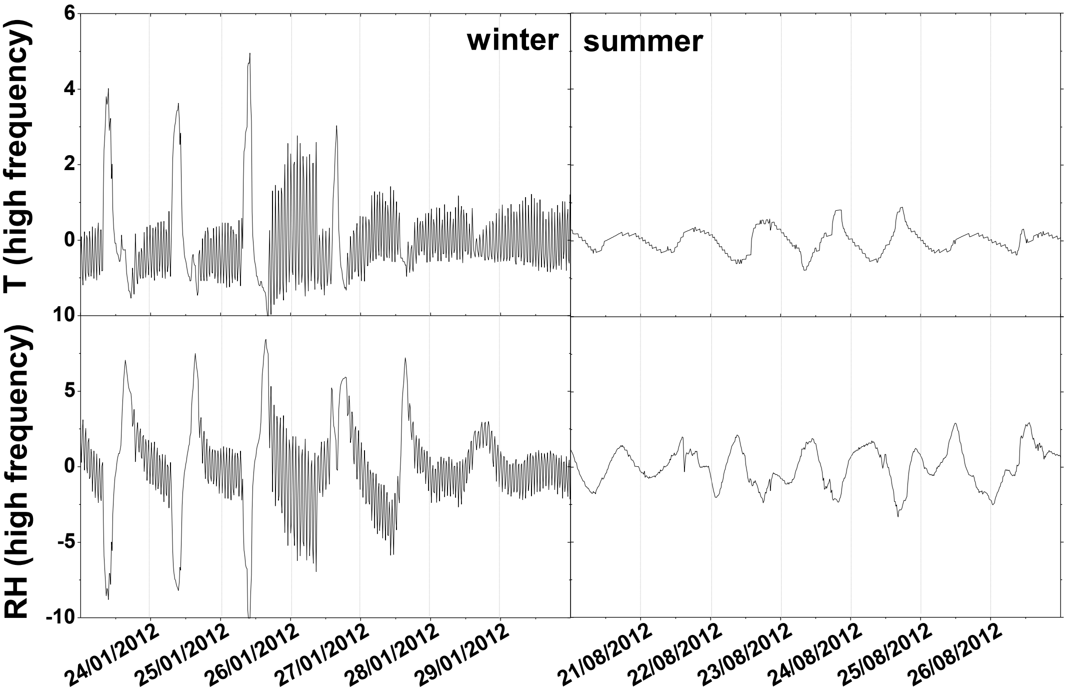


Fig. 32: Details of the graphs in Fig. 31. Winter period from Monday 23/01/2012 till Sunday 29/01/2012 (i.e., 1 week). Summer period from Monday 20/08/2012 until Sunday 27/08/2012.

4.1.4. Conclusions

The temperature and relative humidity graphs can be read as a complex superposition of responses to a large number of hazards. The fluctuations are reflected as peaks and drops in the graphs and are considered as undesired situations because they are associated with well-defined periods of elevated *risk*. The identification of the (individual) hazards that are responsible for the fluctuations is facilitated when the fluctuations of different frequency ranges are isolated. The low-frequency fluctuations are disturbances that take place in a period of months; the mid-frequency fluctuations typically take place in a period of days to weeks, while the high-frequency fluctuations take place within hours. The case study clearly shows the presence of large mid- and high frequency changes in RH of more than 20%. Such fast and strong changes could affect the wooden objects in the chapel (Alten, 1999, Jakiela et al., 2007).

The HVAC-system provides good human comfort during the winter period but at moments where outdoor temperature drops below zero, the indoor relative humidity drops down to 20%. This is caused by the heating up of cold outdoor air to the required indoor temperature. These mid-frequency fluctuations can be considered as a large risk for the moisture-sensitive heritage objects inside the chapel. The fluctuations for all frequencies are more pronounced during the periods with heating. Thus, the heating installation induces more unstable RH-conditions. Therefore, the installation of an HVAC systems should not only be considered as a solution that improves the preservation conditions but also introduces new risks due to machine failure, inability to stabilize climatic conditions or to improper maintenance. These hazards need to be considered as well when invasive renovations are planned. During summer, the high relative humidity and the temperature peaks should also be considered as a risk. In addition, when high temperature set points are used heating during almost 8-9 months a year is required.

Hazards detected during the measuring campaign can reoccur in future with a possible higher level of risk. Therefore, it is advised to perform mitigation actions to avoid or reduce the identified hazards to occur in future, and, as such, reduce the level or risk to which the heritage collections will be exposed. Thus, the identification of undesirable situations contains valuable information for preventive conservation and should not be neglected, even when they did not cause any noticeable harm so far.

4.2. Mitigation action in a small archive in Brussels

In this case study, the preservation conditions of a small archive (Fig. 33) in Brussels are studied and improved by a mitigation action. The archive houses paper documents from the early 19th century up till today. It consists of manuscripts, printed documents, and small collection of gelatin silver black and white photographs made after World War II. The large variation in age of the documents means their composition is varied: cotton rag paper, ground wood paper, lignin free paper, iron-gall ink, carbon-based inks, gelatine, silver, baryta, etc. The documents are protected in acid-free boxes designed for document storage. The sensitivity distribution throughout the collection is not homogeneous. However, it can be stated that all documents are hygroscopic, meaning that relative humidity is important.

Fig. 33: The HVAC ducts are placed on either side of the room, each one above a compactus archive closet. Each duct has 3 exhausts. The duct in the photo bottom right was closed with a valve. Documents are stored in cardboard boxes, stacked in the compactus.

The archive room is located deep within a large building located in the city center of Brussels, with big traffic axes nearby. No sunlight can penetrate the room, for there are no windows. There are 2 entry doors that are closed all the time unless authorized staff enters or leaves, resulting in a low frequency of opening the entrance doors. The room has a total volume of 360 m^3. About 60 % of the total volume of the room is air, the other 40 % is occupied by either paper material or storage equipment. There is a high-end HVAC climate system regulated by strict operational procedures that controls temperature, relative humidity and filters particulate matter. On two opposite sides of the archive, air ducts enter the room, providing and retracting air from and to the HVAC-system. The 2 ducts with 3 exhausts each can be opened or closed with a valve. Fig. 33 shows the position of the ducts above the compactus archive closets. Therefore, when the HVAC-system is working properly, the protective layers of enclosure are considered capable of delivering and maintaining a stable and behaviour preservation conditions for this type of collection. The HVAC-system group controls the climate for the archive under study together with an additional archive and a library. The climate settings are 20 °C and 45% RH. Only a minimal amount of fresh outdoor air is mixed with the recuperated indoor air from the archives and the library.

During a measurement campaign, it was noticed that relative humidity in the archive was too high according to conservation recommendations. It appeared that one of two valves of the HVAC-system were closed. The decision was made to open it, doubling the air exchange via the HVAC-system. This contribution will demonstrate that the impact of the mitigation action on the preservation conditions can be evaluated by simultaneous monitoring environmental parameters and real-time material behaviour. From this evaluation, it is even possible to estimate the effectiveness of the mitigating action in a quantitative way.

4.2.1. Graphical analysis of the trends

Fig. 34 shows CO_2, particulate matter (PM) and motion for the period well before and after the mitigation action that was taken on day 12. The signal of each parameter consists of a slowly moving background with sharp peaks on top. It is known that these parameters are highly affected by human activity (presence) and might explain the presence of peaks. The data shows peaks of CO_2 and PM, but they are (not all) unrelated to motion. The 2 high motion peaks on days 12 and 22 are due to implementation and control of the mitigating action by work men. This means that the presence of peaks must be caused by activity outside the archive. The green arrows point to opening days of the library (i.e., another room in the building), which is acclimatized with the same HVAC-system group. This suggests that at least some of the peak correlations between CO2 and PM originates from the library and affects the archive through the HVAC-system. These parameters are not affected by the mitigation action.

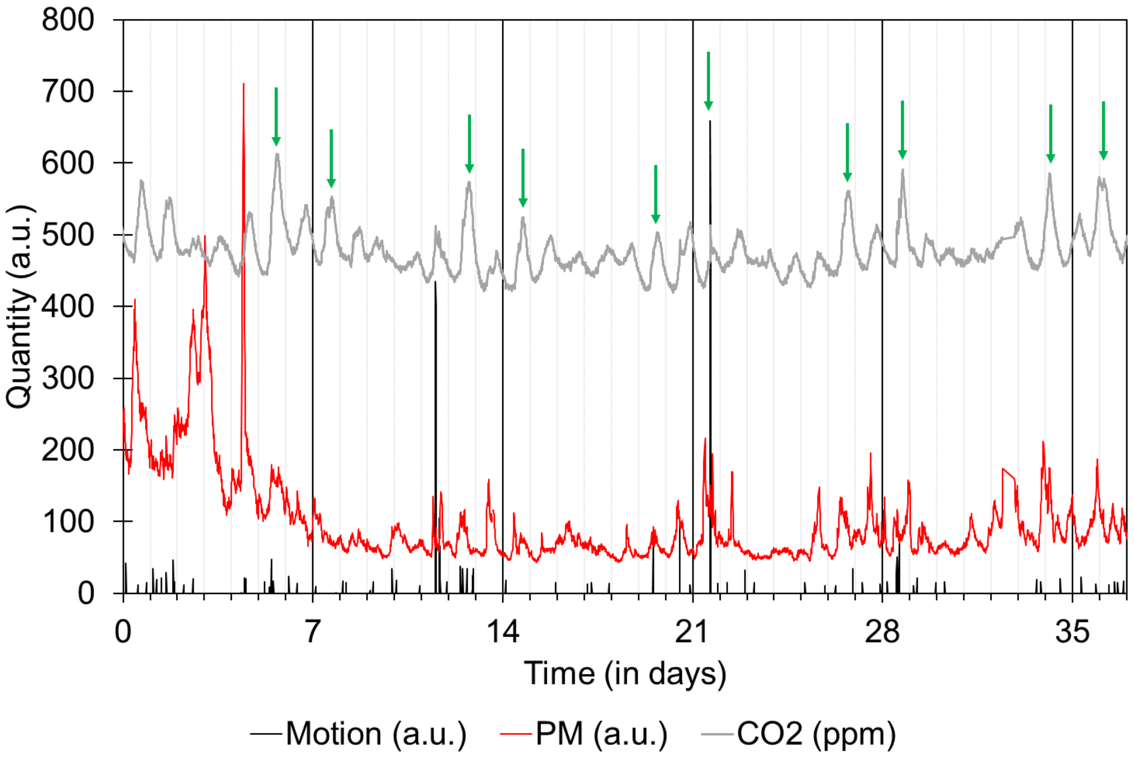


Fig. 34: The concentration of CO_2, the relative concentration of particulate matter and the motion of persons in front of the sensor over time. The peaks marked with green arrows can be related to moments when the library is open to public, a different room in the building which is connected to the same HVAC-group.

Fig. 35 clearly shows the impact of the mitigation action (i.e., the opening of the valve of the second duct) on temperature and relative humidity. It shows the trends in the centre of the archive at about 1 m height from the floor (i.e., position 1) and the measuring position close to the valve (i.e., position 2). For both positions, the relative humidity suddenly starts to drop and reaches a new stable state in day 20. The small difference between the 2 locations suggest that the relative humidity of the complete volume changed rather homogeneously. The relative humidity was about 60% before the mitigating action. Just after the mitigation action at day 12, the relative humidity drops with 11% in a period of 24 hours. Eight days later (day 20 on the graph) a new stable environmental situation around 45% RH (and 20°C) is obtained, which is the set point for the HVAC. During the drastic change, the temperature remained fairly constant about 20°C and was not affected by the mitigation action.

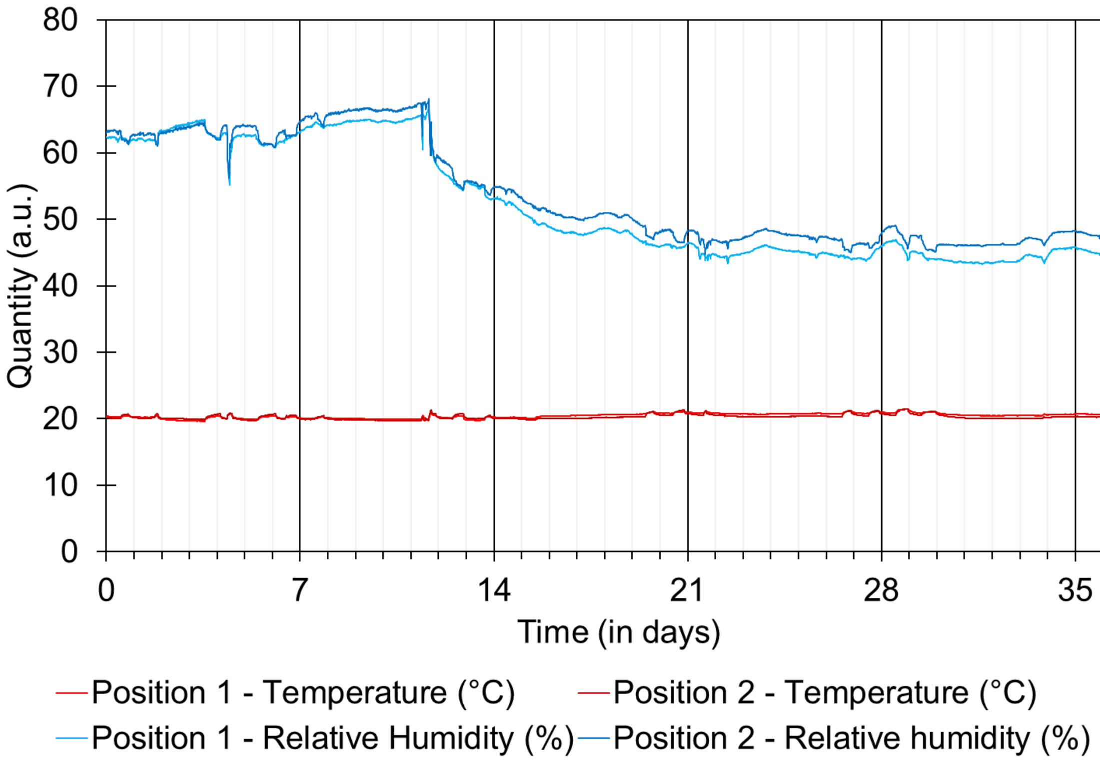


Fig. 35: The temperature and relative humidity over time from the situation before the mitigating action (Time < 12) and after the mitigating action. Position 1 is the centre of the archive at a height of about 1 m above the floor; position 2 is close to an exhaust.

Fig. 36 shows the material behaviour during the measuring campaign. It demonstrates that the real-time silver corrosion rate (i.e., the slope is a measure for corrosion rate) measured with an electrical resistance probe remains fairly constant and is not affected by the mitigation action. The surface of the wooden block swelled in the beginning of the measuring campaign because it originated from a drier location but just after it almost reached its equilibrium at the start of the mitigation action. Once the valve is opened, the surface started suddenly to shrink. The response of the wood follows the change of the relative humidity. Both follow a typical decaying behaviour: fast in the beginning and slow at the end. The shrinkage continued up to day 25. This means that the environmental conditions can be improved in a short period of time but that some materials need more time before they achieve a new equilibrium state. This means that also other hygroscopic materials such as the archival documents in boxes will need more time before they reach their new equilibrium, maybe even longer than the wooden block. The experiment clearly demonstrates that a mitigation action can be an improvement for one material and but remains invisible for another material. This means that the indoor air quality around heritage collections is to a large extent determined by the materials that are present in the collections.

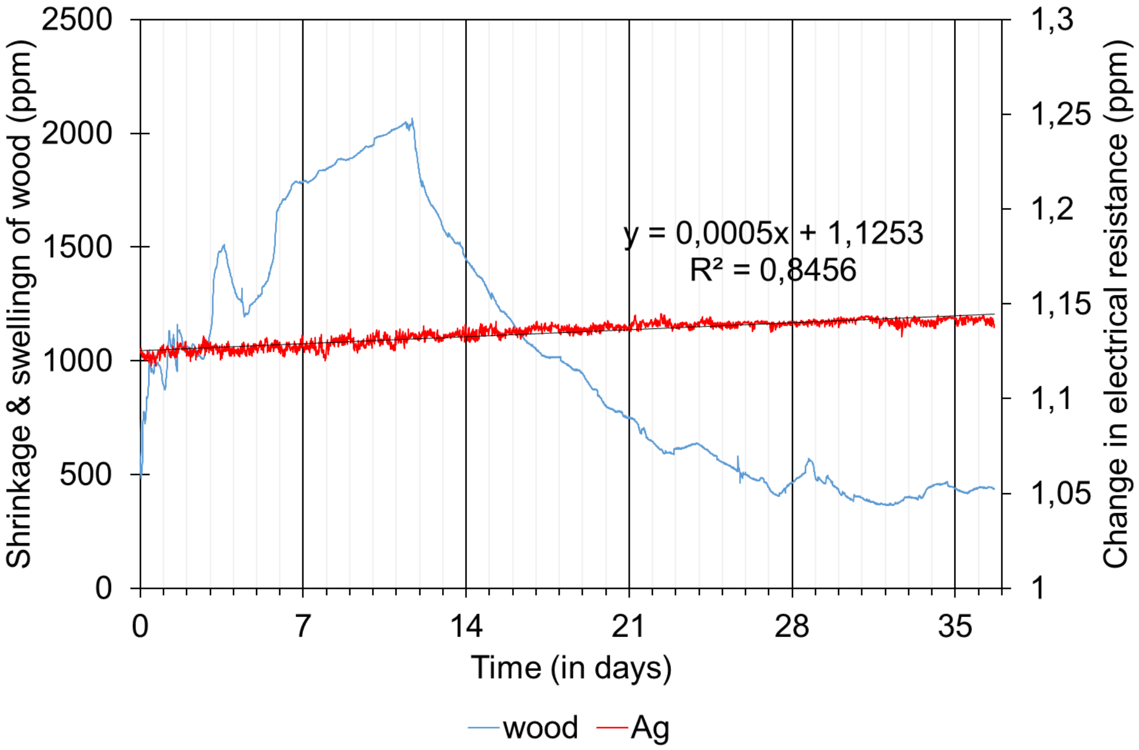


Fig. 36: Shrinkage and swelling of the surface of a block of 16th century oak wood expressed in ppm and relative to day 0 and the silver corrosion rate expressed in ppm and relative to day 0.

4.2.2. Indoor air quality analysis

Fig. 37, 38 and 39 visualize the trends in indoor air quality of the same room and the same period for silver, wood and paper containing ground wood respectively. The dark blue colour in the colour scale represents excellent indoor air quality; lighter blue to cyan indicates a less ideal situation. The overall indoor air quality for silver (see Fig. 37) shows an excellent indoor air quality before and after the mitigating action. This agrees with the behaviour of the silver sensor as can be seen in Fig. 36. When the individual environmental parameters are considered, it is clear that the absolute values of the relative humidity are too high before the mitigating action, but improves after it. This improvement did not affect the overall IAQ index because relative humidity has a small contribution to the corrosion rate of silver when compared to other parameters such as pollutants. For silver, the overall IAQ index did not show a significant improvement of the indoor air quality induced by the mitigation action.

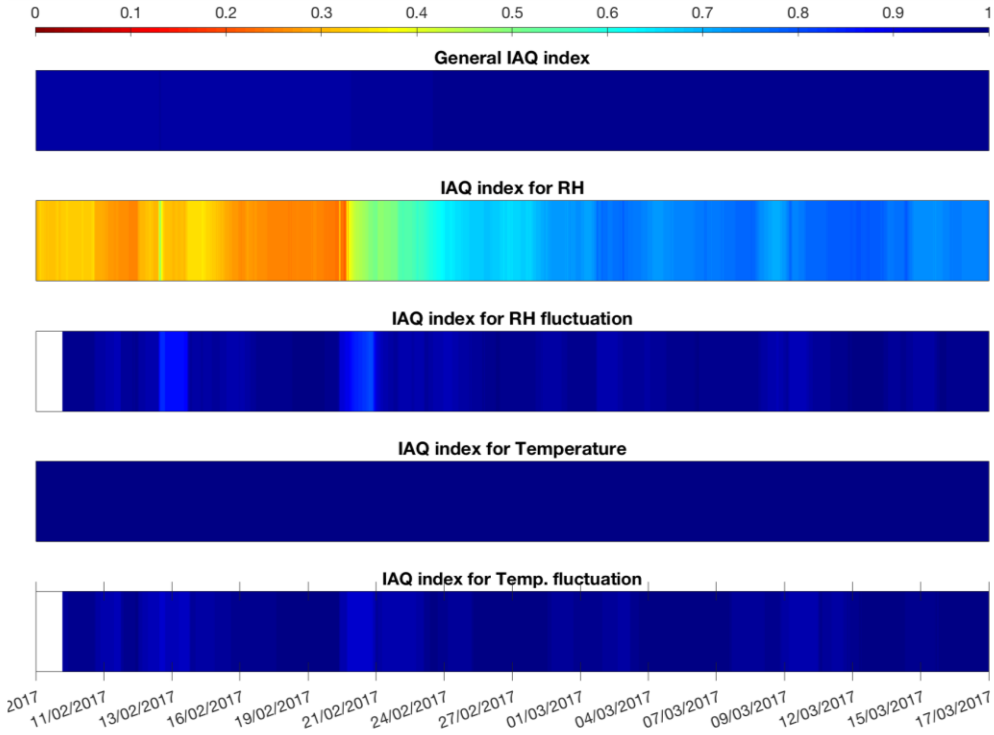


Fig. 37 Evolution of the general indoor air quality over time calculated for silver together with the appropriateness of the environmental parameters.

The colour bars in Fig. 38 represent the indoor air quality of the same room at the same moment as in Fig. 37. The only difference is that Fig. 38 considers wood instead of silver. The implementation moment of the mitigation action is clearly visible as a sudden colour shift. In the second bar, the transition of cyan (i.e., less ideal IAQ) to dark blue (i.e., better IAQ) illustrates the change in appropriateness of the RH levels. At the beginning of the transition from day 12 till day 15, the RH fluctuation is clearly too high. The behaviour of the wooden block in Fig. 36 agrees with the period of lower appropriateness for RH fluctuation (i.e. sudden shrinkage) but did not suggest that the period before the mitigation action the RH was too high. The bottom two bars in Fig. 38 are the absolute value of temperature and temperature fluctuation are not much affected by the mitigation action and are considered as appropriate. This conclusion agrees with the graphs shown in Fig. 35 where temperature remains stable at c. 20°C during the entire measuring campaign.

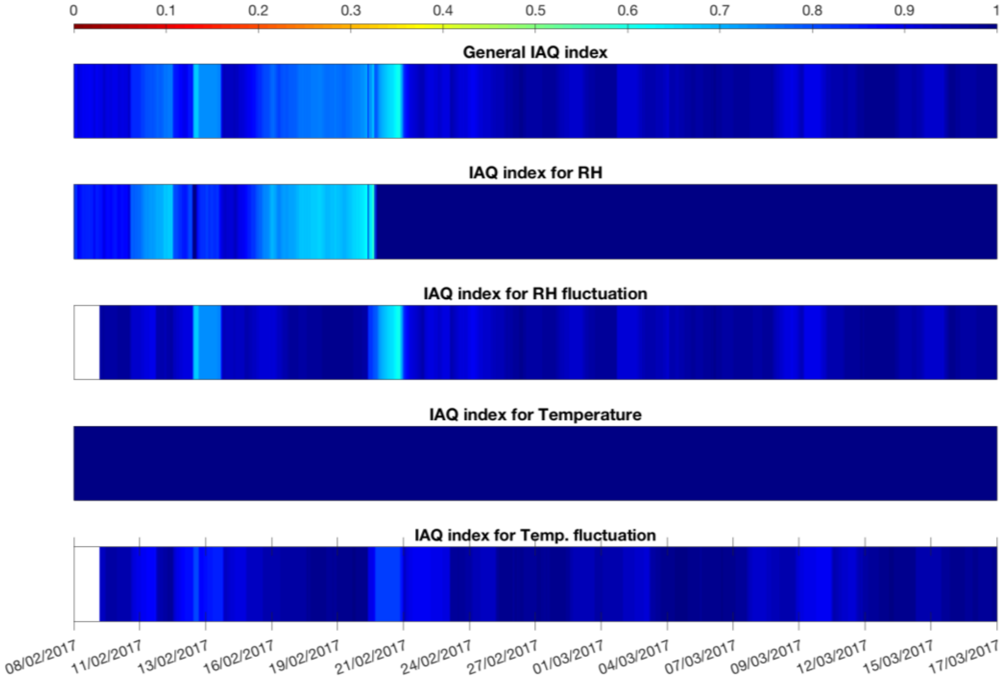


Fig. 38: Evolution of the general indoor air quality over time calculated for wood for the same period as in Fig. 37 together with the appropriateness of the environmental parameters.

The collection constitutes (almost) entirely of paper objects. Figure 38 shows the colour bars for ground wood paper. Prior to the mitigation action, a worsening IAQ is visible in both the first (general IAQ) and the second (RH) bars. This is due to the increasing RH level. After a new steady state or equilibrium state is reached after the mitigation action, the general IAQ has become blue to dark blue. This change is due to the improvement of the absolute value of the relative humidity. The third colour bar (RH fluctuation) shows safe blue colour overall, except for the short period after the mitigation action because of the sudden drop in RH.

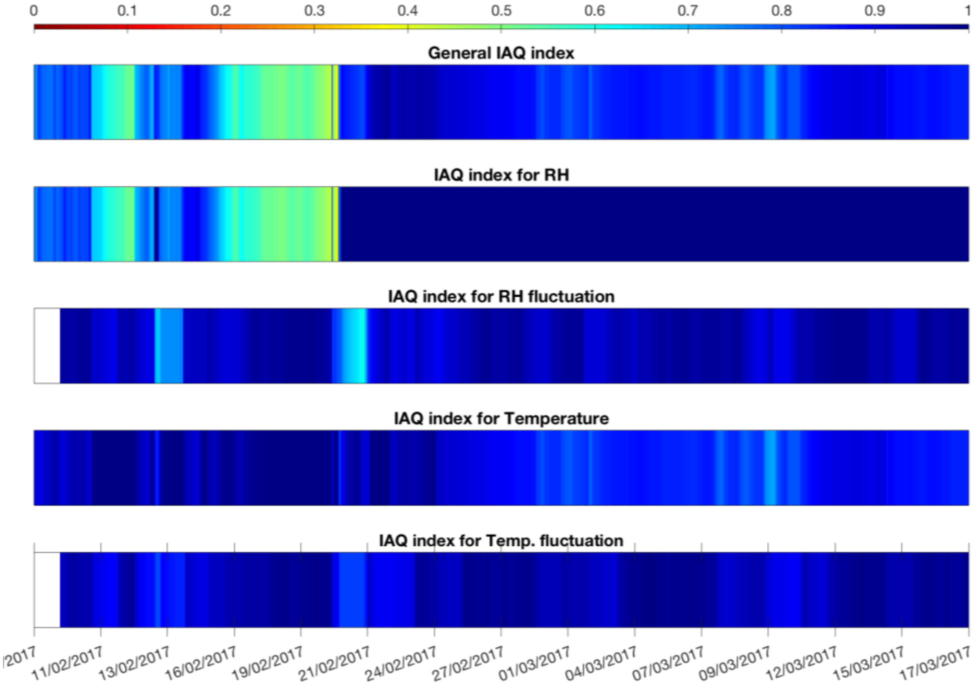


Fig. 39: Evolution of the general indoor air quality over time calculated for ground wood paper of the same period as in Figs. 37 and 38 together with the appropriateness of the environmental parameters.

Table VI summarizes the IAQ-index for in relation to ground wood containing paper 1 day before (20/02/2018 at 16:00h) the mitigation action and the IAQ-index after the change caused by the mitigation action became small (i.e. the last day of the measuring campaign at 17/03/2018 at 15:45h). The change in IAQ (i.e., ΔIAQ) represents the improvement of the indoor air quality due to the mitigation action for that parameter. That change is given for the overall IAQ and for the parameters temperature and relative humidity. From this analysis, it can be stated that the preservation conditions in the archive for ground wood containing paper have improved with 41,2%. That improvement is mainly caused by the RH levels (improvement with 65,5%) while the T levels has a negative impact on the overall IAQ (-2,9%).

TABLE VI: Numerical values for the IAQ for ground wood paper. The calculated numbers are for 20/02/2018 at 16:00, one day before the mitigating action was performed; and 17/03/2018 at 15:45, the last day of the measuring campaign.

Parameter	IAQ_{before}	IAQ_{after}	$\Delta IAQ = IAQ_{after} - IAQ_{before}$
IAQ	0,345	0,757	0,412
RH	0,345	1	0,655
T	0,996	0,967	-0,029

4.2.3. Conclusions

This case study has demonstrated that the simultaneous analysis of environmental parameters and real-time material behaviour gives good insight in how heritage materials and environment respond to the same mitigation action. The following observation were made: (1) the real-time material behaviour shows that the improvement of the indoor air quality is highly dependent on the material type, (2) the silver material behaviour did not give an indication that he stable but too high RH was a problem, (3) the wood behaviour is strongly related to the change in relative humidity, and (4) the wood continued to shrink for some days even when the environmental conditions attained a stable state. In addition, some hazard related parameters have no direct effect on heritage objects, e.g. carbon dioxide and motion, but they can be valuable in the identification process of hazards. Such in depth knowledge about the hazards is essential to take well-informed decisions about mitigation actions.

The visualization of environmental measurements by means of graphs only give an indirect impression of indoor air quality. One could guess that the relative humidity before the mitigation action is too high (but how bad is it?), but that the sudden drop is also affecting indoor air quality might be overlooked. The colour bars show the indoor air quality in a direct way and facilitates the interpretation of the collected data: (1) the overall appropriateness is directly visible and understandable to heritage guardians, decision makers and even the greater public, (2) a certain preservation state can be assessed whether a mitigation action is needed, (3) the effectiveness of the mitigation action can be quantified for different materials. In addition, the colour bars are also a communication tool and can be used to convince decision makers to invest in mitigation actions. These benefits should help the implementation of preventive conservation in the daily management.

4.3. Impact of a new heating system on the furniture in the St. Martin's church of Aalst

A new heating system has been installed in the Saint-Martin's church of Aalst. The heating system consists of a low-temperature heating system with condensing boilers and heat stations built into the church floor. The heat stations are prefabricated units with built-in heating batteries and fans. Insulated plastic distribution pipes run in two circuits via slots under the church floor from the technical room to the heat stations. The heating system provides mixed heating, i.e., constant background heating (10°C) with temporary temperature increase during celebrations and events to increase the comfort level (with a maximum of 15°C). The heating system was tested on 25/01/2018 and started up from 01/02/2018 onwards.

To evaluate the impact of the new heating system on the church interior, an extensive measurement campaign was performed, covering 2 winter periods (03/07/2017-21/03/2019). The measuring campaign started during the placement works of the heating system well before the start up of the heating system. The monitoring unit has been placed on the organ-loft close to the organ at a height of 7 m. During the measuring campaign, various environmental parameters are monitored, including the real-time shrinkage and swelling behavior of wood and the real-time corrosion rate of silver.

4.3.1. Results from the measuring campaign

Due to the long-term measuring campaign, it is possible to identify smaller periods with an increased *risk* that church furniture might be harmed. By comparing the periods of elevated risk with the moments that the heating system is operational, it is possible to evaluate the impact of the heating system. Fig. 40 shows the ambient parameters temperature, relative humidity, particulate matter and air speed for the full measuring period. The following can be determined:

- **Temperature:** The air temperature in the church follows the rhythm of the seasons, with a high temperature in the summer and a low temperature in the winter. Several smaller peaks can be observed. They are a result of weather changes. The indoor temperature clearly follows the outdoor climate. Due to the heating installation, the temperature in the church does not fall below 10°C. In the colder periods, temperature peaks are still possible when the outdoor temperature exceeds 10°C. In the winter periods there are regular short rises in temperature to 14-15°C to meet human comfort during celebrations and events. These temperature peaks are accompanied by decreases in relative humidity of approximately 10%;
- **Relative humidity:** The relative humidity in the church strongly follows the outdoor trend, although the church can buffer the strong fluctuations that we see in the outdoor measurements of the Belgian Royal Meteorological Institute. The relative humidity increases as the winter approaches but decreases when the heating is active. The heating ensures that the relative humidity in the church remains below 75% even in the winter period, although the outdoor humidity regularly reaches 100%. This contrasts with the winter period of 2017 (no heating), where the humidity in the church reached a maximum of 90%;
- **Particulate matter:** The PM concentration (PM2.5) has a constant background on which many peaks are visible. No seasonal fluctuation is perceptible. The measurement campaign took place in the period where the floor was removed to install the heating installation. Other building restoration works were also carried out after the heating installation. Such activities cause considerable dust and explain numerous peaks. Presumably there are also peaks due to visitors and surrounding traffic or industry;
- **Air speed:** The air speed varies throughout the year. During the periods that the heating system is operational, there is a clear increase in air speed. These higher values are observed on a height of 7 m above the floor grid. The increased air speed fluctuates strongly because the heating system introduces warm air into the room in a pulsating way. No significant relationship can be seen with other environmental parameters. However, increased air circulation causes an increased dust deposition. An air speed between 0.1 and 0.3 m s^{-1} is recommended in churches, which is in agreement with the observations. The air speed is slightly higher (up to 0.8 m s^{-1}) when the heating is active. This parameter clearly indicates the periods that the heating system is active and facilitates the identification of the periods

with heating when compared to temperature only. Note the high air speed around mid-March. This is due to the break-down of a stained glass window above the organ loft due to a storm. In this period, the air speed data in highly influenced by the outdoor (windy) conditions. Therefore, these data cannot support whether the heating system was active or not.

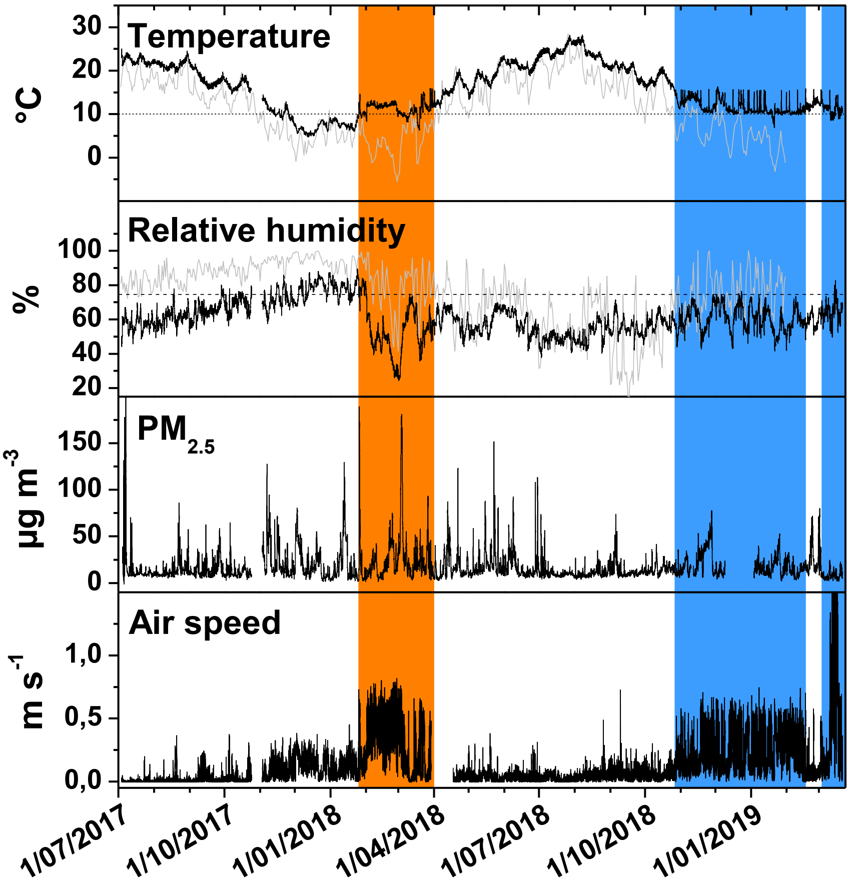


Fig. 40: Overview of the environmental parameters temperature, relative humidity, particulate matter (PM2.5) and air speed for the period 03/07/2017 till 21/03/2019. For temperature and relative humidity, the outdoor data (daily averages) of the Royal Meteorological Institute (Uccle) are plotted in gray. The periods the heating system was operational are marked: winter 1 in orange, winter 2 in blue.

For the data of temperature, relative humidity and particulate matter in the Saint-Martin's church, the IAQ index for a *general collection* has been calculated. This is a collection in which no exceptionally sensitive objects are present. For a general collection, correct relative humidity is considered the most important parameter. Therefore, this will be the most important factor in the IAQ index calculation. A relative humidity between 55 and 70% is considered acceptable. In Fig. 41, the evolution of the IAQ-index is visualized via colour bars. A red colour corresponds to a low index and shows periods in which the environment poses a real risk to the collection. A blue color corresponds to a high IAQ-index and represents periods with a limited risk of damage to the collection. Fig. 41a provides an overview of the entire measurement period (03/07/2017 to 21/03/2019). Fig. 41b and c zoom in on the 2 consecutive winter periods.

- **First winter period (01/11/2017 to 01/04/2018, Fig. 41b):** This winter period is characterized by 40 frost days (minimum day temperature below 0°C) with a cold wave (daily averages below 0°C) between 25/02/2018 and 02/03/2018 with minimum daily averages of -5.5°C and 41.6% relative humidity. At the beginning of this period there is no church heating. It is only on 25/01/2018 that the new heating system was tested for the first time. The installation is started up on 01/02/2018. The sudden change from a period with a remarkably poor IAQ index to a period with a much better index is striking. This sudden change is mainly influenced by the relative humidity. In the period before the heating starts, the relative humidity in the autumn and winter periods is regularly above 75%. This is a potential risk of mold growth. The heating caused the relative humidity to drop. That the relative humidity continues to fall for a number of consecutive days is not considered bad by the algorithm. However, the standards may be interpreted in another way: only a variation in relative humidity may fluctuate around a fixed value over 24 hours is accepted and may not drop freely. Shortly after the heating has started, there are a number of periods for which the index turns orange. These periods are characterized by a too low relative humidity due to the heating of very cold outdoor air, making it even drier. To compensate somewhat for the sharp decrease in relative humidity inside the church, it was recommended to lower the set temperature of the heating system (temporarily). From 01/04/2018 the heating installation has no longer been switched on due to the warmer outdoor temperatures. During this winter, the heating system was able to drastically improve the indoor air quality, but a problem arose during the cold wave when the cold and dry outdoor air was heated.
- **Second winter period (01/10/2018 to 21/03/2019, Fig. 41c):** That winter is characterized by 26 frost days. During the period that the heating is active, the relative humidity of the outdoor climate fluctuated around 70%. The heating started working on 28/10/2018. There was a short period without heating due to higher outdoor temperatures (18/02/2019-02/03/2019). It is remarkable that no period turned red throughout this winter period. The church heating ensures that extremely humid conditions are avoided, which means that the risk of mold growth becomes smaller. During this period, the heating was able to keep the temperature above a minimum value and to keep the relative humidity in an intermediate range so that there are no significant differences in preservation conditions between the period without and with heating. Note that in mid-march there is a small period that turns red in the color bars. This is due to the break-down of the stained glass window above the monitoring equipment. Therefore, the wind speed highly increased, and it is hard to say whether the heating system was active or not. In this short period, a too high relative humidity was measured at the organ loft (up to 83%).

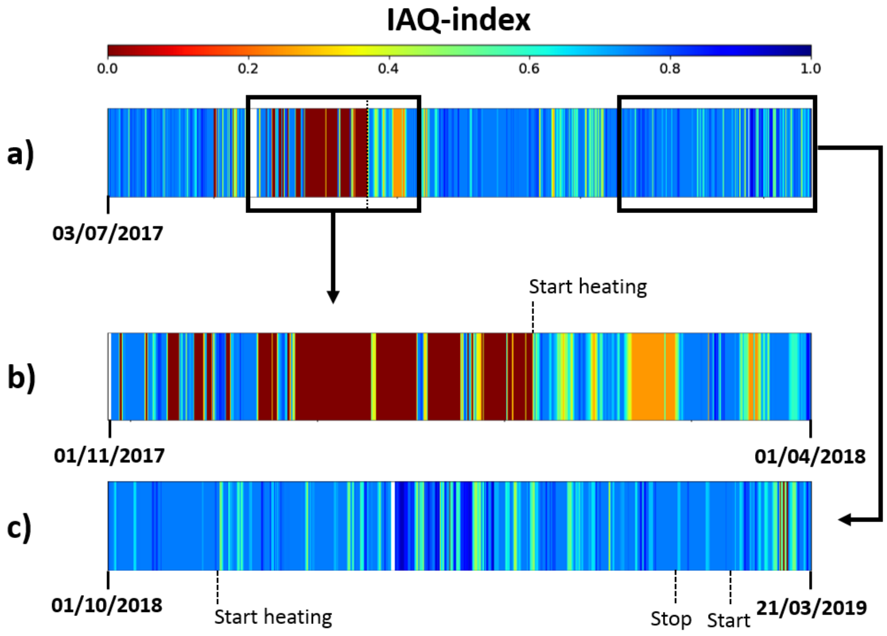


Fig. 41: IAQ index for a general collection. A) period from 03/07/2017 to 21/03/2019; b) period 01/11/2017 to 01/04/2018 with indication of the start-up of the heating on 01/02/2018; c) period 01/10/2018 to 29/01/2019. The church is heated again from 28/10/2018 to 17/02/2019 and from 03/03/2019 to 21/03/2019.

4.3.2. Conclusions

The new church heating had a positive effect on human comfort. From the point of view of heritage conservation, it ensures that a minimum temperature could be maintained during the coldest moments (avoiding freeze-thaw cycles) and that extremely humid periods in the winter are avoided. This reduces the risk of mold growth and condensation. However, there are a few points of attention as described in the list below. In general, however, it can be said that this type of underfloor heating is relatively comfortable, and reasonably safe for the preservation of the church interior, provided it works continuously without interruptions during the entire cold season.

- In the periods with heating we see that the fluctuations in the mid-frequency range over a period from days to weeks are up to twice as large as during the periods without heating. These fluctuations cause the most pronounced shrinking and swelling and shrinking behaviour of the wood, which means that they have the greatest damage potential (graphs not shown here).
- Care must be taken that in periods with very cold and dry outdoor air, the heating is not set too high. This leads to extremely dry indoor conditions, which can cause cracks in the wooden interior elements. The installed heating system has the option to program a minimum RH. Once reached, the heating system will switch off automatically.
- In the future, it must be determined whether the increased air circulation as a result of the heating leads to an increased dust deposition.

4.4. Mitigation action in the historical room of the Army museum

The complex of the Jubilee Park in Brussels (Belgium) was built to commemorate the 50th anniversary of Belgium's independence in 1880. After that, the Jubilee Park was used for several large events such as 2 World Fairs (1897 and 1910). The military museum, founded in 1910, was permanently accommodated in the Jubilee Park since 1923. This means that the collection of 19th century militaria of the Belgian armed forces together with paintings, drawings, photos and busts in the Historic Gallery are housed in a building that was never intended for permanent museum purposes. The construction of the Historic Gallery consists of solid brick walls without insulation. The zinc roof is supported by a steel frame with a triangular steel and glass structure on top. The sunlight that penetrates the room through the glass structure in the roof can directly irradiate numerous objects at the north wall. The collection can be qualified as a mixed collection with some materials (i.e., textile, paper, photographs) showing an enhanced sensitivity to the high influx of natural light.

Actions to reduce the light intensity are highly necessary without compromising the ambiance of the scenography. Photographic records of the Historic Gallery show that the current scenography with oakwood showcases has not changed much for over 80 years. The historic presentation is regarded as a part of the visitor experience and is even protected by law since June 1, 2017. The protected scenography seriously limits the options regarding the refurbishment of the historical showcases to improve the protection of sensitive objects against their environment. An alternative option is to reduce the sunlight entering the Historic Gallery through the glass structure in the roof and at the same time avoiding heat gains. Previous attempts partly blocked the sunlight from the inner side of the glass structure, but this resulted in a greenhouse effect

A temporary mitigation action was performed in this study. It consisted of putting up 180 white Forex panels of 3 mm thickness on the outer side of the glass structure. The southern side (facing the sun) of the glass structure is 90 m long and has been covered over its complete length. Because sunlight is blocked before it enters the building, no greenhouse effect should occur. The design of the mitigation action allowed for some natural light to enter the room, thus respecting the historic scenography and interior ambiance. The design also permitted to avoid any significant changes to the roof construction, thus respecting the integrity of the listed historic building.

Temperature, relative humidity, intensity of visible light and intensity of UV radiation were continuously measured before and after the mitigation action. From these measurements the evolution of the indoor air quality (IAQ) is visualized using the AIRCHECQ software. The improvement of the IAQ can be visualized, allowing the evaluation of the mitigation action.

4.4.1. Background

The Historic gallery is oriented from east to west. Thus, the glass roof construction has one side facing south (mostly direct sunlight), the other north (little direct sunlight and more stray light). Incident sunlight from the south impacts the northern wall of the Historic gallery. Fig. 42a gives an impression of the Historic Gallery with its protected scenography. Fig. 42b is a photo taken inside the glass structure. The top glass surfaces of the triangular structure are sloped at an angle of ca. 32°. Fig. 42c is a photo taken on top of the roof and demonstrates that sun rays hit the glass almost perpendicular in late spring and early summer. This means that almost all energy of the sun rays penetrates the structure, making it the ideal greenhouse. Fig. 42d is a photo taken during the implementation of the mitigation measures. The mitigation action considered the following boundary conditions:

- **Integrity of historic buildings:** During refurbishments and renovations of historical and protected buildings, the architecture, the setting of the objects and the visitor experience must be considered;
- **Integrity of heritage guardians:** Heritage guardians aim to create and maintain a suitable indoor climate so that the degradation rate of heritage collections would be as low as reasonably achievable;
- **Integrity of decision making:** Any initiative from heritage guardians to improve indoor preservation conditions must consider the financial strains of the institute and strive for sustainable solutions where possible.

Fig. 42a: Interior of the Historic Gallery of the Royal Museum for the Armed Forces and Military History showing the northern wall. The glass structure can be seen at the top of the photo.

Fig. 42b: The steel and glass structure in the roof.

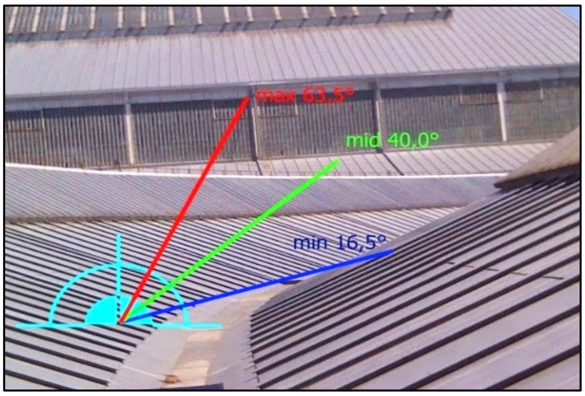


Fig. 42c: Sloped roof and glass structure (32°) and angle of sun rays in summer (red, 63°), spring and autumn (green, 40°), and winter (blue, 16°).

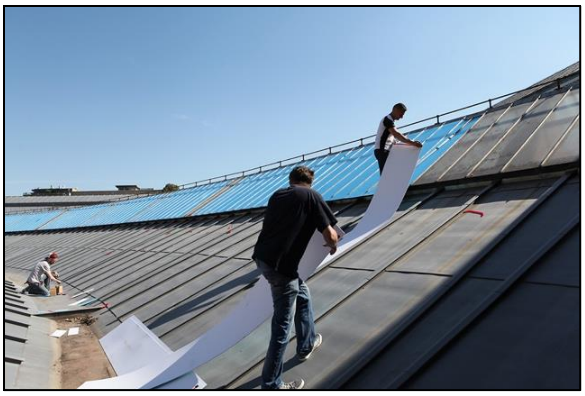


Fig 42d: Installing the forex panels on the glass structure of the Historic Gallery.

4.4.2. Experimental

The mitigation action consists of putting up 180 white Forex panels covered by a blue foil of 3 m length, 0.496 m width and a thickness of 3 mm on the south side (facing the sun) of the glass structure. The panels were attached with clamps and double-sided tape. The mitigation action is a temporary arrangement to evaluate the improvement of the preservation conditions. It resisted most of the Belgium weather conditions. Only during a storm, a few panels were detached and had to be replaced. The setup was used to show and convince decision makers to invest in a more permanent solution. The Forex panels block sunlight when it is most harmful (radiation and heat). Sunlight can still enter the Historic Gallery by the north side of the glass structure. Three pairs of loggers were used to monitor the situation before and after the realisation of the mitigation action. Each pair can measure temperature, relative humidity, and the intensity of visual light and UV radiation. Table VII gives an overview of the locations, measuring systems and their number. They were installed in 3 locations of interest: halfway the Historic Gallery on opposite sides (the northern and southern walls, see Fig. 43), and inside the glass structure to monitor the greenhouse effect. All loggers recorded a period of three months before and three months after the mitigation action. The loggers started monitoring on 01/04/2018. The mitigation action was performed at 01 & 02/07/2018, taking full effect on the 3th of July. The mitigation action was then monitored until 30/09/2018. This span includes a large part of spring and the whole summer. The data loggers measured every 5 minutes.

Table VII: Loggers used to evaluate the mitigation action.

Location	Number	Logger type
Inside the glass structure	103	Hanwell ML4106 Temperature and Humidity data logger
	204	Hanwell ML4703 LUX and UV data logger
Northern side of the Historic Gallery	102	Hanwell ML4106 Temperature and Humidity data logger
	202	Hanwell ML4703 LUX and UV data logger
Southern side of the Historic Gallery	104	Hanwell ML4106 Temperature and Humidity data logger
	201	Hanwell ML4703 LUX and UV data logger

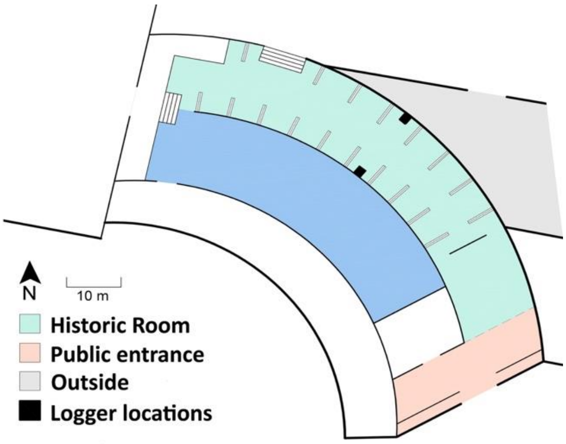


Fig. 43: Ground plan of the Historic Gallery and the 2 locations of the data loggers inside the room.

4.4.3. Results

The measurement campaign at 3 different locations in the Historic Gallery covers a period of 6 months. The mitigation action was realised in the middle of that campaign, after 3 months. The trends of the environmental parameters measured throughout the campaign are shown in Fig. 4. The climatic periods of the outdoor situation show variations in temperature, relative humidity, precipitation and duration of sunlight but the daily averages can be considered as constant. It should be remarked that a heat wave occurred in Belgium between 13/07/2018 and 07/08/2018. A heat wave is defined in Belgium as a period with at least 5 consecutive days with maximum temperatures above 25°C, of which at least 3 are with a maximum above 30°C. The heatwave is reflected in the daily maximum average temperature (see Fig. 44).

Although the temperature drops a bit at the end of the measuring campaign, there is no obvious seasonal trend to be noticed in Fig. 44. This means that there is no obvious interference with drastic climatic variations with the measurements before and after the mitigation action. In depth information about the indoor air quality of the Historic Gallery is given in Table VIII. It summarizes the percentage of time that a parameter resides in one of the consecutive ranges. The results of the measuring campaign will be discussed for the 3 different locations before and after the mitigation action:

- **Inside the glass structure, before the mitigation action:** Prior to the mitigation action, lux and UV radiation levels during day time shown in Fig. 45 exceeds at many occasions the measuring range of the monitoring device (i.e., 10000 lux and 2500 μW/lm). The temperature consisted a slowly changing background where the valleys at night follow the daily average outdoor temperature (see Fig. 44). On top of that background, the peaks during day time reach temperatures with a maximum of 67.5°C. Inside the Historic Gallery at the south side, the temperature is more in agreement with the daily maximum temperature. This means that the air volume in the Historic Gallery cools down slower than the air volume within the glass structure. The peaks in the relative humidity follow the outdoor relative humidity and contains steep valleys down to a minimum of 2.3%.
- **Inside the glass structure, after the mitigation action:** The average intensity of sunlight entering the glass structure suddenly drops resulting in intensities that fall within the measuring range of the instruments. The moment the mitigation action is realised can clearly be noticed in the graph visualizing the trends of light intensity. On sunny days in the period just after the realisation of the mitigation action (no clouds), peaks between 4000 lux and 8000 lux are obtained. On cloudy days (i.e., the period August – September), the values remain below 2000 lux. The trend of UV-radiation shows less variation between sunny and cloudy days with maxima around 800 μW/lm ± 200 μW/lm. Despite the heatwave in that period, the mitigation action significantly lowered the temperature peaks during day time. However, the general trend in Fig. 44 and 45 (i.e., the trend is obtained using a moving average) do not clearly demonstrate if the volume inside the glass structure became cooler. The percentage of time that temperature can be found below 20°C increased while the

percentage of time that the temperature can be found above 40°C dropped. This means that the mitigation action resulted in more cool periods.

- **North side of the Historic Gallery, before the mitigation action:** The intensity of visible light at that side of the Historic Gallery frequently reaches values above 4000 lux. The UV-radiation exceeds at regular occasion 300 μW/lm. The temperature clearly shows day-night cycles. Fig. 44 demonstrates that the indoor situation is warmer during the summer than the outdoor temperature, suggesting the occurrence of a greenhouse effect.
- **North side of the Historic Gallery, after the mitigation action:** After the mitigation action light levels never exceeded 100 lux and UV-radiation is severely reduced as well. The reduction of direct sunlight had an overall cooling effect inside the Historic Gallery, especially in August and September. For the temperature and relative humidity there is no sudden change to be noticed induced by the mitigation action. Although the indoor situation remained warmer than the outdoor situation, the difference between indoor and outdoor became smaller. The percentage of time with temperatures below 20°C (see table VIII) increased, explaining the cooler appearance of the room. The indoor relative humidity follows the outdoor trend (see Fig. 45). Before the mitigation action, the indoor RH is significantly lower than the outdoor RH. After the mitigation action, the difference becomes smaller because the indoor RH increased;
- **South side of the Historic Gallery, before the mitigation action:** The temperature and relative humidity of the north and south side of the Historic Gallery are very similar, although only the south side of the glass structure has been covered. The (peak) values at the north side are slightly higher (ca. 1°C) due to the penetration of direct sunlight through the glass structure to that side. The fraction of time with warmer periods is also double (see Table VIII);
- **South side of the Historic Gallery, after the mitigation action:** The mitigation action has little effect on the light intensity at the south side because that side is mainly illuminated by stray light that remained unchanged with the mitigation action. For this period, the daily averages are 209 lux and 32 μW/lm. However, Table VIII does show a small improvement when looking at the fraction of time with an intensity below 250 lux.

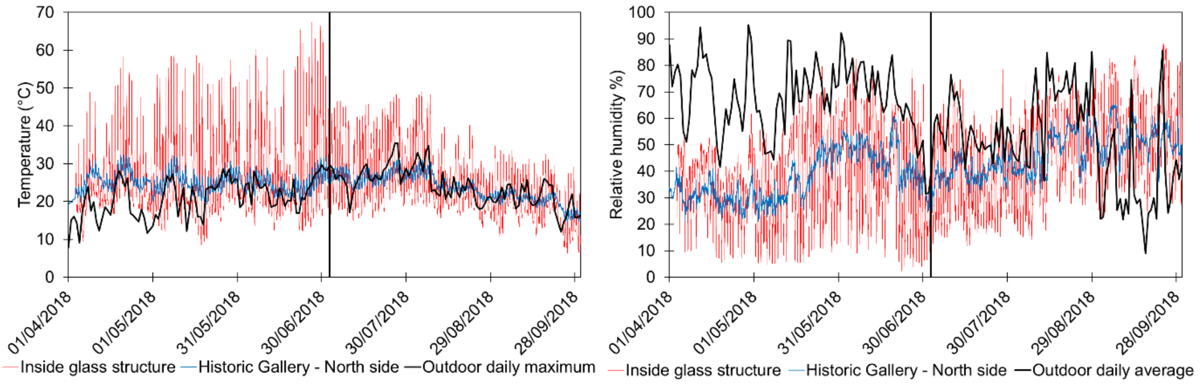
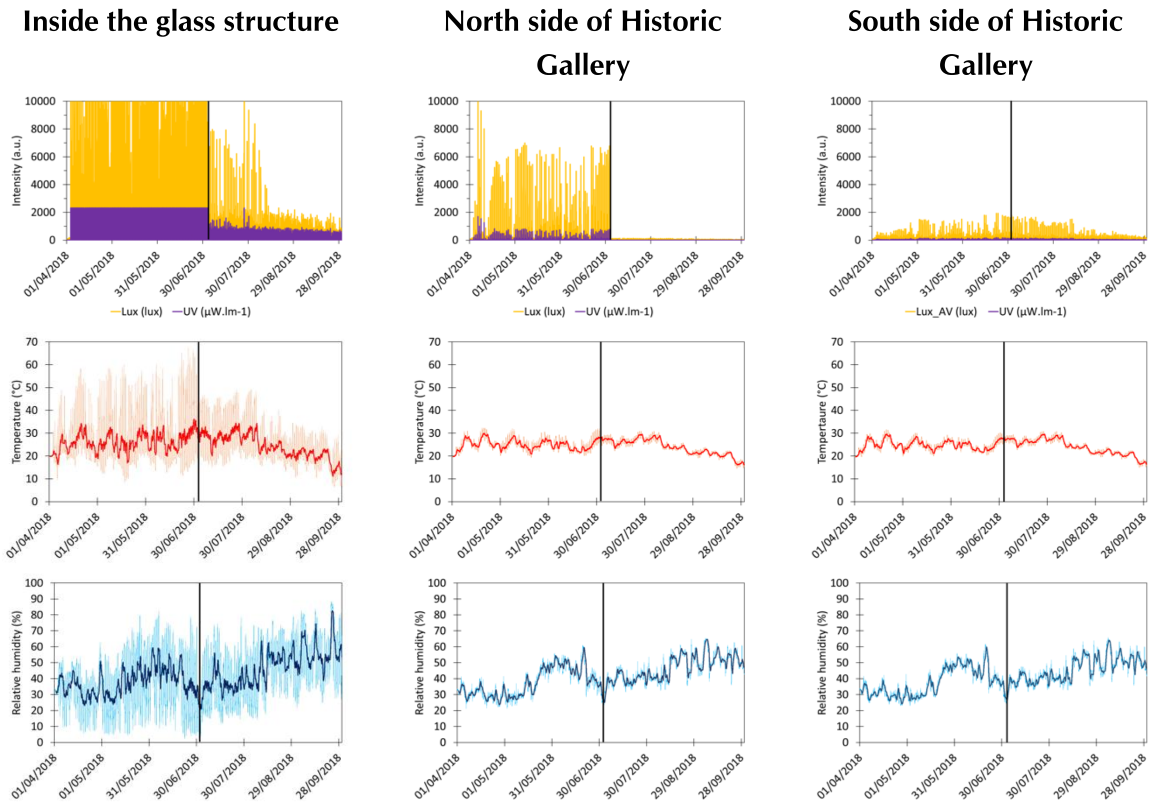


Fig. 44: Comparison of the outdoor temperature and relative humidity with the situation inside the Historic Gallery and inside the glass structure.


Inside the glass structure

North side of Historic Gallery

South side of Historic Gallery

Fig. 45: Intensity of visible light in lux, intensity of UVA radiation in μW lm^{-1}, temperature and relative humidity for the period 3 months prior to the mitigation action up to 3 months after the mitigation action. The general trend is obtained with a central moving average of 150 data points (i.e., a time frame of 12 hours and 20 minutes). The moment the mitigation action was realized is visualized by the vertical line.

TABLE VIII: The percentage of data points or the percentage of time that an environmental parameter falls within a specific range.

	Inside the glass structure		North side of the Historic Gallery		South side of the Historic Gallery	
	Before	After	Before	After	Before	After
≤ 20°C	30.4 %	36.6 %	**1.8 %**	**14.0 %**	**1.9 %**	**12.8 %**
[20°C, 30°C[	41.7 %	41.8 %	94.6 %	83.9 %	96.7 %	85.1 %
[30°C, 40°C[	17.9 %	15.5 %	3.5 %	2.1 %	1.4 %	2.0 %
≥ 40°C	10.0 %	6.1 %	0 %	0 %	0 %	0 %
≤ 30%	33.7 %	18.0 %	**25.1 %**	**0.4 %**	**25.9%**	**0.5%**
[30%, 50%[	42.7 %	37.1 %	64.1 %	64.5 %	63.6%	67.5%
[50%, 70%[	21.3 %	35.8 %	10.8 %	35.0 %	10.5%	32.0%
≥ 70%	2.3 %	9.1 %	0 %	0 %	0%	0%
≤ 250 lux	42.9 %	51.4 %	76.1 %	100 %	81.4 %	87.9 %
[250 lux, 1000 lux[	7.6 %	26.9 %	16.9 %	0 %	17.4 %	11.0 %
[1000 lux, 2500 lux[	11.7 %	20.2 %	4.3 %	0 %	1.2 %	1.0 %
[2500 lux, 5000 lux[	**13.2 %**	**0.7 %**	1.8 %	0 %	0 %	0 %
≥ 5000 lux	**24.7 %**	**0.8 %**	0.8 %	0 %	0 %	0 %
≤ 50 μW/lm	39.0 %	46.6 %	82.1 %	100 %	88.2 %	92.2 %
[50 μW/lm, 250 μW/lm [	3.8 %	11.6 %	14.7 %	0 %	11.8 %	7.8 %
[250 μW/lm, 500 μW/lm [	2.8 %	8.6 %	2.1 %	0 %	0 %	0 %
[500 μW/lm, 1000 μW/lm [	4.6 %	27.7 %	1.1 %	0 %	0 %	0 %
≥ 1000 μW/lm	**49.6 %**	**21.7 %**	0 %	0 %	0 %	0 %

The mitigation action clearly had an immediate effect on the intensity of sunlight irradiation on the northern side of the Historic Gallery. However, the trends in absolute values as shown in Fig. 4 do not visualize the indoor air quality. Using inhouse developed algorithms, it is possible to transform the environmental trends into IAQ assessments. The transformation process depends on the material or object type that is considered. Fig. 5 shows the evolution in IAQ assessments of the dataset of the loggers near the northern side in the Historic Gallery for a 'general collection'. Prior to the mitigation action, the lux and UV colour bars show to a large extent deep blue hues. The deep blue hues are mainly due to night-time values and lower light intensities in the morning and evening. Before the mitigation action, numerous yellow, orange and red lines are clearly visible. After the mitigation action, such unacceptable moments did not appear. The most obvious improvement is the appropriateness of the RH. The lower temperatures resulted in higher and better RH. The overall IAQ colour bar shows orange, yellow and green hues prior to the mitigation action, after the action turquoise and blue hues are dominant. This indicates that the situation improved. The IAQ for the period April – June 2018 was 0.62 ± 0.16 while the period July – September (i.e., after the mitigation action) became 0.77 ± 0.11. However, the change in overall preservation conditions does not appear as distinct as the trends in Fig. 45 would suggest.

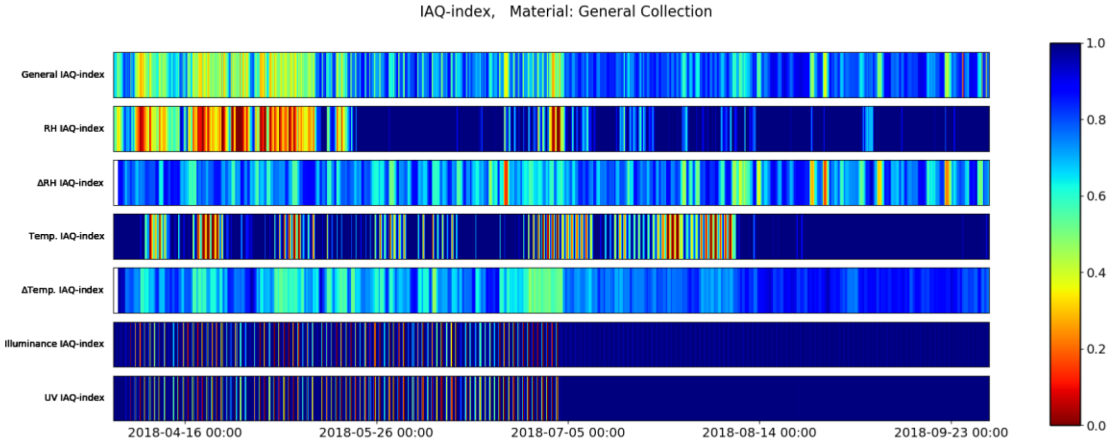


Fig. 46: Visual representation of the dataset *collected at the north side of the Historic Gallery* compared to threshold values for a general collection. The meaning of the colours is explained in the colour scale *at the right side*: red means unacceptable risk while dark blue means acceptable risk.

It should be remarked that a general collection containing mixed materials is not considered as very light sensitive. Even though the light intensities are high before the mitigation action (see Fig. 45), the effect of that parameter on such collections remains limited. For such collections, other parameters such as RH should also be taken into account to improve the overall IAQ. The situation is different when more light sensitive materials such as textile based on vegetable fibers are considered during the IAQ assessments. The impact of visible light and UV radiation on the preservation conditions of textile is larger than on a general condition. However, the overall IAQ for textile is clearly influenced by the official heatwave period where the temperature exceeds 30°C. For textile, both temperature and sunlight affect the degradation rate to a similar extent. Due to the high temperatures, the impact of the mitigation action focused on lowering the intensity of the incoming sunlight is rather limited.

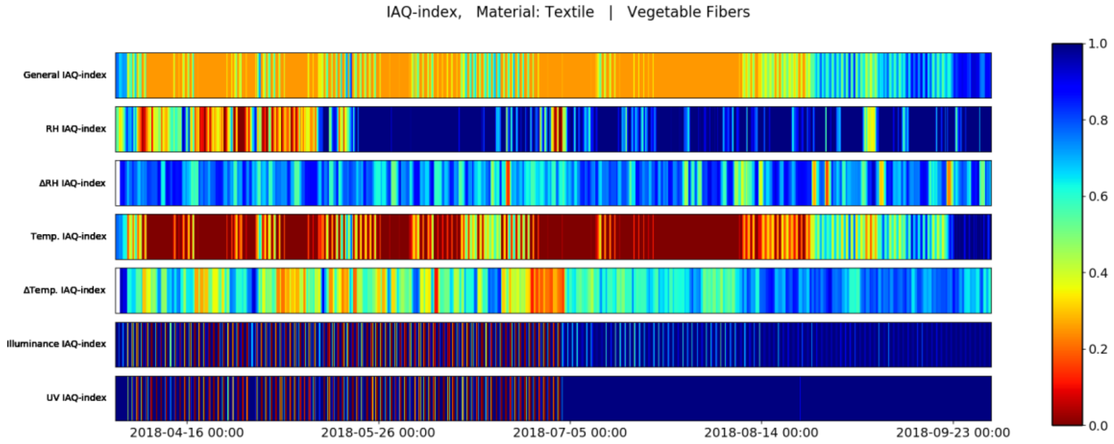


Fig. 47: Visual representation of the same dataset as in Fig. 46 when compared to threshold values for a textile collection based on vegetable fibers.

4.4.4. Conclusions

Heritage guardians were confronted with a problem of excess natural light in the Historic Gallery of the KLM-MRA, posing a real danger to a collection of 19th century militaria. A thorough study of several mitigation possibilities has been performed, considering the integrity of the historic building, preservation of the historic scenography, attention to current visitor experience, and amelioration of the conservation quality. From all possibilities, one mitigation action has been selected: covering the southside of the glass structure in the roof from the outside. A monumental but temporary (i.e., reversible) setup has been implemented to evaluate the impact of the mitigation action while not modifying the construction of the building. In that way, the mitigation action can be evaluated before substantial resources are used for its implementation.

The measurements demonstrate that direct sunlight and UV radiation in the Historic Gallery is reduced, that there are more cooler moments and that the relative humidity became a bit higher. For a general collection the overall IAQ has been improved. However, for the overall IAQ of a general collection the RH plays a more important role then the intensities of sunlight. For a textile collection based on vegetable fibers, the intensity of sunlight is a crucial parameter. However, the impact of the mitigation action is less obvious because the overall IAQ during the hot summer is not only determined by sunlight but also by the periods where the temperature exceeds 25°C.

The case-study of the Historic Gallery has learned that while the problem of excess of sunlight has been mitigated, the visitor's experience has been affected simultaneously. On cloudy days, the level of light inside dropped below a critical level and hampered the visitor view. This loss in 'natural light ambiance' can be compensated by providing artificial lightning to reinstate a lively visitor experience. Together with the mitigation action, a new lightning system needs to be adopted as well.

The visualization of the IAQ evolution using colour bars facilitates the understanding of the situation before and after the mitigation action: the preservation conditions have indeed been improved. The valuable knowledge of the visitor's experience combined with both the IAQ-index and its colour bar visualization should convince decision makers to replace the temporary setup by a permanent solution. The colour bars also suggest that the situation is still far from ideal and that a next mitigation action is needed to avoid high temperatures during hot periods. The experimental setup gives a better insight in the total resources that are needed to perform the mitigation action.

5. DISSEMINATION AND VALORISATION

Besides the development of new knowledge, the AIRCHECQ project has also developed new tools with a technology readiness level between 4 and 5 that can be used by the heritage community. Considerable efforts were made to close the gap between the academic world and heritage professionals. For this, the results obtained during the project were disseminated to the heritage community, the academic community, students and lecturers, decision maker, etc. using different types of communication channels. In the list below, the most important dissemination and valorisation actions are described.

5.1. Overview of the communication channels used

- **The AIRCHECQ website:** During the preparation of the kick-off of the project, a logo, a banner and a website (https://www.uantwerpen.be/en/projects/airchecq/) has been developed. The website was used to launch the project, it was used to organize the registration of the international AIRCHECQ conference and the workshop. Also the final deliverables such as reports and the software are published on the website and will remain available after the termination of the project;
- **National follow up committee:** At regular occasions, the national follow up committee joined the AIRCHECQ team for the meetings where the progress and the results so far were discussed. The meetings were considered as open meetings. This means that not only the national follow up committee was invited but also other interested persons such as colleagues, master students involved in a research that is related to AIRCHECQ, etc. Throughout the project, meetings and discussions have been organized with several individual researchers and companies. Their suggestions and opinions played an important role in refining the AIRCHECQ deliverables.
- **AIRCHECQ Facebook page:** During the project, photos and messages about actions such as the installation of a monitoring system, the conference, etc. have been posted on the AIRCHECQ Facebook page at www.facebook.com/airchecq/;

- **International AIRCHECQ conference:** The international AIRCHECQ conference was organized halfway the project and took place at 28-29 April 2016, Brussels (Belgium) at the Royal Museums of Art and History. The international conference was organized halfway the project because it allowed us to gather all the necessary expertise and feedback on the first version of our deliverables. The conference program is given in Annex 2;
- **Closing AIRCHECQ workshop:** Near the end of the project the AIRCHECQ concept and a step by step course about how to use the AIRCHECQ software was organized for the heritage community. In that way, we translated academic knowledge to heritage professionals. The workshop was organized in cooperation with FARO;
- **Parliamentary question referring to the AIRCHECQ project (Feb. 2017 09):** Manuela Van Werde asked Minister Sven Gatz about the impact of particulate matter on heritage collections of the Plantin Moretus museum. The Minister referred in his answer to the AIRCHECQ project. This means that the project also reached the level of decision makers.
- **Contributions to conferences:** All coworkers delivered contributions to a large variety of scientific conferences. The list in paragraph 5.2. gives an overview of all contributions.

5.2. Contributions to scientific conferences

- Willemien Anaf, Caroline Meert, Eyasu Ayalew, Lucy 'T Hart, Diana Leyva Pernia, Elke Otten, Joost Vander Auwera Karolien De Wael, Serge Demeyer, Olivier Sschalm, A promising monitoring kit to evaluate air aggressiveness, 12th International Conference of Indoor Air Quality in heritage and historic environments, Birmingham, Thinktank , 3-4 March 2016, Oral presentation
- Diana Leyva, Serge Demeyer, Olivier Schalm, Willemien Anaf and Caroline Meert, New Approach to Indoors Air Quality Assessment for Cultural Heritage Conservation, The 14th International Conference of Indoor Air quality and Climate, Ghent, Belgium, 3-8 July 2016, Oral presentation
- Lucy 't Hart, Patrick Storme, Willemien Anaf and Olivier Schalm, Monitoring the Impact of the Indoor Air Quality on Metallic Heritage, 2nd International Conference on Innovation in Art Research and Technology, Ghent, Belgium, 21-25 March 2016, Oral presentation
- Diana Leyva Pernia, Serge Demeyer, Olivier Schalm, Willemien Anaf and Caroline Meert, New Approach to Indoors Air Quality Assessment for Cultural Heritage Conservation, The 14th International Conference of Indoor Air quality and Climate, Ghent, Belgium, 3-8 July 2016, Oral presentation
- Lucy 't Hart, Patrick Storme, Willemien Anaf and Olivier Schalm, Monitoring the Impact of the Indoor Air Quality on Metallic Heritage, 2nd International Conference on Innovation in Art Research and Technology, Ghent, Belgium, 21-25 March 2016, Oral presentation
- Olivier Schalm, Questions that need to be answered, Colloquium 'Advanced Tools for Preventive Conservation', Brussels, Belgium, 28-29 April 2016, Oral Presentation
- Elke Otten, Large and mixed collections in the Royal Army Museum of Brussels. How to deal with it?, Colloquium 'Advanced Tools for Preventive Conservation', Brussels, Belgium, 28-29 April 2016, Oral presentation

- Diana Leyva Pernia, Caroline Meert, AIRCHECQ: What is the meaning of 'Indoor Air Quality'? Risk management or mathematical algorithm approach, Colloquium 'Advanced Tools for Preventive Conservation', Brussels, Belgium, 28-29 April 2016, Oral presentation
- Willemien Anaf, Sanaz Pilehvar, AIRCHECQ: How do we measure the Indoor Air Quality? Results of the first measuring campaigns, Colloquium 'Advanced Tools for Preventive Conservation', Brussels, Belgium, 28-29 April 2016, Oral presentation
- Olivier Schalm, Lucy 't Hart, Hoe belangrijke zijn plotse veranderingen in de binnenlucht op ons erfgoed?, Studiedag historische orgels: materialenonderzoek en conservatie, Antwerp, Belgium, 10 Feb. 2017
- Lucy 't Hart, Corrosie monitoring, Studiedag historische orgels: materialenonderzoek en conservatie, Antwerp, Belgium, 10 Feb. 2017
- Olivier Schalm, Willemien Anaf, Jan Callier, New generation monitoring devices for heritage caretakers to detect multiple events and hazards, HeriTech 2018, Firenze, Italy, 16-18 May 2018, Oral presentation
- Diana Leyva, Serge Demeyer, Olivier Schalm, A data mining approach for indoor air assessment, an alternative tool for cultural heritage conservation, HeriTech 2018, Firenze, Italy, 16-18 May 2018, Oral presentation
- Olivier Schalm, Willemien Anaf, Diana Leyva Pernia, Jan Callier, A decision support system for preventive conservation: From measurements towards decision making, 3rd International Conference on Innovation in Art Research and Technology, Parma, Italy, March 26-29, 2018, Oral presentation
- Jan Callier, Olivier Schalm, Willemien Anaf, Comprehending the effects of climate enhancing measures through real-time climate monitoring, YOCOCU 2018, Matera, Italy, May 23-25, 2018
- Diana Leyva Pernia, Willemien Anaf, Serge Demeyer, Olivier Schalm, Indoor air quality assessment in heritage conservation: development of a user-friendly software, YOCOCU 2018, Matera, Italy, May 23-25, 2018
- Olivier Schalm, Willemien Anaf, Ana_Cabal, Jan Callier, New generation of monitoring systems for heritage guardians: detection of a larger range of undesired situations and corresponding material behavior, 13th international conference 'Indoor Air Quality in Heritage and Historic Environments, Krakow, Poland, October 10-12, 2018
- Diana Leyva Pernia, Willemien Anaf, Olivier Schalm, Serge Demeyer, Impact of the guidelines selection for indoor air quality assessments in cultural heritage preservation, 13th international conference 'Indoor Air Quality in Heritage and Historic Environments, Krakow, Poland, October 10-12, 2018
- Willemien Anaf, Diana Leyva Pernia, Olivier Schalm, An IAQ-index for cultural heritage applications, 13th international conference 'Indoor Air Quality in Heritage and Historic Environments, Krakow, Poland, October 10-12, 2018
- Andrea Marchetti, Willemien Anaf, Olivier Voet, Ana Cabal, Piet Van Espen, Jan Callier, Olivier Schalm, Karolien De Wael, Field testing of low-cost sensors for the monitoring of PM and gaseous pollutants for heritage applications, 13th international conference 'Indoor Air Quality in Heritage and Historic Environments, Krakow, Poland, October 10-12, 2018

- Willemien Anaf, Diana Leyva Pernia, Olivier Schalm, Een luchtkwaliteitsindex voor erfgoedtoepassingen, Studiedag Klimaatnetwerk, Leuven, Belgium, November 16, 2018
- Willemien Anaf, Olivier Schalm, Jan Callier, Maud Rochez, Isolde Verhulst, Impact van een verwarmingssysteem op de conservatie van een kerkinterieur, International WTA-Precom³os colloquium, Leuven, Belgium, April 3-5, 2019

6. PUBLICATIONS

- ‘t Hart L., Storme P., Anaf W., Nuyts G., Vanmeert F., Dorriné W., Janssens K., de Wael K., Schalm O., Monitoring the impact of the indoor air quality on silver cultural heritage objects using passive and continuous corrosion rate assessments, 122(10):923, doi: 10.1007/s00339-016-0456-2, impact factor: 1.444
- Diana Leyva, Serge Demeyer, Olivier Schalm, Willemien Anaf and Caroline Meert, New Approach to Indoors Air Quality Assessment for Cultural Heritage Conservation, Proceedings of the 14th International Conference of Indoor Air quality and Climate, Ghent, Belgium, 3-8 July 2016
- Marchetti A., Pilehvar S., ‘t Hart L., Leyva Pernia D., Voet O., Anaf W., Nuyts G., Otten E., Demeyer S., Schalm O., De Wael K., Indoor environmental quality index for conservation environments: The importance of including particulate matter, Build. Environ. 2017 (126) 132-146
- Schalm O., Anaf W., Callier J., New generation monitoring devices for heritage caretakers to detect multiple events and hazards, IOP conference series : materials science and engineering. 2018 (364), 012056
- Leyva D., Demeyer S., Schalm O., A data mining approach for indoor air assessment, an alternative tool for cultural heritage conservation, IOP conference series : materials science and engineering. 2018 (364) 012045
- Anaf W., Leyvia Pernia D., Schalm O., Standardized indoor air quality assessments as a tool to prepare heritage guardians for changing preservation conditions due to climate change, Geosciences. 2018 (8:8) 276
- Anaf, W., Schalm, O., Climatic quality evaluation by peak analysis and segregation of low-, mid-, and high-frequency fluctuations, applied on a historic chapel, Building and Environment. 2019 (148) 286-293
- Anaf, W., Schalm, O., Callier, J., Rochez, M., Verhulst, I., Impact van een verwarmingssysteem op de conservatie van een kerkinterieur. In: Verstrynge, E., van Bommel, B., Vernimme, N., van Hees, R. (Eds.) Preventieve conservatie. Van klimaat- en schademonitoring naar een geïntegreerde systeembenadering, WTA Vlaanderen-Nederland, 2019

7. ACKNOWLEDGEMENTS

The AIRCHECQ-team wishes to thank all persons who have contributed to the project. Some contributions may have been small, such as asking (apparently obvious) questions. Some of these answers had a large impact on the entire project. Other contributions consisted of showing enthusiasm and believe in the project. In particular we would like to thank all the members of the national follow up committee, the speakers and participants of the international AIRCHECQ conference and to all contributors of the closing AIRCHECQ workshop. We also want to express our gratitude to Caroline Meert, Eyasu Ayalew, Sanaz Pilehvar, Lucy 't Hart, Ana Cabal and Piet Van Espen.

ANNEXES

Annex 1: Glossary of terms

The AIRCHECQ project relies on the literature from multiple disciplines such as *preventive conservation*, environmental monitoring, risk management used outside the heritage community, or safety management. In some cases, the same terms are used with a (slightly) different meaning. During the project, it became clear that we needed to merge the vocabulary of different disciplines. Therefore, an explicit definition of several terms played a crucial role in the development of our methodology. After all, one cannot tell more than language allows us. The key terms that play an important role in this research are defined in the glossary.

Bias	There are several types of biases such as cognitive bias, conflicts of interest, statistical bias or prejudices. In the context of this research, biases are rules of thumb that describe the real world in a simplified way but their application result in systematic errors.
Black box	A black box model aims to describe the behaviour of a process. It does not intend to understand the structure of the process causing that behaviour. The description of that behaviour relies on mathematical relationships between input and output of the process so that output can be predicted. It is possible that the model uses parameters that have no physical meaning. The opposite of a black box is a system where the inner components or logic of the process are available for inspection, which is most commonly referred to as a white box.
Decision-making	Decision-making is a skill. It is an action-oriented process where one must choose an action from a set of alternative possibilities (Tversky and Kahnemen, 1974). The decision-making process can be regarded as a check and balance system that keeps a person or organisation evolving towards a given goal. Decision making is easy when one alternative is way better than all the others; decision making becomes problematic when one alternative is better in some ways and another alternative in other ways while neither is better than the other. When trying to make a good decision, a person or organisation must (1) identify all possible options and determine whether some options are missing, and (2) rank the options by weighting the positives and negatives of each option. For effective decision-making, the person or organisation must also be able to forecast the outcomes of each possible action (i.e., action – outcome combination) and determine which option is the best for that particular situation. To fulfil these requirements, decision making follows a procedure that is usually based on the following steps:

1. Defining the problem
2. Gathering information and comparing the choices
3. Rank the different options
4. Choosing best possible option
5. Plan and execute
6. Take follow up action

Decision-making must sometimes be performed in a situation of *uncertainty* (i.e., lack of knowledge, doubt about the validity of information we have, the inability to predict the outcome of a certain action), complexity (i.e., one must consider many interrelated factors, so much information that it is difficult to know what is relevant), high-risk consequences (i.e., the possibility of substantial losses) or time pressure (i.e., stress).

Decision support system	A decision support system (DSS) is a computer program that analyses data and visualizes it in such a way that heritage guardians can make decisions more easily. It helps them in making good decisions without imposing a particular choice. An expert system goes a step further. It is a computer program that uses artificial intelligence to emulate the decision-making ability of a human expert.
Degradation rate	The degradation rate is the increase of the total amount of harm of an object or collection per unit of time. The total amount of harm of an object is not a physical quantity that can be directly measured but is rather a mathematical variable that describes the degradation path of the object. However, the amount of accumulated harm can be followed indirectly using markers/proxies such as volume change, colour change or change in electrical resistance (e.g., probes).
Early warning system	A system that generates and disseminates timely and meaningful warning information so that individuals, communities and organizations threatened by a hazard can prepare and act appropriately and in enough time to reduce the possibility of harm or loss.
Event	An event is anything that happens, especially something important or unusual that attracts our attention. It is an occurrence or change of a particular set of circumstances. An example of an event is a situation where one of the environmental parameters goes beyond a *threshold* near the upper (or lower) end of the range of observed values. The occurrence of such a situation is often beyond the control of humans

	and can have multiple outcomes. One of the outcomes may be severe.
Environmental appropriateness	Environmental conditions where the accumulation of *harm* of the heritage collection can be tolerated by an individual, organization or society.
Exposure	Only when an object or a collection is exposed to a source of harm and for that reason to the dangerous occurrences it causes, there is a risk that *harm* may occur to some of the objects. Therefore, exposure is the link between source of harm and risk. The relationship between source of harm and risk is dependent on the nature of the exposure. Two types of exposure can be distinguished: • **Stochastic exposure:** Collections are sporadically exposed to hazards during discrete and short periods of time. These occasions occur at random occasions and are interspersed by (longer) periods without any exposure. The short moments of exposure are characterized by random hazard intensities and are denoted as *undesirable situations*. This type of exposure can be described by the following markers: (1) the fraction of time to which a collection is exposed to hazards, or (2) the frequency of sporadically occurring exposures; • **Continuous exposure:** Collections are always threatened by hazards (e.g., relative humidity, UV radiation). For this type of exposure, periods of elevated hazard intensity occur at random occasions. Such periods are recognized by sudden changes in one of the environmental parameters (i.e., peaks or drops). When a *threshold* is used to distinguish a limited number of periods with unacceptable risk from periods with acceptable risk, the continuous exposure can be simplified as a stochastic exposure. Continuous exposure can be described with the following markers: (1) the average exposure level or (2) the accumulated exposure dose. The fraction of time where the hazard intensity is unacceptably high can be used as a marker to describe the risk of the exposure.; Several measures can be used to describe how much time a collection is subjected to dangerous occurrences. Some scientists use such exposure markers to evaluate the appropriateness of preservation conditions. For example, the 'performance index' is defined as the percentage of time (i.e., fraction of time) in which a measured parameter such as relative humidity lies within the required tolerance

	range (i.e., level of exposure) (Corgnati et al., 2009). It should be emphasized that the analysis of exposure to dangerous occurrences is only one aspect of risk. Therefore, it cannot be used to give a full insight of risk.
General collection	A general collection is a mixed collection with all objects in relatively good condition and no objects that are remarkably more sensitive to a specific parameter.
Harm	Harm is the physical injury or damage to the health of people, damage to an object or to the environment (ISO, 2007). Harm can accumulate in 2 different ways: • **Stochastic process:** An undesirable situation will lead to an increased level of risk. However, it is not possible to predict if harm will occur. Even at high risks there is always a chance that no harm will occur. Since undesirable situations occur at discrete moments, an object accumulates harm with sudden steps. There is no accumulation of harm between *incidents*. • **Deterministic process:** Any hazard intensity will result in harm in a predictable way. The relationships between level of harm and risk can be described by a mathematical function. The slope describes the sensitivity of the collection towards risk. It is the degree to which a collection is susceptible and unable to cope with risk. An object accumulates harm until it reaches a point of failure;
Hazard	A source of harm can reside in 2 states: (1) a harmless state known as a hazard (e.g., a river remote to you), and (2) a harmful state known as a threat or a dangerous occurrence (e.g., a flood that reaches you). Usually, the source of harm resides in a harmless state but has the potential to change into a dangerous occurrence. The threat caused by the source of harm is described by the hazard intensity. By means of a mitigation action, a dangerous occurrence can be changed into a hazard. Only when a set of objects is exposed to a source of harm and the dangerous occurrences it causes, it is probable that some of the objects might be harmed. Therefore, the *exposure* to dangerous occurrences is the link between source of harm and risk. Several measures can be used to describe the hazard intensity. Some scientists use such markers to evaluate the appropriateness of

	preservation. One approach is to calculate the percentage of the collected monitoring data that corresponds with the different ASHRAE climate classes (Martens, 2012, Bucur et al., 2017, Klein et al., 2017).
Heuristics	Heuristics are usually considered as cognitive shortcuts that are used in intuitive reasoning. Heuristic methods work well in many circumstances and result in reasonable but not perfect (or the best) answers. However, they can lead to mistakes as well. *Biases* are rules of thumb that are used to simplify complicated decisions but that result in systematic errors. People rely on a limited number of heuristic principles to reduce complex tasks in simpler operations. The simplified problem-solving methods usually ignore a great amount of existing information and deliberately avoid much computation rather than aiming for as much as possible of both. Examples of heuristic methods are: • **Attribute substitution:** When confronted with a difficult question, people often answer an easier question instead. The complex question is replaced by a more easily question (Kahneman, 2002). • **Rule of thumbs:** In situations where an exhaustive search is impractical, oversimplified rules of thumb are used to speed up the process of finding a satisfactory solution. The rules of thumb exist as shared or general knowledge.
Incident	Reportable period where the environmental conditions induce harm to at least 1 object of the collection. This is usually the case when at least 1 environmental parameter exceeds the alarm *threshold* value.
Indoor air quality (IAQ)	There is no standardised concept defining IAQ for cultural heritage conservation. The vast majority of IAQ devoted studies focus on the impact over human health or human comfort, and even there, their definition and representation differ considerably from source to source. In general, IAQ refers to the quality of the air inside buildings as represented by concentrations of pollutants and thermal conditions (temperature and relative humidity) that affect the health, comfort and performance of occupants. In the specific case of preventive conservation, the interest is focused on the environmental conditions that threatens the integrity of the objects within a room. *Indoor air quality* is a measure that summarizes the impact of all environmental parameters. However, orientation of the metal sensors relative to air movements tremendously affects the results. This means that indoor air quality should be considered as a vector quantity.

Indoor air quality (IAQ) index	The IAQ-index describes the overall air quality in relation to the preservation conditions of a specific material or object type. It is a quantity with a value that can vary from 0 (unacceptable risk for deterioration due to an aggressive environment) to 1 (excellent environmental conditions with acceptable risk). The IAQ-index summarizes the measurements of temperature, relative humidity, illuminance, ultraviolet radiation, etc. into a single value. It also gives the corresponding assessment by comparing the measurements with guidelines.
Key risk indicator (KRI)	The environmental parameters used to evaluate the level of risk should be considered as *markers* that easily distinguish acceptable risk from unacceptable risk. These markers are called key risk indicators (KRI).
Level of risk	Most of the environmental trends consist of a background with peaks or drops on top. The height of a peak or depth of a drop gives an indication of the level of risk. By comparing the height or depth with corresponding guidelines, the short moments where the peaks or drops occur can be classified as an acceptable risk (i.e., *environmental appropriateness*) or unacceptable risk.
Marker	Some objects or collections can be found in a limited number of states (e.g., a state of environmental appropriateness or a state of inappropriate preservation conditions) and we only want to know in which state they reside. Often, that state can be determined by measuring a few parameters. Such parameters are called markers. They are defined as distinguishing, easily measurable features that give an objective indication of the state in which the object resides.
Mitigation action	Since *hazards* can always reoccur in the future with a possible increased *level of risk*, human interventions are needed to avoid or reduce the identified hazards to reoccur in future. As a result, heritage collections will be exposed to a reduced level of risk in the future. Such human interventions are called mitigation actions.
Preventive conservation	Preventive conservation entails all measures and actions aimed at avoiding and minimizing future deterioration, damage or loss to cultural heritage. The measures and actions are carried out within the context or on the surroundings of an object and are indirect – they do not interfere with the materials and structures of the items and do not

	modify their appearance.[1] An example is improving the environmental management (light, humidity, pollution and pest control) to slow down the *degradation rate* of the entire collection.
Proxy	A proxy is a measurable quantity that is used to estimate another quantity. Proxy variables are used when the variable of interest is not available in the data, either because it is not measured or because it is an unobservable or immeasurable variable. For example, the exposure of heritage collections to *hazards* can hardly be measured but environmental parameters can be considered as proxies. For a variable to be a good proxy, it must have a close correlation, not necessarily linear, with the variable of interest.
Quality	The meaning of quality in daily life is a subjective term that can vary from moment to moment and from person to person. This high variability in meaning makes it hardly impossible to propose an unambiguous definition, except for the general but vague meaning 'level of goodness'.
Resilience	Resilience is considered as a component of *vulnerability*. It is the ability of a collection to resist *harm* and change when exposed to *hazards*.
Risk	A risk (in the informal sense of the word) is a situation where we are exposed to external dangers and do not know whether we will lose something of value. Risk is a consequence of a lack of knowledge about the future, i.e., to something that may happen in the future. If we know with certainty that we will lose something of value, we no longer speak of risk. A collection at risk means that it is exposed to one or more *hazards* (I.e., external dangers) with the possibility that the collection will be harmed. Risk can also be defined as a numerical quantity. In that approach, the level of risk is given by the product of an *event*'s probability with some measure of its undesirability. The level of risk of any object in the collection can be evaluated in 2 different ways: • **By considering the harmful environment:** A collection is continuously exposed to a harmful environment. The threat of the environment on a collection can be estimated by measuring a limited set of environmental parameters. These parameters can be

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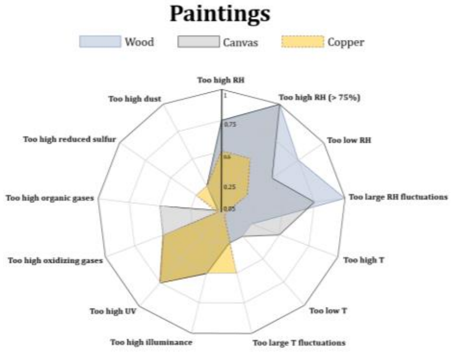
[1] Terminology to characterize the conservation of tangible cultural heritage - http://www.icom-cc.org/242/#.VNHm6t40Fz8. Accessed at 28 August 2016.

considered as markers. For every parameter, a target value distinguishes acceptable risk (i.e., an informed decision to take a particular risk such as preservation conditions that are good enough for the time being and where one agrees to set risk equal to zero, $R = 0$) from unacceptable risk (i.e., high chance that harm will occur such as accelerated degradation has a risk $R = 1$). In some cases, a transition zone between both situations exist where risk changes gradually. Usually, several guidelines and norms exist about a specific situation, but they do not agree about the exact location of the *threshold* value;

- **By considering harmful incidents:** A collection is exposed to a series of discrete *events* and only some of the events will result in harm. In this context, risk R is defined as a multiplication of several markers: usually the probability that an incident will occur multiplied by its impact. However, not everybody is using the same set of markers to quantify the level of risk. If each marker can be represented as an axis in an n-dimensional space, then R is the volume of a hyper cuboid in n dimensions.
    - Probability: A risk is related to an event that "may" occur. The probability of it occurring can range anywhere from just above 0% to just below 100%. (Note: It can't be exactly 100%, because then it would be a certainty, not a risk. And it cannot be exactly 0% or it wouldn't be a risk.). The probability is usually determined from the frequency of sporadically occurring exposures;
    - Extent: If a collection is permanently exposed to a hazard, the probability that an event will occur is equal to 1. In such cases, the extent to which the degradation mechanism occurs is used;
    - Impact: A risk, by its very nature, always has a negative impact. However, the size of the impact varies in terms such as loss in value or accumulated harm;
    - Fraction: The part of the collection that is at risk. Not all objects are sensitive to a certain hazard;
    - Exposure: The fraction of time a collection is exposed to *hazards*;
    - Hazard intensity: The hazard intensity to which the collection is exposed to;
    - Sensitivity: The sensitivity of the collection or the potential level of harm that would occur when it is exposed to a given hazard intensity;
    - Vulnerability: The fragility of the protection shield surrounding

	the collection.
Risk perception	Risk perception is the subjective judgement that people make about the characteristics and severity of a *risk*. It is formed by two components: (1) a rational part related to the hazard and that is described by the risk, and (2) the intuitive part called outrage (Sandman, 2012).
Risk profile	Each material is characterized by a risk profile. That profile consists of a spider graph in which the different axes represent *key risk indicators*. On each axis, the impact of the indicator on the *degradation rate* is described by a weight. The total area of the spider graph or the sum of all the scores indicates the average sensitivity of the material/object to the overall preservation conditions. 
Rule of thumb	A rule of thumb refers to a principle with broad application that is not intended to be strictly accurate or reliable for every situation. It is an easily learned and easily applied procedure or standard, based on practical experience rather than theory. Rules of thumb are simple algorithmic models and are used to solve complex problems. They do not guarantee optimal, perfect, logical, or rational answers, but are good enough for reaching an immediate goal.
Safety	Safety is sometimes defined as a situation without accidents and on other occasions as a situation with an acceptable probability of accidents. The relation between *risk* R and safety S is given as follows: $R + S = 1$.
Sensitivity	In risk analysis, the sensitivity is a property of the object or collection. It is the potential level of harm that would occur when it is exposed to a given hazard intensity. Sensitivity is sometimes confused with the concept of *vulnerability*.
Threshold level	A cut-off point or critical limit distinguishes exposure with acceptable *risk* for degradation from exposure with unacceptable risk. Usually, there is no agreement among experts about the exact position of such

cut-off points. In addition, such points can shift over time when knowledge about degradation mechanisms is increasing. Finally, degradation can occur at the macroscopic level (e.g., cracks), microscopic level (e.g., change in surface roughness), or even at the molecular level (e.g., breaking of bonds). It is not always clear what unacceptable harm precisely means.

Uncertainty

Uncertainty is a fundamental – and unavoidable – feature of daily life. Uncertainty is sometimes classified into 2 categories:

- **Aleatoric uncertainty:** This type of uncertainty is also known as statistical uncertainty and is due to the varying and unpredictable outcome each time the same experiment is conducted (e.g., events with random hazard intensity);
- **Epistemic uncertainty:** Epistemic uncertainty is also known as systematic uncertainty and is due to things one could in principle know but doesn't in practice (e.g., uncertain knowledge).

Uncertainty arises from a lack of knowledge about the present condition, doubt whether our knowledge is correct, the lack of control concerning ongoing processes, the increasing number of possibilities from which a person needs to select the true option, or the inability to predict the future. It is an expression of the degree to which a quantity of an object or a relationship within a process is unknown. The uncertainty is a sliding scale and expresses the degree to which a value or relationship is unknown. The uncertainty can be the result of many reasons such as:

- Quantifiable errors in collected data;
- Ambiguously defined concepts or terminology;
- Disagreement among experts about what is known;
- The complexity of heritage objects composed of many material types that respond differently to the environment (e.g., silver threads in textile);
- The presence of mixed collections in the same gallery, enhancing the complexity of the problem;
- The technical barriers that hamper the measurement of some relevant parameters in monitoring campaigns (e.g., air pollution) so that there is no access to the required knowledge;
- The overwhelming amount of data that is hard to process if the heritage guardian has no background in data processing or environmental science;
- The alternative target values that exist in standards and guidelines

	and in which a choice must be made; • The blanks in our current knowledge concerning degradation mechanisms (i.e., ignorance); • The research-implementation gap (i.e., gap between the supply of scientific information from the academic community and the knowledge that is applied by practitioners); • The partial understanding or even misconception of existing theories by some heritage guardians; • The absence of an ideal mitigation option for some preservation problems; • The doubt we have concerning the validity of the result of a measurement.
Uncertain quantity	An uncertain quantity is a quantity where no agreement can be found among experts about the exact value. However, experts agree more for a certain outcome than for other outcomes. The level of agreement among a set of experts is described as the expert's judgmental probability distribution of all possible outcomes.
Undesirable situation	An undesirable situation is a reportable period with elevated *risk* for accelerated accumulation of harm. In a line graph that visualizes an environmental parameter over time, periods with elevated risk are visually identified as sharp well-defined peaks (or drops) that arise on top of a relatively constant background level. The height of such a peak or drop gives an insight in the intensity of the hazard and determines if the situation is acceptable or unacceptable.
Visual cue	Visual features that attract the observer's attention to a particular area of an object and that allow the observer to estimate a physical property. For example, the preservation state of an object can be estimated from visual cues such as cracks or discolorations. Features in line graphs visualizing environmental trends can also act as a visual cue.
Vulnerability	In cases where some risks are unavoidable, appropriate control measures should be implemented to minimize exposure to *hazards*. Vulnerability refers to the fragility of the protection shield (i.e., the building, safety culture of the organisation, accident response, etc.) in which the heritage collection is embedded. A heritage collection is supposed to be protected by the 6 layers of enclosure (i.e., frame, display case, room, building, surroundings of the building, geographic are where the building is located). The weaknesses in the 6 layers of

enclosure will cause the following problems:

1. **Failure of protective properties:** Known weaknesses can turn into additional hazards and might have an impact on the collection in the future
2. **Existing hazards are insufficiently buffered:** Due to the weaknesses, already existing hazards can have an impact on the collection.

This means that the vulnerability is determined by the potential impact of the physical weaknesses of the layers of enclosure on the collection. The quality of the 6 layers of enclosure is determined by the level of control on hazards (basic level, intermediate level, advanced level) by avoiding, blocking, diluting or absorbing the hazards. Vulnerability is also determined by the safety culture of the organisation responsible for the heritage collection. The safety culture can be perceived as the product of the individual and group values, attitudes, competencies and patterns of behaviour that determine the commitment to, and the style and proficiency of, an organization's safety programme. In addition, vulnerability is also determined by a diminished capacity of the organisation. Capacity refers to the resources and assets people possess to resist, cope with and recover from the impact of hazards. *Resilience* is also considered as a component of vulnerability. It is the ability of a collection to resist harm and change when exposed to hazards.

Vulnerability can be considered as threats to the safety of a heritage collection. This means that if the vulnerability increases, the effectiveness of the protection shields or control measures decreases. The opposite of vulnerability of the protection shield is 'protectiveness'. *Preventive conservation* aims to maximize the protectiveness so that occurring risks can be buffered.

Annex 2: Questionnaire to assess an area where cultural heritage is preserved

1. Introduction

This questionnaire is a tool for understanding the potential threats and events that might affect the preservation conditions. It is known that events (e.g., visitors entering a room with wet cloths, periodic heating, cleaning, etc.) have hyper-local, adverse effects on the indoor climate of rooms. The occurrence of such events is often governed by several features related to the building, the maintenance and its use. This questionnaire is designed to gain insight in the cause-effect relationships between indoor air quality and some typical features of the collection and its surroundings. The answers of the questionnaire will improve the quality of mitigation decisions.

The questionnaire is a user-friendly method to estimate the *vulnerability* of the surroundings (or the level of protectiveness of the consecutive layers of enclosure) and the *sensitivity* of the collection (i.e., amount of increased harm per unit of hazard intensity). The vulnerability is governed by (1) the outdoor climate, (2) the protective layers of enclosure, (3) the indoor climate control technology, and (4) the accessibility of the room by humans. The sensitivity of the collection is governed by the materials, preservation state, etc. The answers of the questionnaire provide context to ongoing measurements of environmental parameters and help in the assessment of environmental measurements.

The questionnaire will guide you in the inspection of your collection and its surroundings. There are 5 topics in the questionnaire: outdoor climate, building, utilities, human activity and collection. Each topic contains 3 to 4 questions. The average time spent on the entire questionnaire is approximately 1 hour. Most questions are easy to answer. They require the analysis of visual features that somehow attract your attention to a particular area in the surroundings or object within the collection. A few questions are slightly more demanding, but manageable with little effort. Help texts are provided in blue to find the proper answer.

The advantages of the questionnaire are a more targeted improvement of the planning of preventive preservation actions, identify easy to perform actions that considerably improves the preservation conditions (i.e., quick wins), etc. At the same time, the questionnaire helps reducing the energy consumption needed for climate control while maintaining the same level of environmental appropriateness. An additional advantage of the questionnaire is that museum personnel can be involved in *preventive conservation* management and that personnel gains more insight in the protective enclosures. Being able to explain and prioritize adjustments related to preventive conservation to management, architects, technicians, etc. will probably be the best return for your time and effort. Good luck!

Inspect surroundings

Outdoor climate

1. What is the outdoor climate like?

Specific climate class can be found in the Koppen-Geiger climate classification. More specific weather data can be found on the website climate-data.org.

o Tropical climate
o Dry climate
o Moderate (marine) climate
o Continental climate
o Polar climate

2. How would you describe the immediate vicinity around the building?

o City centre surrounded by roads and buildings
o City centre with at least 50 m of vegetation on at least 2 sides of the building
o Suburban environment
o Rural area with open vegetation
o Rural area in a forest area
o Isolated

3. What pollution sources can be found in the vicinity of the building?

Multiple answers are possible.

o Industry within a radius of 1000m (examples: wholesale in raw materials, waste processing, production installations, port activities and mining)
o Industry and shopping centres within a radius of 400 m
o Major traffic axes within 400m (at least 4 lanes for motorised traffic)
o Small traffic axes next to the building
o Heating of residential buildings and offices
o Agricultural activities

Building

1. Depending on the building envelope, what kind of building is it?

o Old historical building envelope (historical construction with bricks without insulation and single-glazed windows in the original frames)

o Slightly modified historical building envelope (previous option, but the windows were replaced and contain double glazing, or an additional protective glass has been fitted over the original; minimal isolation may have been applied on the inside or outside.)

o Fully adapted historical building envelope (previous option, but fully isolated; modern window frames and at least double glazing)

o Specially designed (modern) museum or storage (built or renovated after 1970)

2. What is the position of the room in the building?

Multiple answers are possible.

o Inside a detached building with no outer walls shared with other buildings

o Inside a building with adjoining buildings on 2 sides

o At least 1 side of the room is an outer wall

o At least 1 side is an outer wall and the room is located on the lowest floor or under the roof

o The room has no outer walls, but it is located on the lowest floor or under the roof

o The room is surrounded by different air-conditioned rooms on all sides

3. How large is the volume of the room?

o Small volume smaller than 250 m^3 (Half tennis court, 2 meters high)

o Medium volume between 250 m^3 and 1,000 m^3 (Complete tennis court, 4 meters high)

o Large volume between 1,000 m^3 and 4,000 m^3 (Full basketball court, with five rows of spectators, the ceiling as high as the third floor of an average house)

o Massive volume between 4,000 m^3 and 10,000 m^3 (Entrance hall of a large museum comparable to 2 basketball courts next to each other and a few floors high)

o Mono-volume larger than 10,000 m^3 (Volumes of churches, train stations, concert halls, world exhibition buildings, sports halls)

Utilities

1. What climate systems are present? And if so, is it a portable system?

	Yes	No	Portable system?
Heating			
Cooling			
Humidification			
Dehumidification			
Ventilation			
Considerable natural ventilation through windows, doors and walls.			

2. Is the location under inspection a room or a part of a larger zone?

o Single volume
o Part of zone with multiple connected rooms

3. How and where is sunlight kept out of the room?

o No specific measures
o Measures inside the building envelope to reduce or block light
o Measures outside the building envelope to reduce or block light
o No (diffuse) sunlight enters the room

Human activity

1. How many visitors enter the room?

    o Almost no access (< 5 people/day for less than 2 hours)
    o Limited access (< 10 people/day for less than 4 hours)
    o Accessible (on average up to 100 people/day)
    o Limited interest (on average up to 400 people/day)
    o Public interest (more than 400 people/day, but no frequent peaks of more than 100 people in the room at the same time)
    o Mass tourism (more than 400 people/day, with frequent peaks of more than 100 people simultaneously in the room)

2. What role does comfort play in the adjustment of the climate system?

    o Priority for conservation standards
    o Adapted to the comfort of visitors, but in line with conservation standards
    o Regularly adapted to the comfort of visitors

3. How strict is the climate control check?

    o No measurements
    o Rudimentary (data loggers + no standardized follow-up of the data)
    o Substantial (data loggers + standardized follow-up)
    o Thorough (data loggers + standardized follow-up + direct action)
    o Advanced (continuous data processing of many parameters + standardized follow-up + direct action + long-term strategy)

4. What are the cleaning procedures?

Multiple answers possible.

o No control by heritage guardians
o Specific training of cleaning staff for cleaning in a heritage environment
o Regulation of the used cleaning products
o Quality control of the cleaning activities
o Evaluation of cleaning procedure (planning and/or activities)

Inspect collection

1. What is the general nature of the collection?

  o Mainly inorganic materials
  o General collection (a mixed collection with all objects in relatively good condition and no objects that are remarkably more sensitive to a specific parameter)
  o Mainly organic materials
  o Very light-sensitive objects are part of the collection

2. Is there an item that is given priority (in connection with climate requirements) over the collection?

  o No
  o Yes, because of:
    o Sensitivity of the material
    o Cultural value of the object
  o And what material is the most important for the climate requirements: ………… ..

3. What is the general condition of the collection?

  o No signs of degradation
  o Relatively good (less degradation than the expected degradation)
  o Acceptable (in balance with the natural degradation of the materials in good storage conditions)
  o Point of attention (degradation due to poor storage in the past, but the current climate conditions (including storage) are good)
  o Problematic (the collection or object has become extremely sensitive due to an emergency, treatment (s), or a very poor quality of the material or the manufacturing procedure)

4. Are the specifications for scenography and showcases tailored to preventive conservation?

  o Yes, with a check on correct implementation
  o Yes, but little control on correct implementation
  o No

Annex 3: Program of the international AIRCHECQ conference

Thursday April 28th (9 am – 5 pm)

Olivier Schalm (University of Antwerp, Conservation studies)

Welcome

Jean Tétreault (Canadian Conservation Institute)

Past and present pollutant concentration targets and how they are used or misused

Elke Otten (Royal Museum of the Army and of Military History)

Large and mixed collections in the Royal Army Museum of Brussels. How to deal with it?

Diana Leyva Pernia (University of Antwerp, Department of Mathematics – Computer Sciences) and
Caroline Meert (Royal Museums of Fine arts of Belgium)

What is the meaning of 'Indoor Air Quality'? Risk management or mathematical algorithm approach.

Hannelore Römich (New York University, The Conservation Center of the Institute of Fine Arts)

Environmental impact dosimeters: what are the possibilities of glass sensors and light dosimeters?

Johanna Leissner (Fraunhofer EU Office Brussels)

What is the impact of climate change on cultural heritage? Implementing climate models andbuilding simulation

for the prediction of risks, changes in monitoring strategies and target values.

Diana Leyva Pernia (University of Antwerp, Department of Mathematics – Computer Sciences)

AIRCHECQ: Demonstration software

Followed by round table discussions and a guided tour at the Royal Museum of the Armed Forces and of Military History, Brussels

Friday April 29th (9 am – 4.30 pm)

Joost Vander Auwera (Royal Museums of Fine Arts of Belgium)

Welcome

Bart Ankersmit (Cultural Heritage Agency of the Netherlands)

How can we use the history of the collection to determine target values for environmental parameters?

Koenraad Van Balen (University of Leuven, Building Materials and Building Technology Section)

The importance of systems thinking in the preventive conservation of heritage collections

Willemien Anaf (Royal Museum of the Army and of Military History) and
Ayalew Eyasu Mekete (University of Antwerp, Department of Chemistry)

AIRCHECQ: How do we measure the Indoor Air Quality? Results of the first measuring campaigns.

Stefan Simon (Yale University, Institute for the Preservation of Cultural Heritage)

How to monitor the behaviour of a building?

Marjolijn Debulpaep (Royal Institute for Cultural Heritage, Preventive conservation unit) and
Veerle Meul (Dienst Erfgoed, Adviseur erfgoeddepots)

AIRCHECQ – reality check: challenges in the measuring and practical use of environmental parameters in the heritage field

Olivier Schalm (University of Antwerp, Conservation Studies)

AIRCHECQ: Demonstration monitoring unit

Followed by round table discussions

Annex 4: List of main deliverables and the role of contributors

Product or concept	Owner	Contributors	Promotor	Contribution
Monitoring system 1 with air velocity sensor	UA, CR	Olivier Schalm UA, CR	Olivier Schalm, UA, CR	Selection of sensors, overall configuration
		Andrea Marchetti UA, CHEM	Karolien De Wael UA, CHEM	Performance study of cheap PM sensor
		Ana Cabal UA, CR	Olivier Schalm, UA, CR	Wiring of sensors, testing of the prototype
		Piet Van Espen UA, CR	Olivier Schalm, UA, CR	Wiring of sensors, testing of prototype
		Jan Callier ARM & FIN	Elke Otten, ARM Joost Vander Auwera, FIN	Design of enclosure, adapting the wiring to the design
Monitoring system 2 with extended series of gas sensors	UA, CR	Olivier Schalm UA, CR	Olivier Schalm, UA, CR	Selection of sensors, overall configuration
		Ana Cabal UA, CR	Olivier Schalm, UA, CR	Wiring of sensors, testing of prototype
		Piet Van Espen UA, CR	Olivier Schalm, UA, CR	Wiring of sensors, testing of prototype
		Jan Callier ARM & FIN	Elke Otten, ARM Joost Vander Auwera, FIN	Design of indoor & outdoor enclosure, adapting the wiring to the design
Concept to calculate indoor air quality assessments from environmental measurements	ARM, UA, CR UA,WIS Public	Willemien Anaf ARM	Elke Otten, ARM	Definition of threshold values, risk functions and weighing factors
		Diana Leyva UA, WIS	Serge Demeyer UA, WIS	Development of the algorithm
		Olivier Schalm UA, CR	Olivier Schalm UA, CR	Initial idea
Software to automatically transform a data stream into assessments	UA, WIS Public	Diana Leyva UA, CR	Serge Demeyer UA, WIS	Design software and program codes.
Work process describing the subsequent steps in the analysis of museum rooms	Public	Jan Callier FIN	Joost Vander Auwera, FIN	Description of the subsequent steps and development of the questionnaire
		Olivier Schalm UA	Olivier Schalm UA	Design of the overall procedure

UA, CR: University of Antwerp, Conservation Studies
UA, WIS: University of Antwerp, Department Mathematics – Informatics
UA, CHEM: University of Antwerp, Department of Chemistry
ARM: Royal Museum of the Armed Forces and Military History
FIN: Royal Museums of Fine Arts of Belgium

Annex 5: Use of the deliverables after the termination of the project

Product or concept	Owner
Monitoring system 1 with air velocity sensor	The monitoring system is currently located in the Saint Martin church in Aalst for at least March 31. Then it will be free for other measuring campaigns. The revision of the sensors can be paid with the CR-budget of the BOF-academiseringsproject.
Monitoring system 2 with extended series of gas sensors	The monitoring system will be moved at the Antwerp Maritime Academy for improvement. There it will be prepared for a measuring campaign in a restoration studio at CR and in a ship. Both measuring campaigns are part of research projects in close collaboration with CR. Then it will be free for other measuring campaigns.
Concept to calculate indoor air quality assessments from environmental measurements	The concept has been published and can freely be used in the following open access publication. *Anaf W., Leyva Pernia D., Schalm, O., Standardized Indoor Air Quality Assessments as a Tool to Prepare Heritage Guardians for Changing Preservation Conditions due to Climate Change, Geosciences 2018, 8(8), 276*
Software to automatically transform a data stream into assessments	The software is released on an open coding platform (https://github.com/dleyva/AIRCHECQ-0.1.3) under an open source license. This allows for future extensions and applications. One such application is already planned for related to the assessment of air quality in relation to human health.
Work process describing the subsequent steps in the analysis of museum rooms	The work process can freely be used and will be described in detail in the end report.

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