Development of an Indoor Air Quality Index for Heritage Conservation
An Exploratory Study

Proefschrift voorgelegd tot het behalen van de graad van Doctor in de Wetenschappen aan de Universiteit Antwerpen te verdedigen door:

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Development of an Indoor Air Quality Index for Heritage Conservation, An Exploratory Study

Een Verkennend Onderzoek Omtrent de Haalbaarheid van een Luchtkwaliteitsindex Voor Conservering van ons Cultureel Erfgoed

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Proefschrift ingediend tot het behalen van de graad van
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To Guse, Ileana & Tony, Daina,
Maria & Antonio, Gina & Luis

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Diana Leyva Pernia
February 8th, 2019

ABSTRACT

Indoor air quality plays a significant role in the preservation of cultural heritage. Multiple studies have demonstrated that it is possible to slow the degradation speed of heritage objects by improving environmental parameters such as temperature, relative humidity, the intensity of visible light, the intensity of ultraviolet radiation, particulate matter and gaseous pollutants. However, the assessment of how adequate storage conditions are for heritage conservation is a complex and challenging task. Experienced heritage guardians can intuitively determine indoor air quality through sensorial perceptions. Nevertheless, this intuitive perception is very personal and results in different or contradictory opinions, and it is not always in agreement with a rational analysis of risk: apathy for certain risks or panic for small risks might occur. Therefore, an objective air quality assessment requires the acquisition of environmental information, which implies registering and managing a considerable amount of data. The absolute values and trends of the monitored parameters can be visualised via graphs. Unfortunately, this gives an indirect impression of the air quality. Many heritage guardians perceive such information as too technical and difficult to interpret, or as meaningless and without value.

This thesis investigates the possibilities of an indoor air quality index as a method to directly assess, quantify and visualise the quality of the storage conditions. Moreover, the present study also shows that evolution in quality can also be visualised over time. Several methods were used for this, such as the interpretation of existing guidelines and standards, the measurement of a larger number of environmental parameters than just temperature and relative humidity with corresponding limit values collected through literature research, and data mining techniques. In order to give heritage guardians access to the proposed methods for processing data, a user-friendly software was developed to convert measurements of environmental parameters into an intuitive indoor air quality index. The main goal of this research is to provide a comprehensive assessment and an intuitive but consistent and reproducible representation of the quality criteria that characterise the air quality in museums, churches and storages.

NEDERLANDSTALIGE SAMENVATTING

Binnenluchtkwaliteit speelt een belangrijke rol bij het behoud van cultureel erfgoed. Meerdere studies hebben aangetoond dat het mogelijk is om de degradatiesnelheid van erfgoedobjecten te vertragen door omgevingsparameters zoals temperatuur, relatieve vochtigheid, intensiteit van zichtbaar licht, intensiteit van UV-straling, fijnstof en gasvormige polluenten te verbeteren. De beoordeling hoe goed bewaaromstandigheden precies zijn is echter een complexe en uitdagende taak. Ervaren erfgoedmedewerkers zijn in staat om de binnenluchtkwaliteit op intuïtieve wijze via zintuigelijke waarnemingen te bepalen. Deze intuïtieve perceptie is echter zeer persoonlijk en resulteert in verschillende of tegenstrijdige meningen, en het is niet altijd in overeenstemming met een rationele analyse van risico's: apathie voor bepaalde risico's of paniek voor kleine risico's kunnen optreden. Daarom vereist een objectieve luchtkwaliteitsbeoordeling een grote hoeveelheid aan informatie betreffende de bewaaromstandigheden. Dit betekent dat er een aanzienlijke hoeveelheid gegevens moeten worden vergaard en beheerd. De absolute waarden en trends van de gemeten parameters kunnen via grafieken worden gevisualiseerd. Jammer genoeg geven dergelijke grafieken een indirecte indruk van de luchtkwaliteit. Veel erfgoedmedewerkers ervaren dergelijke informatie als te technisch en moeilijk te interpreteren, of als zinloos en zonder waarde.

Dit proefschrift onderzoekt de mogelijkheden van een luchtkwaliteitsindex als een methode om de kwaliteit van de bewaaromstandigheden rechtstreeks te bepalen, te kwantificeren en te visualiseren. Bovendien toont het proefschrift aan dat de evolutie in kwaliteit doorheen de tijd ook kan worden gevisualiseerd. Hiervoor werden meerdere methoden gebruikt zoals de automatisering van bestaande richtlijnen en normen, het vergelijken van een groter aantal omgevingsparameters dan enkel temperatuur en relatieve vochtigheid met overeenkomstige grenswaarden die via literatuuronderzoek werden verzameld, en datamining technieken. Om erfgoedbewakers toegang te geven tot de voorgestelde methodes om gegevens te verwerken, werd een gebruiksvriendelijke software ontwikkeld die metingen van omgevingsparameters omzet in een intuïtief leesbare luchtkwaliteitsindex. Het belangrijkste doel van dit onderzoek is het bieden van een uitgebreide beoordeling en een intuïtieve maar consistente en reproduceerbare weergave van de kwaliteitscriteria die kenmerkend zijn voor de luchtkwaliteit in musea, kerken en depots.

PUBLICATIONS

The following peer-reviewed publications were directly included in this thesis:

A data mining approach for indoor air assessment: an alternative tool for cultural heritage conservation
Diana Leyva Pernia, Serge Demeyer, Olivier Schalm, Willemien Anaf
In IOP Conference Series: Materials Science and Engineering (Vol. 364, No. 1, p. 012045). IOP Publishing.
Olivier and Serge proposed the initial idea. Diana proposed the specific methods and implemented them. Olivier and Willemien conducted the measuring campaign for the data collection. Serge, Olivier and Willemien contributed to refine the methods and the interpretation of the results. Diana wrote the paper and all the co-authors reviewed and modified it accordingly.

Standardized indoor air quality assessments as a tool to prepare heritage guardians for changing preservation conditions due to climate change
Willemien Anaf, Diana Leyva Pernia, Olivier Schalm
In Geosciences, 8(8), 276.
Olivier provided the initial idea. Willemien determined the relevant Key Risk Indicators, Risk Functions and Weighing Factors. Diana proposed and implemented the model for calculating the IAQ index. Olivier and Willemien conducted the measuring campaign for the data collection. Willemien wrote the paper. Olivier and Diana reviewed and modified it accordingly.

New approach to indoor air quality assessment for cultural heritage conservation
Diana Leyva Pernia, Serge Demeyer, Olivier Schalm, Willemien Anaf, Caroline Meert
In Proceedings INDOOR AIR 2016, The 14th International Conference on Indoor Air Quality and Climate, Ghent, Belgium, July 3 – 8
Olivier and Serge provided the inspiration. Diana proposed, developed and implemented the given model. Willemien, Olivier and Caroline proposed the specific guidelines and contributed in the selection of the visualization method for the results. Olivier provided the experimental data. Diana, Serge and Olivier wrote the paper. All the co-authors reviewed and modified it accordingly.

The following peer-reviewed publications were not directly included in this thesis:

New generation monitoring devices for heritage guardians to detect multiple events and hazards
Olivier Schalm, Willemien Anaf, Jan Callier, Diana Leyva Pernia
In IOP Conference Series: Materials Science and Engineering (Vol. 364, No. 1, p. 012056). IOP Publishing.
Olivier proposed the idea and wrote the paper. Olivier, Willemien and Jan developed and tested the monitoring system. Diana developed and implemented

the method for the data analysis. All the co-authors reviewed and modified the paper accordingly.

Indoor environmental quality index for conservation environments: the importance of including particulate matter
Andrea Marchetti, Sanaz Pilehvar, Lucy ‘t Hart, Diana Leyva Pernia, Olivier Voet, Willemien Anaf, Gert Nuyts, Elke Otten, Serge Demeyer, Olivier Schalm, Karolien De Wael
Building and Environment, 126, 132-146.
Andrea, Sanaz, Lucy, Willemien and Elke conducted the measuring campaigns. Andrea and Karolien analysed and interpreted the data collected; and wrote the paper. Diana defined and calculated the translation of the data to the Indoor Air Quality index; and wrote the sections of the paper referring to it. All the co-authors reviewed and modified the paper accordingly.

CONTENTS

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CHAPTER 1

INTRODUCTION

Partially based on:

AIRCHECQ: Air Identification & Registration for Cultural Heritage: Enhancing Climate Quality, Contract - BR/132/A6/AIRCHECQ, FINAL REPORT

Olivier Schalm, Andrea Marchetti, Diana Leyva Pernia, Jan Callier, Willemien Anaf

To be available in May 2019

Cultural heritage is defined by the United Nations Educational, Scientific and Cultural Organization (UNESCO) as “the legacy of physical artifacts and intangible attributes of a group or society that are inherited from past generations, maintained in the present and bestowed for the benefit of future generations.” [1, 2]. Heritage constitutes a source of identity and cohesion for communities, a key factor in the way we perceive and experience history, and one of the principal elements establishing the foundations for vibrant, innovative and prosperous knowledge societies [2]. Therefore, its preservation is one of our greatest responsibilities towards future generations.

The awareness that heritage objects should be provided with appropriate environmental conditions boomed after the World Wars when, for safety reasons, many objects were moved to railway tunnels, secret tunnels or quarries [3]. These temporarily new conditions appeared either disastrous or superior to the earlier museum and gallery conditions [3]. Visible damage due to unsuitable conditions triggered the development of standards and guidelines for a climate that would be ‘safe’ for the collections [4].

Nowadays, it is widely accepted that the environmental conditions play a crucial role in de degradation process of materials and that their consideration is critical in determining the degradation rate and life expectancy of heritage objects [4-6]. However, the assessment and evaluation of their impact still is an open field of study and discussion inside the heritage community.

1.1 INDOOR AIR QUALITY AND INDOOR AIR QUALITY INDEX.

Studies dated in the 70s already refer to term Indoor Air Quality (IAQ) as a complex function of pollutant concentrations, thermal and other physical conditions inside a room[7-9]. A more recent definition from the United States Environmental Protection Agency refers to IAQ as "the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants" [10]. Combining both definitions, we can say that, ***in general, IAQ regards to the quality of the air inside buildings as represented by concentrations of pollutants and thermal conditions that***

affect the health, comfort, and performance of occupants, or that threatens the integrity of the objects within.

Over the last twenty years the number of scientific publications in which the IAQ is mentioned has exponentially increased (Figure 1.1). The vast majority of these studies focus on the impact over human health or human comfort, and only a 2.7 % referred the IAQ in the field of cultural heritage. However, the trend in the heritage field is also oriented towards an exponential increment in the number of published IAQ studies (Figure 1.2).

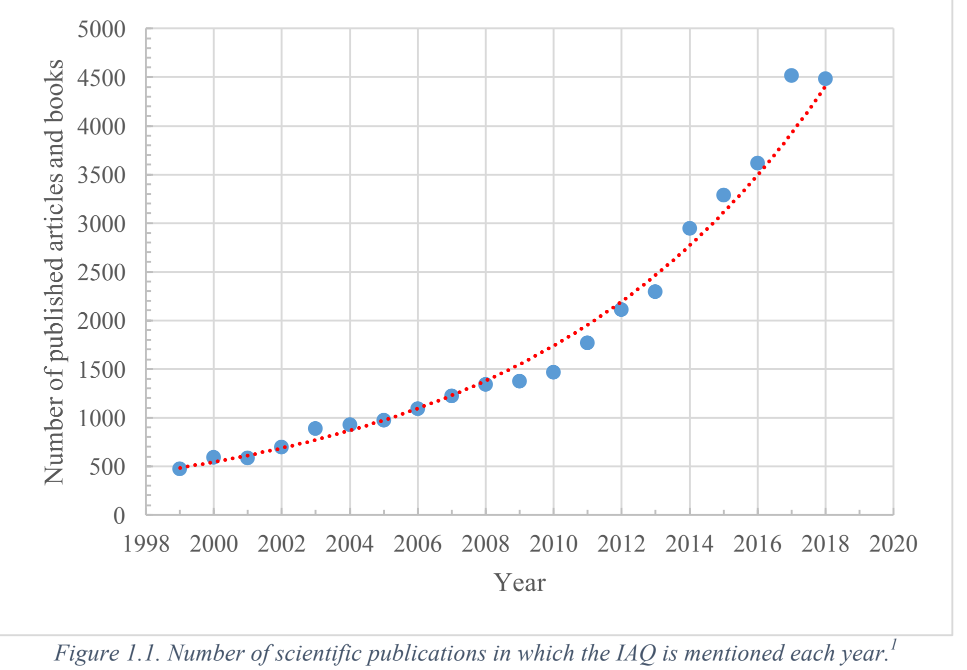


Figure 1.1. Number of scientific publications in which the IAQ is mentioned each year.[1]

[1] Information from the scientific database Science Direct, retrieved the 12 of November of 2018. https://www.sciencedirect.com key words: *indoor air quality*

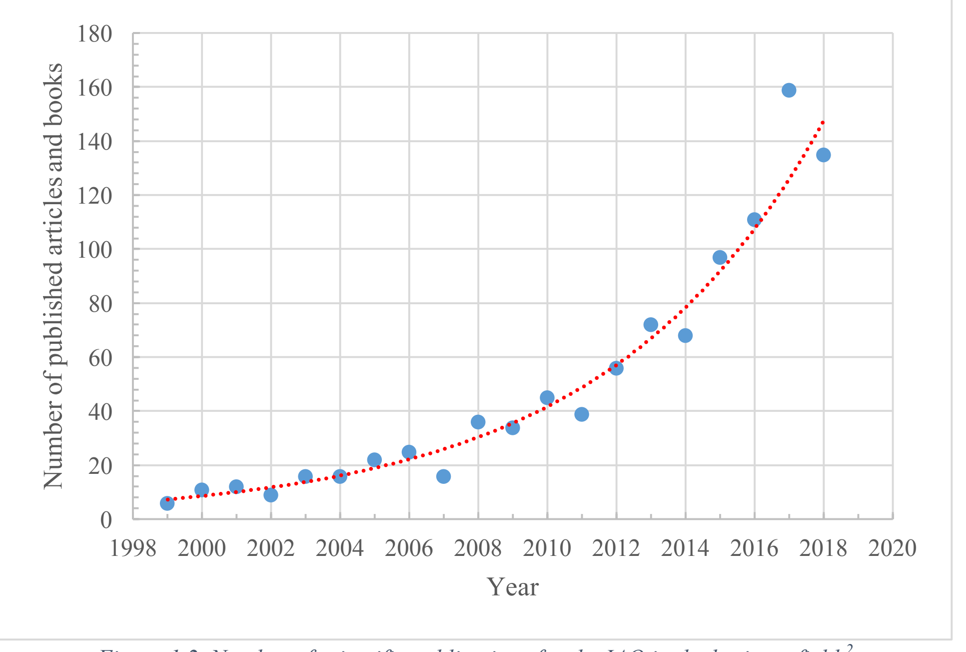


Figure 1.2. Number of scientific publications for the IAQ in the heritage field.[2]

There is no standardised concept defining IAQ for cultural heritage conservation, nonetheless, it can also be defined for heritage materials. Poor IAQ affects the integrity of the objects exposed to it by causing an accelerated degradation of the materials composing them [6, 11, 12]. Consequently, ***the concept of IAQ in heritage relies on the fact that certain environmental conditions in a room can minimize the degradation rate of the objects contained inside and consequently prolong their life expectancy***. This is the main reason why IAQ plays such a crucial role in preventive conservation, and why heritage guardians and institutions have an increasing interest in managing and evaluating it [13, 14].

An IAQ-index is a simple and cost-effective tool for the evaluation of IAQ [15, 16]. The use of indices for air quality assessment was first introduced in 1969, focussing only in the outdoor environment but stablishing the advantages of the method for fast and intuitive interpretation of the environmental conditions [17, 18]. In the specific case of indoor environment, the use of quality indices was introduced in 1982, when Jhon E. Yocom presented an index based on the indoor/outdoor concentration ratio for different pollutants [19]. This first IAQ-index was soon classified as insufficient to characterize the IAQ, but then again, it illustrated the advantages of the method and settled the basis for further studies [15]. Nowadays the use of IAQ-indices is vastly common and, the number of scientific publications mentioning an IAQ-index has also increased in an exponential way (Figure 1.3). In 2018, for example, the approximately 42% of IAQ related publications

[2] Information from the scientific database Science Direct, retrieved the 12 of November of 2018. https://www.sciencedirect.com key words: *indoor air quality* AND *cultural heritage*

also mentioned the use of an IAQ-index[3]. However only less than 3% of those publications also mentioned its application on the heritage sector. [4]

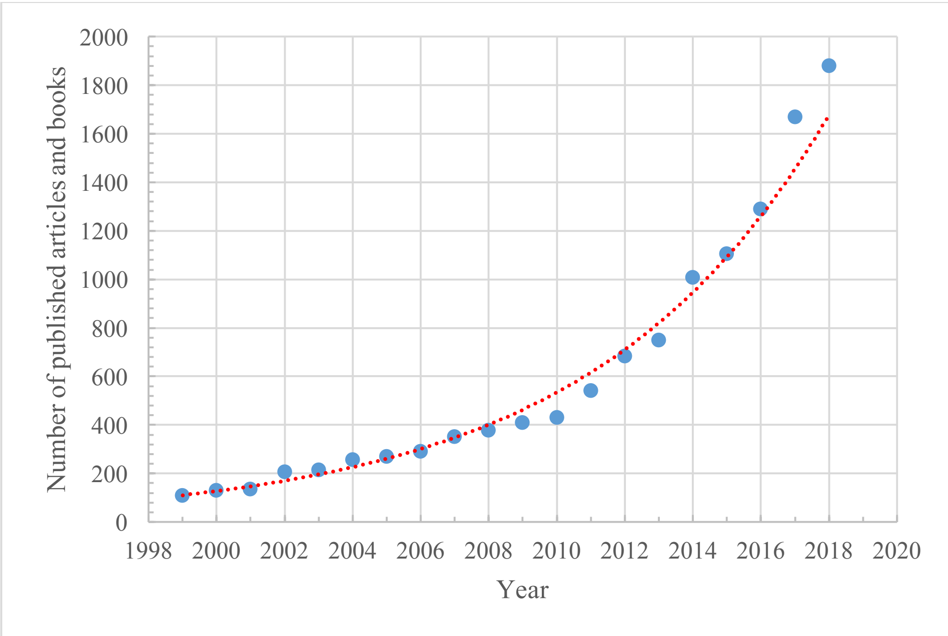


Figure 1.3. Number of scientific publications in which IAQ-indices are mentioned each year.[3]

1.2 THE AIRCHECQ PROJECT

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 War Heritage Institute in Brussels is responsible for more than 300.000 objects, resulting in exhibition rooms that are fully packed. If we assume that every object 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. Public budgets are limited, while high tourist influxes increase revenues but result at the same time in enhanced environmental and physical pressure.[5] *Preventive conservation* is considered as a solution to this problem. It entails all measures and actions aimed at avoiding and minimizing future deterioration or loss [20]. 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. An example is improving the

[3] Information from the scientific database Science Direct, retrieved the 6 of December of 2018. https://www.sciencedirect.com key words: *indoor air quality index*

[4] Information from the scientific database Science Direct, retrieved the 6 of December of 2018. https://www.sciencedirect.com key words: *indoor air quality index* AND *cultural heritage*

[5] Information from Climate for Culture - http://www.climateforculture.eu/ , retrieved the 2 September 2016.

environmental preservation conditions (light, humidity, pollution and pest control) to slow down the degradation rate of the entire collection.

In this context appears the interdisciplinary research project BR/132/A6/AIRCHECQ - Air Identification & Registration for Cultural Heritage: Enhancing Climate Quality. The AIRCHECQ project approached the search of appropriate preservation conditions as a decision-making process. This means that appropriate preservation conditions are not considered as a technical solution that eliminates the problem at once. Instead, it is a goal that should be strived for where decisions reduce the probability that hazards occur. The adaptation of preservation conditions 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 ∞, $v(t)$ becomes 0. At a management level, this approach can be considered as a method that prioritize resource allocation to preventive conservation under conditions of uncertainty.

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

The evolution towards better preservation conditions is then realized by performing a consecutive series of (low-cost) mitigation actions that are sufficiently good for the time being, interspersed with some high-cost but drastic mitigation actions. To implement this approach is not possible to rely on a unique analysis at the end of an extended measuring campaign. Instead an *in vivo* approach, where a systematic analysis is performed while the environmental conditions are monitored.

The AIRCHECQ project developed three practical tools that supports preventive conservation as a decision-making process. These tools are visualised in Figure 1.4. The combination of tool 1 and 2 forms a *decision support system* and the three of them are interconnected in the general method proposed to improve preservation conditions (Figure 1.5).

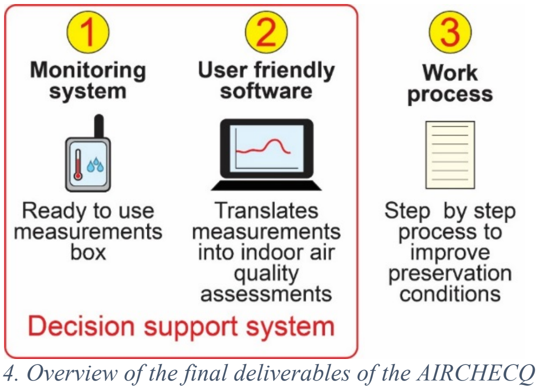


Figure 1.4. Overview of the final deliverables of the AIRCHECQ project.

The *work process* (Final deliverable 3) is used to find weak spots in buildings and inappropriate environmental conditions that need to be improved. The *monitoring unit* (Final deliverable 1) measures 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 (Final deliverable 2) that can easily be read by laypeople. The monitoring unit and the software forms together a *decision support* *system* that visualises 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.

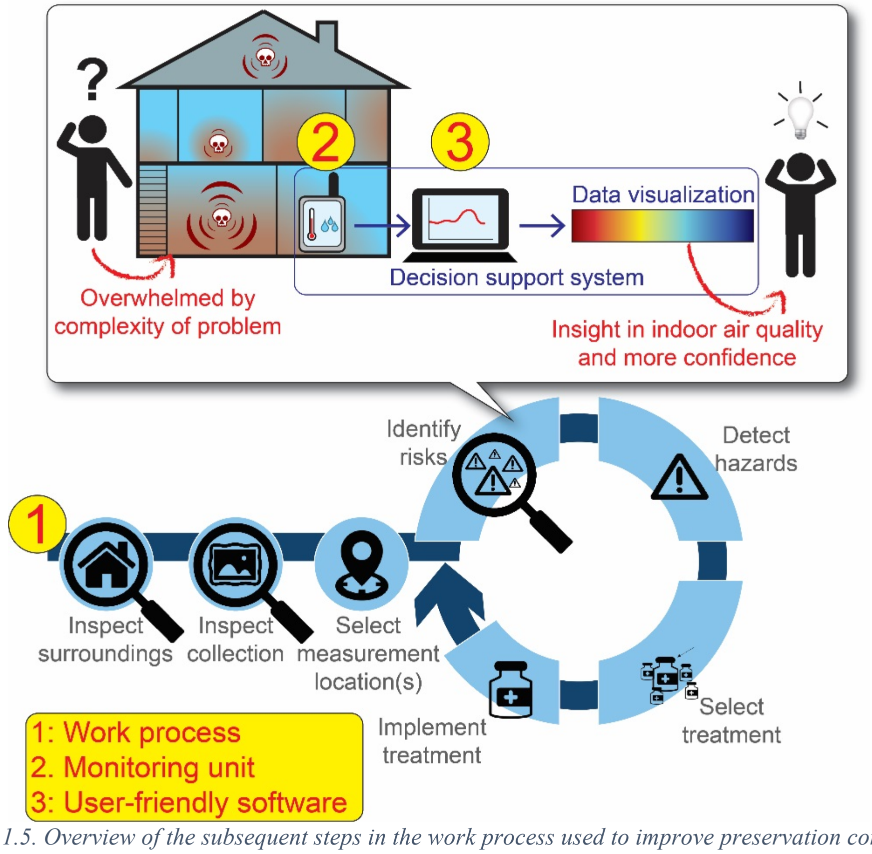


Figure 1.5. Overview of the subsequent steps in the work process used to improve preservation conditions and the role of the monitoring unit and the software in that process.

To accomplish this, the project required the close collaboration of four different groups of specialists:

1. Specialists from the Department of Chemistry at the University of Antwerp, for the validating sensors and performing chemical analyses of indoor environments.
2. Specialists from the Department of Mathematics and Computer Science at the University of Antwerp, for transforming data streams in IAQ indexes, and developing a user-friendly software.
3. Heritage guardians from the Royal Museums of Fine Arts of Belgium and the Royal Museum of the Armed Forces and of Military History, specialized in facility and collection management.
4. Conservation scientists from Conservation Studies, University of Antwerp, for the translation of the IAQ indexes in realistic mitigation measures.

The interdisciplinary nature of this work and the constant interaction between the different groups provided the opportunity of covering a wider field of knowledge. Furthermore, it also motivated the communication of results in a more intuitive manner for a better exchange between partners from different specialization fields.

1.3 THE AIRCHECQ PROJECT CONTEXT

1.3.1. 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 [21, 22]. This dual-processes 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 [23]). For example, the preservation state of an object can be estimated from visual cues such as cracks or discolorations. For that reason, an object's preservation state can be monitored by regular visual inspections. The disadvantage of this method is that the hazards cannot be identified until there is visible damage. Another example of visual cues is the evaluation of the appropriateness of environmental conditions by the peaks and drops in temperature and relative humidity graphs. Such information can trigger the selection of a mitigation action [2]. 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). At the same time, 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 [3]). It can tempt heritage guardians to postpone decision-making, unless they know that waiting is even worse.

- **Rational process:** In the heritage community, different kinds of measuring systems are installed to measure temperature and relative humidity [24]. An overview of such systems is given in Figure 1.6. In some cases, that information is supplemented with the intensity measurements of visible light and ultraviolet radiation. Besides the access of the <u>absolute value</u> of certain environmental parameters, also the <u>trends</u> of these parameters are of interest.

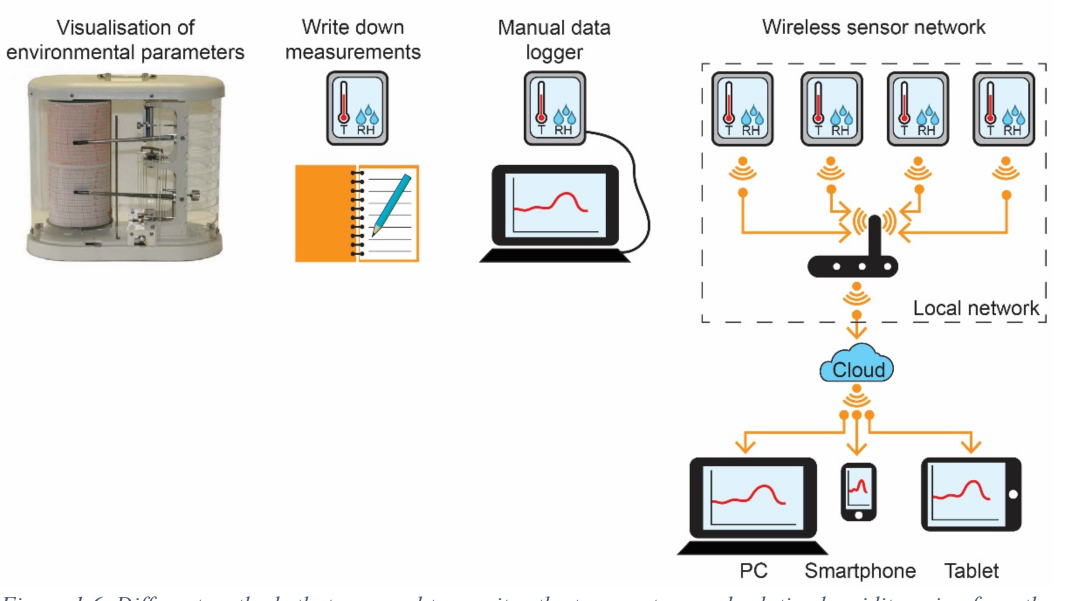


Figure 1.6. Different methods that are used to monitor the temperature and relative humidity going from the thermohygrograph (completely left) to a network (completely right) where measurements are accessible in real time.

The AIRCHECQ project considered both data collection processes as important. For that reason, it made an attempt to bring both processes together. However, the project has chosen to develop tools that help heritage guardians in decision-making by focussing on the rational process (i.e., data collection and data processing by using final deliverables 1 and 2). The bridge between intuitive and rational approaches is assured by maximizing the intuitive access of huge amounts of measurements. Moreover, it should be noted that the work process (i.e., deliverable 3) is also usable when there is a focus on intuitive data collection by visual inspections.

1.3.2. TIME-AVERAGED VERSUS CONTINUOUS MEASUREMENTS

In order to describe the relationships between *hazards* and the loss in value of a collection in the context of the AIRCHECQ project, it is necessary to consider 4 sets of parameters. These sets are shown in Figure 1.7. The elements in the sets are exemplary cases. In reality, more elements are needed to describe these relationships. The arrows between the elements in adjacent sets visualise which elements affect each other. The overall picture shows the complexity of all these relations.

- **Set A in Figure 1.7:** This set contains all possible hazards that endanger the heritage collection. Several types of hazards can affect the same environmental parameters. For example, sun light, acclimatisation systems and the presence of people influences the temperature inside a room. Set A determines all the dangers to which a collection is exposed to;

- **Set B in Figure 1.7:** This set contains all the environmental parameters that drive the degradation processes. They describe the exposure of a collection towards hazards. However, due to the complex relations between environmental conditions and hazards it is not straight forward to identify hazards from environmental measurements;

- **Set C in Figure 1.7**: 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, many types of degradation mechanisms must be considered. All these degradation mechanisms are influenced in their own way by the environmental parameters in set B. Moreover, the response determines how sensitive the heritage collection is for the exposure to hazards;

- **Set D in Figure 1.7:** People associate 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 located in set D. In preventive conservation, the visual inspection of a collection is in fact an analysis of set C and D together. It affects the analysis of *sensitivity* of the heritage collection towards exposure.

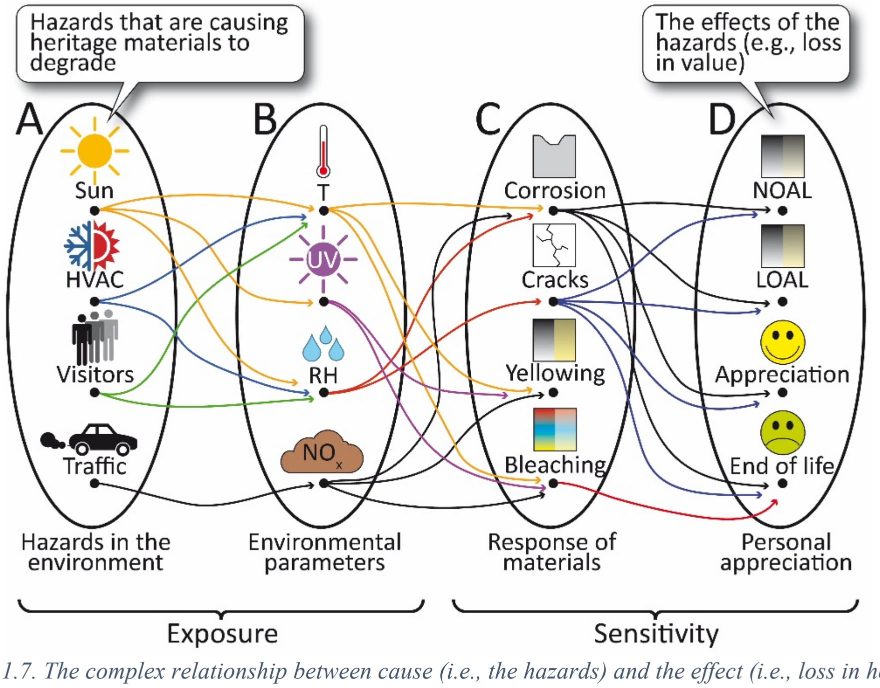


Figure 1.7. The complex relationship between cause (i.e., the hazards) and the effect (i.e., loss in heritage value).

Figure 1.7 clearly illustrates the complexity of the relationships between hazards, environmental parameters, degradation mechanisms (i.e., response of materials) and the loss in value of objects. It also shows the distinction between (1) the *exposure* of collections to hazards that threatens a collection, and (2) the *sensitivity* of collections to that exposure. The exposure is the reason why heritage collections degrade. The sensitivity describes how much the collection is affected by the exposure. The importance of exposure and sensitivity is illustrated in Figure 1.8.

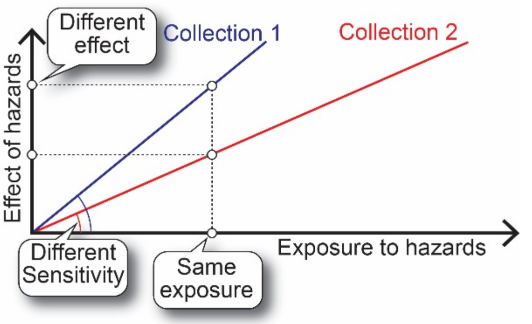


Figure 1.8. The relationship between exposure, effect and sensitivity of a collection.

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). Due to the (partially) unknown and complex relationships between hazards (set A) and environmental parameters (set B), further information is needed in order to understand these relationships.

1.3.3. DIFFERENT METHODS TO ESTIMATE DEGRADATION RATES

The heritage community usually monitor only environmental parameters to determine the aggressiveness of the environment, while their main concern is the behaviour of their objects. 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 a number of reasons that explains this:

- 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 heritage sector demands that interventions on heritage objects do not leave traces in the long term. This limits the possibilities to measure the behaviour of materials directly. For example, gluing strain gages is not allowed in the vast majority of cases.

- The number of objects in a room can be so large that it is nearly impossible to analyse them all. Analysing a small sample of objects is also problematic because heritage collections are usually so heterogeneous that the representativeness of the samples can be questioned.

This means that we have to measure environmental conditions (i.e., set B in Figure 1.7) and with inference the corresponding effect on materials (i.e., set C in Figure 1.7) must be estimated. Only by estimating the effect on materials, it is possible to estimate how dangerous certain hazards are. Therefore, the relationship between environmental parameters and degradation rate plays a crucial role in preventive conservation. That relation can be described by a cause-effect model, which can be approached in 4 different ways. Each approach is described in the list below and illustrated in Figure 1.9.

1. **Understand cause & effect relationships:** Degradation mechanisms need to be elucidated in order to understand the relationship between environmental parameters (i.e., input of the model shown in case 1 Figure 1.8, set B in Figure 1.7) and the degradation rate of a series of common heritage materials (i.e., the output of the model, set C in Figure 1.7). In addition, also the ability to estimate degradation rates are needed. The method to obtain that insight often consists of examining many individual aspects of the degradation mechanism separately. 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 Figure 1.9. 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. In fact, the content of the box is not white as shown in Figure 1.9, case 1, 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 Figure 1.9). These relationships describe the overall behaviour of the degradation mechanism without considering all the separate issues of that mechanism. They enable the prioritization of the agents of deterioration and the definition of damage thresholds [2,10,11]. An example of an algorithm based on such mathematical functions is the preservation metrics developed by the Image Permanence Institute [12]. 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. Thus, 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 [13–15]. Such assessments tackle the following questions [16]: 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 Figure 1.7). With the limited knowledge inside the box (i.e., for that reason the box in Figure 1.9, case

3 is grey) it is possible to identify some of the hazards that cause the harm (set A in Figure 1.7). 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.[6] 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 and sometimes contradictory. The problem of degradation cannot be easily answered. An alternative approach is to simplify the problem so that degradation rates can be estimated. Such strategies can be considered as *heuristics*. Although heuristics are usually associated with intuitive thinking, they can also be used in a rational way. The approach is illustrated in Figure 1.7, case 4. The use of heuristics does not guarantee optimal, perfect, logical, or rational answers, but are sufficient for reaching an immediate goal.

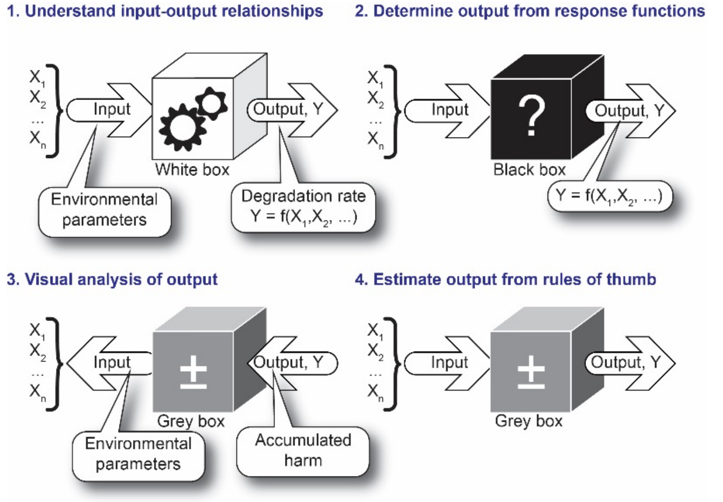


Figure 1.9. Different approaches to estimate the degradation rate of materials.

The first 3 approaches in Figure 1.9 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 the third case because it is very practical and able to approach preventive conservation as a decision-making problem.

[6] Van Duin, P., What real object scan teach us about the influence of climate conditions, in Climate for Collections, Standards and Uncertainties, Munich 2012.

1.4 PROBLEM STATEMENT

Despite the IAQ relevance 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[25-27]. 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 [25]. 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 visualised 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.

Existing standards and guidelines can be used to distinguish preservation conditions with an acceptable risk of degradation from the ones with an unacceptable risk for accelerated degradation. Some standards define a simple target value that can be added on graphs using yardsticks; other standards require data that covers a period of 12 months before the analysis can be performed. A large variety of data processing methods can be found [6, 28]. Nevertheless, these methods usually focus on either the thermal and physical conditions or the concentrations of pollutants, they require a full year of collected data, they do not incorporate an analysis of the temporal evolution of the parameters, and mostly focus in qualitative evaluations, difficult to interpret by a non-expert public.

Furthermore, there is no agreement about the target values that distinguishes preservation conditions with acceptable and unacceptable risk [29]. This might be caused by the incomplete knowledge of the relationships between environmental parameters and degradation rates, different sensory appreciations of the lowest observed adverse effect level, or the different responses of materials to the same environment. As a direct consequence of these variations, the assessment of the same environmental data depicts different results depending on which guidelines (norms) are being followed.

Thesis Goal: ***This thesis explores the possibilities of providing an IAQ-index as a direct method to assess, quantify and visualise the IAQ, while following its evolution through time.***

The present work was executed inside the frames of the AIRCHECQ project, focussing on translating measurements into indoor air quality assessments (Final deliverable 2, Figure 1.4) that can easily be read by laypeople. The author is part of the AnSyMo (Antwerp Systems and software Modelling) group, based on the Department of Mathematics and Computer Science of the University of Antwerp. This Ph.D. project was carried out under the programme of Doctorate in Sciences.

1.5 CONTRIBUTIONS

The main contributions of this thesis are as follows.

C1. We propose the assessment of the IAQ through a unique numerical IAQ-index to transform environmental data into quality judgments, based on the direct interpretation of existing guidelines or norms.

C2. We study different possibilities for this method by including the combined effect of different environmental parameters and more flexible interpretation of existing guidelines.

C3. We analyse the impact of the guideline selection on the IAQ assessment of the same different instances of guidelines and environmental datasets.

C4. We propose a unifying method that combines target values of all relevant environmental parameters for a large series of materials.

C5. We explore the possibilities of an analysis independent of the use of guidelines by applying data mining related techniques.

C6. In order to give heritage guardians access to the proposed data processing methods, we develop a user-friendly software allowing an intuitive interpretation of environmental data.

1.6 THESIS OUTLINE

The graphical representation of the main topics studied in this thesis is shown in Figure 1.10. We centre our efforts in the study of the IAQ assessment for heritage conservations from three different approaches:

1. The use of an IAQ-index based on existing norms or guidelines (Standards)
2. The use of an IAQ-index based on material specific criteria (Weighted Thresholds)
3. The use data mining related techniques (Data Mining)

The development of a user-friendly tool (Software) supports the application of the three different approaches.

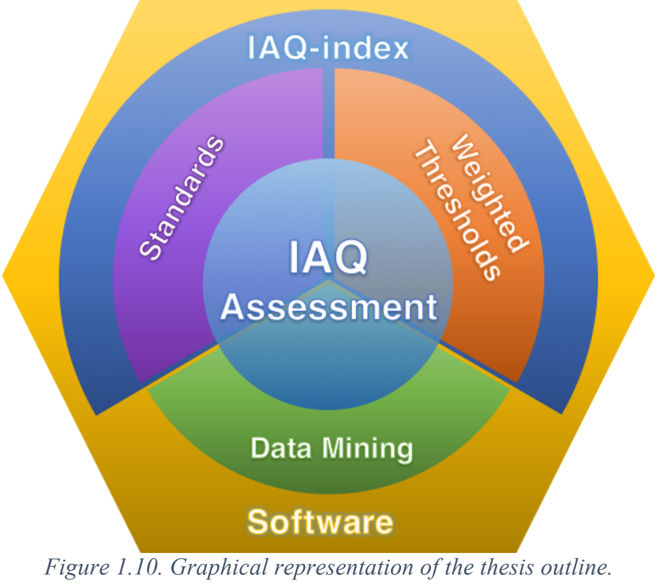


Figure 1.10. Graphical representation of the thesis outline.

IAQ-index and Standards:
Chapter 2 studies the development of a time-dependent IAQ assessment, considering only temperature and relative humidity while applying the environmental guidelines from Thomson and ASHRAE. Chapter 3 presents a multi-parameter (temperature, relative humidity, light, UV) time-dependent assessment applying the Bizot guidelines and expert criteria. Chapter 4 explores the impact of the guidelines selection in the IAQ assessment.

IAQ-index and Weighted Thresholds:
Chapter 5 presents the development of a comprehensive Indoor Air Quality index for material specific analysis.

Data Mining:
Chapter 6 focusses in a data mining approach for IAQ assessment as an alternative tool for cultural heritage conservation.

Software:
Chapter 7 is dedicated to the development of a User-Friendly Software for IAQ assessment. Finally, Chapter 8 presents the conclusions of the thesis.

CHAPTER 2

INDOOR AIR QUALITY ASSESSMENT BASED ON DIRECT INTERPRETATION OF GUIDELINES

Based on:
New approach to indoor air quality assessment for cultural heritage conservation
Diana Leyva Pernia, Serge Demeyer, Olivier Schalm, Willemien Anaf, Caroline Meert
In Proceedings INDOOR AIR 2016, The 14th International Conference on Indoor Air Quality and Climate, Ghent, Belgium, July 3 – 8
ISBN:9781510836877

ABSTRACT
The *IAQ plays a major role in preventive cultural heritage conservation. Several studies have illustrated that it is possible to slow down the degradation process of objects by controlling environmental parameters such as temperature, relative humidity, light, ultraviolet radiation, particulate matter, and reactive gases. However, its assessment is a complex and challenging task that requires monitoring multiple environmental parameters. Therefore, we propose to combine these parameters into a single IAQ-index, representing the global environmental risk for collections as a function of time. For the creation of the first version of such IAQ-index we consider the direct interpretation of two well-known sets of thresholds. As a first exploratory step, we focus only on two of the most common environmental parameters already controlled at museums: temperature, and relative humidity. We demonstrate on one realistic case how we can use this IAQ-index to visualise the historical evolution of the air quality and identify periods where the collection was at risk.*

2.1 INTRODUCTION

Nowadays, almost all museums monitor temperature (T) and relative humidity (RH). This is done with a frequency that can vary from a readout every minute to only one on daily bases [30, 31]. In addition, many museums did considerable investments in air conditioning systems to stabilize the environmental conditions. Unfortunately, collection caretakers are quickly overwhelmed by the huge volume of measurement data obtained from their monitoring system [32]. In addition, the measurements presented as graphs do not contain the required information to make well informed decisions: they need IAQ judgements, not measurements.

Several publications, guidelines and norms describe preservation conditions with acceptable risk and conditions with unacceptable risk. The guidelines provide a textual relationship between the level of risk (i.e., environmental states) and environmental parameters. The threshold values distinguishing different states can be used to evaluate environmental measurements. Different methods exist to do such evaluation. One particular approach uses the ASHRAE guidelines to evaluate the climatic quality by calculating the percentage of the collected data that corresponds with the different ASHRAE climate classes [13-15]. Alternative approaches define indexes that evaluate the climatic quality. The performance index, for example, is defined as the percentage of time in which a measured parameter such as relative humidity falls within a predefined (tolerance) range [12, 16, 17]. The time-weighted preservation index (TWPI), developed by the Image Permanence Institute, is a single value that captures the total cumulative effect over time of changing temperature and relative humidity conditions. It is based on the rate of chemical deterioration in collections [18, 19]. Other indexes were developed that, for example, estimate the effectiveness of the building's heating, ventilation and air conditioning (HVAC) system [17]. The problem with average values is that they give an overall impression. They do not contain much information.

An alternative approach that contains much more relevant and actionable information, is to calculate an IAQ-index characterizing the trend of the IAQ over time. As a first exploratory study we decided to take the most straightforward approach and base this version of our IAQ-index on the direct interpretation of two well-known guidelines, addressing only the influence of temperature and relative humidity. The resulting index maps every point in time on a risk value between 0 (minimum) and 1 (maximum), and its graphical representation directly highlights periods at risk using intuitive colour codes.

2.2 MATERIALS AND METHODS

2.2.1 RELATED WORK

Environmental standards are not unknown to the cultural heritage conservation community. Sets of thresholds have already been applied for controlling temperature and relative humidity since the end of last century. In general, all these standards can be interpreted as essentially large Decision Trees, where the relationships between the parameters are complex and the definition of thresholds is critical. The interpretation of the standards as Decision Trees facilitates their understanding and application, an approach already used successfully in diverse areas such as radar signal classification, character recognition, remote sensing, medical diagnosis, and expert systems, to name only a few [33, 34].

One of the most recognized and applied standards was the Thomson standard [11]. The Thomson standard specifies two classes: one that assumes the presence of a heating, ventilation and air conditioning system (e.g., in large museums), the other to avoid major danger (e.g., in historic houses and churches). In both cases the classifying criteria comes from the simultaneous behaviour of temperature, relative humidity and their fluctuation.

Thomson explicitly recommended that the thresholds should vary depending on the climate zone, seasonal variations, type of buildings. Unfortunately, this recommendation is often neglected and the standards are interpreted in a straightforward way. The most typical interpretation is detailed in Table 2.1.

Compared to the Thomson standard, the ASHRAE standards for 'Museums, Libraries, and Archives' (1999, with revisions in 2003, 2007 and 2011) represent a more up-to-date perspective on the topic [12]. As shown in Table 2.1, five different classes are defined based on the level of risk towards the collection, each considering complex relations between the values of temperature and relative humidity, their fluctuation and their seasonal depending trends. Despite of depicting a more flexible analysis compared with the Thomson standards, its level of complexity in the interdependencies of the analysed parameters increases considerably. An important limitation of the ASHRAE standard is the need for seasonal adjustments which requires a backlog of one year of data to calculate the seasonal fluctuations. Therefore, the ASHRAE standard cannot be used in shorter measuring campaigns aiming for an early detection of a potentially harmful situation.

Unlike the case of environmental standards, the use of air quality indices is not so common in the field of cultural heritage studies. The aforementioned research of Martens [28] used the ASHRAE classes of control for indoor environment in the same way that an indoor air quality index is used, despite of the fact that it is never referred as that. This classes of control provide general information of the rooms environment based on two different parameters, temperature and relative humidity of the room, considering also the impact of the interrelationship between them. With this method it is possible to analyse a year of data and classify the percent of time spent in each class. The only documentation we could find of an explicit indoor air quality index for cultural heritage is from 2015, when Ferhat Karaca proposed an AHP-based indoor Air Pollution Risk Index Method for cultural heritage collections [35]. This index is based on quantitative data of gaseous and particulate pollutant levels, and qualitative data from the pairwise comparison scores for associated risks. It is used for the comparison of seasonal average pollution concentrations and visualised as stacked columns.

The use of air quality indices, both for indoor and outdoor scenarios, is common practice in environmental studies from other fields, especially in those related with health impact and human comfort. A considerable amount of publications on this subject aim to reach a non-expert public, and therefore they had to apply alternative visualization methods. One of the most common is assigning a colour scale to the values of the index. In *Trend Analysis of Air Quality Index in Catania from 2010 to 2014* Lanzafame *et al.* presented a qualitative air quality index with the categories Good, Moderate, Unhealthy for Sensitive Groups, Unhealthy, Very Unhealthy and Hazardous; also represented by a colour gradient from green to dark purple [36]. Using a similar colour gradient Jianlin Hu *et al.* presented the comparison between numerical air quality indices with values varying from 0 to 300 [37]. The colour-based representation for air quality is also applied for instances where the spatial distribution results relevant [38, 39], and in other cases to assist the interpretation of the temporal evolution of the index [36, 40]. This last application is the most commonly found in specialized websites aiming to inform the general public of the local air quality and its progression[7][8].

The state of the art techniques for assessing the indoor air quality rely on complex decision trees with multiple interrelated parameters and corresponding thresholds. However, these models are rarely adopted in practice. A more versatile IAQ-index is needed to represent the degree of air aggressiveness for collections as a function of time.

2.2.2 CASE STUDY

To demonstrate how the IAQ-index can be used to visualise the historical evolution of the air quality, and identify periods where the collection was at risk, we analysed the conditions registered inside a chapel located in the historical city of Antwerp (Belgium). The chapel contains an HVAC system that is able to heat and humidify air. In this investigation, an ATX-datalogger of the company ATAL has been used. This instrument works in a range of -30°C to +70°C, with a resolution of 0.1°C and an accuracy of ±0.4°C; it also has an Internal Capacitive RH sensor working in the range from 0 to 100% relative humidity [41], with a resolution of 0.1% and ±2.5% accuracy from 5 to 95% RH. The datalogger has been installed inside the chapel, screwed into the south wall at a height of about 3 m. The data stored on the datalogger was regularly uploaded with a frequency of 1 to 3 months. The measurements covered the period from January 1, 2012 up to 31 December 2012 for every 15 minutes and the data streams consisted of 35136 data points. All the data streams processing, IAQ-index calculation and the graphics construction were performed using MATLAB R2015b (The MathWorks, Inc. 2015).

2.2.3 ENVIRONMENTAL GUIDELINES

From the extended list of recommended guidelines for heritage conservation we selected two representative cases:

- The Thomson guidelines [11]:

  They propose two different classifications based on the behaviour of temperature and relative humidity. The class 1 would be appropriate for major national museums and for all important new museum buildings. It recommends keeping the temperature at 19 ± 1°C in winter, and at 24 ± 1°C during summer. For relative humidity they recommend 55 ± 5% (the level may be fixed higher or lower than 55%, but for mixed collections should be in the range 45-60%).

  The class 2 is aimed at avoiding major dangers whilst keeping costs and alteration to a minimum, by recommending a relative stable temperature and a relative humidity between 40-70% (more details in Table 2.1).

[7] http://aqicn.org

[8] https://airnow.gov/index.cfm?action=aqibasics.aqi

- The ASHRAE guidelines for museums and archives [12]:
  The ASHRAE guidelines propose five different classifications according to how safe would the environmental situation be for conservation purposes. These guidelines consider the dynamic behaviour of temperature and relative humidity, their interrelation, seasonal behaviour and short time fluctuations (more details in Table 2.1).

Table 2.1. Thomson and ASHRAE standards (Thomson, 1984; ASHRAE, 2015; Michalski, 2016).

<table>
<tr><th>Standard</th><th colspan="2">Specification</th><th>Temperature</th><th>Relative Humidity</th><th>Remarks</th></tr>
<tr><td rowspan="2">Thomson</td><td colspan="2">Class 1</td><td>19 ± 1°C (winter) / 24 ± 1°C (summer)</td><td>55 ± 5% (the level may be fixed higher or lower than 55%, but for mixed collections should be in the range 45-60%)</td><td>Appropriate for major national museums and for all important new museum buildings. It implies the presence of an HVAC system.</td></tr>
<tr><td colspan="2">Class 2</td><td>Reasonably constant to stabilize RH.</td><td>40-70%</td><td>Aimed at avoiding major dangers whilst keeping costs and alteration to a minimum.</td></tr>
<tr><td rowspan="4">ASHRAE</td><td colspan="2">Class AA</td><td>-Set point or historic annual average:
15-25°C
(Valid for all 5 classes)
-Short fluctuations: ±2°C
-Seasonal adjustments: ±5°C</td><td>-Set point or historic annual average: 50%
(Valid for all 5 classes)
-Short fluctuations: ± 5%
-No seasonal adjustments.</td><td>No risk of mechanical damage to most artefacts and paintings.</td></tr>
<tr><td rowspan="2">Class A</td><td>As</td><td rowspan="2">-Short fluctuations: ±2°C
-Seasonal adjustments: +5°C,-10°C</td><td>-Short fluctuations: ± 5%
-Seasonal adjustments: ±10%</td><td rowspan="2">Small risk of mechanical damage to high vulnerability artefacts; no mechanical risk to most artefacts, paintings, photographs, and books.</td></tr>
<tr><td>A</td><td>-Short fluctuations: ± 10%.
-Seasonal adjustments: No variation.</td></tr>
<tr><td colspan="2">Class B</td><td>-Short fluctuations: ±5°C
-Seasonal adjustments: +5°C,-10°C</td><td>-Short fluctuations: ± 10%
-Seasonal adjustments: ±10%</td><td>Moderate risk of mechanical damage to high-vulnerability artefacts; tiny risk to most paintings and photographs</td></tr>
</table>

				and no risk to most artefacts and books.
	Class C	Not over 30°C	Between 25-75%	High risk of mechanical damage to high vulnerability artefacts; moderate risk to most paintings, photographs, and tiny risk to most artefacts and books.
	Class D		Below 75%	High risk of sudden or cumulative mechanical damage to most artefacts and paintings due to low humidity fracture, but high humidity delamination and deformations. Mould growth and rapid corrosion avoided.

The guidelines provide a textual relationship between the level of risk (i.e., environmental states) and environmental parameters. Most of the guidelines use an interdependent relationship of the absolute value and their variations of several environmental parameters such as temperature and relative humidity. For example, the Thomson guideline specifies two classes: (1) a class that assumes the presence of a heating, ventilation and air conditioning system (e.g., in large museums), and (2) a class to avoid major danger (e.g., in historic houses and churches). In both cases the classifying criteria comes from the simultaneous behaviour of temperature, relative humidity and their fluctuation. Thomson explicitly recommended that the thresholds should vary depending on the climate zone, seasonal variations, type of buildings. Unfortunately, this recommendation is often neglected and the guidelines are interpreted in a straightforward way [42].

2.2.4 DETERMINING THE IAQ-INDEX

For every data point in the data stream, the corresponding IAQ-index is calculated. The IAQ-index does not only summarize all measurements that correspond with the data point, it also gives the corresponding assessment. This transformation is based on a specific guideline or norm where the textual descriptions has been converted into logical expressions. The guidelines provide criteria to classify the behaviour of some environmental parameters as hazardous or innocuous for conservation purposes. With that information, we defined a numerical IAQ-index that would reach its minimum value when the conditions would most likely lead to material damage or degradation and would get its maximum when the environmental parameters reached values recommended for proper conservation.

The IAQ-index is a quantity with a value that can vary from 0 (unacceptable risk for deterioration of a heritage collection due to an aggressive environment) to 1 (excellent environmental conditions with acceptable risk). In order to correlate the data streams of temperature and relative humidity to the IAQ-index, the standards summarized in Table 2.1 have been used.

The target values and relationships presented in Table 2.1 define the quality criteria to estimate the IAQ-index. The textual relationships on these quality criteria must be formalized into conditional statements in order to evaluate the measuring points that are collected every 15 minutes. This results in a multistage decision making process, that can be implemented by means of a Decision Tree Classifier [33, 34]. Decision Tree Classifiers break down complex decision-making processes into a collection of simpler decisions, and provide a solution which is often easier to interpret. Their complexity depends on the number of nodes, or class labels, and branches representing conjunctions of features that lead to those class labels. Figure 2.1 presents the two Decision Trees resulting from the interpretation of the Thomson and ASHRAE standards.

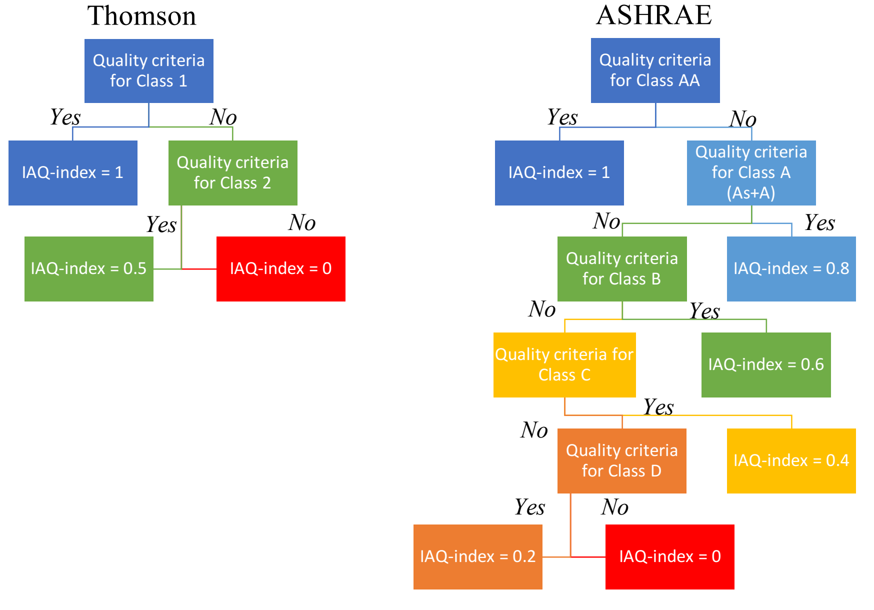


Figure 2.11 Decision Trees Classifiers for the IAQ-index.

In principle, the descriptions in the guidelines, norms and standards contain all the required information to define the conditional statements. However, even for the fairly easy example of the Thomson guideline there are some interpretation issues. For example, the distinction between summer and winter. To tackle this issue, the average temperature is calculated for a complete year that contains all seasons. For temperature below that average the winter conditions are used while in the case of temperature above the average the summer conditions are used.

The IAQ-index = 1 when the temperature is within the given range 18°C-20°C or 23°C-25°C and the relative humidity falls within the range 40%-70%. If the environmental conditions are outside that range but relative humidity is still inside the range 40%-70%

then IAQ-index is set to 0.5. This is a transition state between acceptable and inacceptable risk and a level of risk had to be attributed to that state. For all other situations, IAQ-index = 0. The major advantage of this approach is that the conditional statements can be applied to every measuring point in the data matrix so that the evolution of risk R (IAQ-index = 1 – R) over time can be visualised. In addition, the assessments are reproducible so that different moments in time can easily be compared with each other.

The direct translation of the textual relationships mentioned in the Thomson guidelines into pseudocode statements is presented in Table 2.2, while the direct MATLAB code is presented in Figure 2.2. This interpretation results in a discrete IAQ-index that can only take three possible values, defining the step-like surface like the one presented in Figure 2.3.

Table 2.2. Overview of the conditional statements of the Thomson guidelines translated to pseudocode.

Quality Indicator	Quality judgement	Relation between quality indicator and quality judgement
T(i): Temperature at moment i. T_{ave}: Average temperature. RH(i): Relative humidity at moment i.	IAQ(i): Corresponding general quality IAQ-index.	IF 40%<=RH(i)<=70% AND T(i)<T_{ave} AND T(i) ≥ 19℃ ±1℃: THEN IAQ(i) = 1 ELSE IF 40%<=RH(i)<=70% AND T(i)>=T_{ave} AND T(i) ≥ 24℃ ±1℃: THEN IAQ(i) = 1 ELSE IF 40%<=RH(i)<=70%: THEN IAQ(i) = 0.5 ELSE IAQ(i) = 0

```
%% IAQ Thomson
T_ave = mean(T);
iaq_thomson = zeros(size(data));

for i=1:size(data)
 if 40<= RH(i) && RH (i)<=70 && T(i)<T_ave && 18<=T(i)&& T(i)<=20
    iaq_thomson (i)= 1;
 elseif 40<=RH(i) && RH(i)<=70 && T(i)>=T_ave && 23<=T(i) && T(i)<=25
   iaq_thomson(i)= 1;
 elseif 40<=RH(i)&& RH(i)<=70
   iaq_thomson(i)= 0.5;
 else
   iaq_thomson(i)= 0;
 end
end
```
Figure 2.2. MATLAB code defining the IAQ-index based on Thomson.

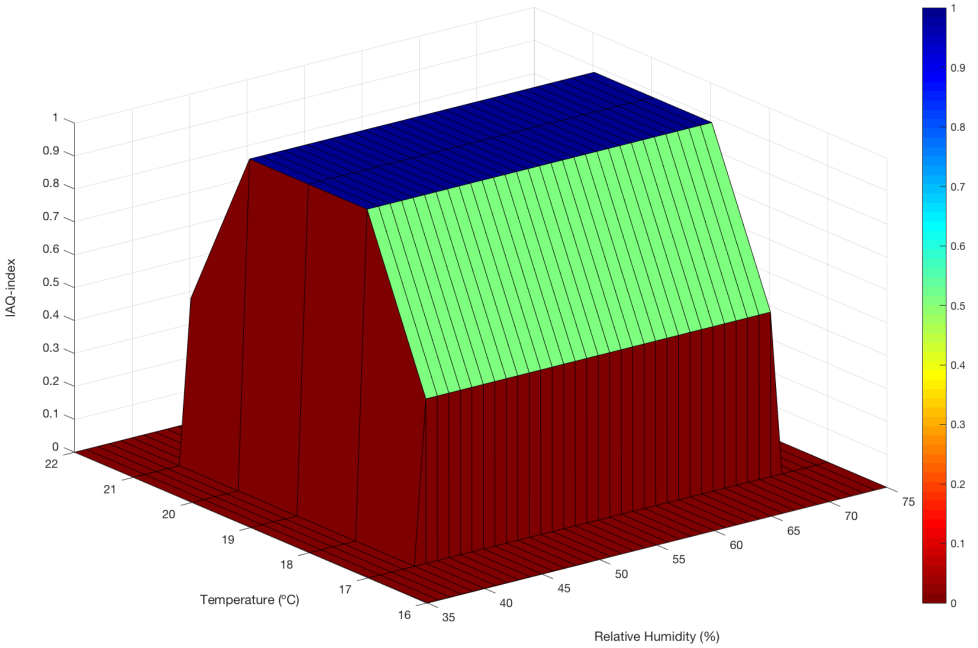


Figure 2.3. Surface defined by the discrete IAQ-index based on the Thomson guidelines for winter.

The ASHRAE guidelines describe the correlation of 5 quality categories (classes AA, A with subdivisions AS and A, B, C, and D; where AA corresponds to the lowest level of risk and D to the highest). 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. In this case, the translation into an IAQ-index results in an index with 6 possible values: IAQ-index = 1 for the situations corresponding to the AA classification, IAQ-index = 0.8 for class A, IAQ-index = 0.6 for class B, IAQ-index = 0.4 for class C, IAQ-index = 0.2 for class D, and IAQ-index = 0 for those situations implying even a higher risk than class D.

Boundary conditions for several frequency ranges are combined: (1) the average situation of the complete measuring period of at least 1 year, (2) the long-term or seasonal fluctuations, and (3) short-term fluctuations. In addition, the target values are based on interdependent relationships of temperature and relative humidity. It is necessary to consult a full year of collected data to directly implement the first two considerations. Like in the case for the Thomson interpretation, here we differentiated winter from summer by comparing the individual values of temperature with the annual average. For the short term fluctuations, we considered a maximum deviation inside a 24-hour window. This time window is mentioned as the typical short-time period for several guidelines and the most accepted for general purposes in heritage studies [42].

Table 2.3. Overview of the conditional statements of the ASHRAE guidelines translated to pseudocode.

Quality Indicator	Quality judgement	Relation between quality indicator and quality judgement
T(i): Temperature at moment i. T_{ave}: Average temperature. $T_{24hdif}(i)$: Maximum fluctuation in temperature in 24 hours prior to moment i. RH(i): Relative humidity at moment i. RH_{ave}: Average relative humidity. $RH_{24hdif}(i)$: Maximum fluctuation in relative humidity in 24 hours prior to moment i.	IAQ(i): Corresponding general quality judgement.	IF $T(i)<T_{ave}$ AND $T_{ave}-T(i)<=5$ºC AND $T_{24hdif}(i)<=2$ºC AND 15ºC$<=T_{ave}<=$25ºC AND $RH_{24hdif}<=5\%$ IAQ(i) = 1; ELSE IF $T(i)>=T_{ave}$ AND $T(i)-T_{ave}<=5$ºC AND $T_{24hdif}(i)<=2$ºC AND 15ºC$<=T_{ave}<=$25ºC AND $RH_{24hdif}<=5\%$ IAQ(i) = 1; ELSE IF $T(i)<T_{ave}$ AND $T_{ave}-T(i)<=10$ºC AND $T_{24hdif}(i)<=2$ºC AND 15ºC$<=T_{ave}<=$25ºC AND $\lvert RH_{ave}-RH(i)\rvert<=10\%$ AND $RH_{24hdif}<=5\%$ IAQ(i) = 0.8; ELSE IF $T(i)>=T_{ave}$ AND $T(i)-T_{ave}<=5$ºC AND $T_{24hdif}(i)<=2$ºC AND 15ºC$<=T_{ave}<=$25ºC AND $\lvert RH_{ave}-RH(i)\rvert<=10\%$ AND $RH_{24hdif}<=5\%$ IAQ(i) = 0.8; ELSE IF $T(i)<T_{ave}$ AND $T_{ave}-T(i)<=10$ºC AND $T_{24hdif}(i)<=2$ºC AND 15ºC$<=T_{ave}<=$25ºC AND $RH_{24hdif}<=10\%$ IAQ(i) = 0.8; ELSE IF $T(i)>=T_{ave}$ AND $T(i)-T_{ave}<=5$ºC AND $T_{24hdif}(i)<=2$ºC AND 15ºC$<=T_{ave}<=$25ºC AND $RH_{24hdif}<=10\%$ IAQ(i) = 0.8 ELSE IF $T(i)<T_{ave}$ AND $T_{ave}-T(i)<=10$ºC AND $T_{24hdif}(i)<=2$ºC AND 15ºC$<=T_{ave}<=$25ºC AND $\lvert RH_{ave}-RH(i)\rvert<=10\%$ AND $RH_{24hdif}<=10\%$ IAQ(i) = 0.6; ELSE IF $T(i)>=T_{ave}$ AND $T(i)-T_{ave}<=5$ºC AND $T_{24hdif}(i)<=2$ºC AND 15ºC$<=T_{ave}<=$25ºC AND $\lvert RH_{ave}-RH(i)\rvert<=10\%$ AND $RH_{24hdif}<=10\%$ IAQ(i) = 0.6; ELSE IF $25\%<RH(i)<75\%$ AND $T(i)<=30$ºC IAQ(i) = 0.4; ELSE IF $RH(i)<75\%$ AND $T(i)<30$ºC IAQ(i) = 0.2; ELSE: IAQ(i) = 0

The direct translation of the textual relationships mentioned in the ASHRAE guidelines into pseudocode statements is presented in Table 2.3, while the direct MATLAB code is presented in Figure 2.4.

```
%% IAQ ASHRAE
T_ave = nanmean(T);
RH_ave = nanmean(RH);

iaq_ashrae = zeros(size(Date));
T24hdif = zeros(size(Date));
RH24hdif = zeros(size(Date));

for j=97:size(Date)
 T24hdif(j) = max(T(j-96:j)) - min(T(j-96:j));
 RH24hdif(j) = max(RH(j-96:j)) - min(RH(j-96:j));
end

for i=1:size(Date)
 if  T(i)<T_ave && T_ave-T(i)<=5 && T24hdif(i)<=2 && 15<=T_ave && T_ave<=25 && RH24hdif<=5
   IAQ(i) = 1;
 elseif  T(i)>=T_ave && T(i)- T_ave<=5 && T24hdif(i)<=2 && 15<=T_ave && T_ave<=25 &&
RH24hdif<=5
   IAQ(i) = 1;
 elseif  T(i)<T_ave && T_ave-T(i)<=10 && T24hdif(i)<=2 && 15<=T_ave && T_ave<=25 &&
abs(RH_ave-RH(i))<=10 && RH24hdif<=5
   IAQ(i) = 0.8;
 elseif  T(i)>=T_ave && T(i)- T_ave<=5 && T24hdif(i)<=2 && 15<=T_ave && T_ave<=25 &&
abs(RH_ave-RH(i))<=10 && RH24hdif<=5
   IAQ(i) = 0.8;
 elseif  T(i)<T_ave && T_ave-T(i)<=10 && T24hdif(i)<=2 && 15<=T_ave && T_ave<=25 &&
RH24hdif<=10
   IAQ(i) = 0.8;
 elseif  T(i)>=T_ave && T(i)- T_ave<=5 && T24hdif(i)<=2 && 15<=T_ave && T_ave<=25 &&
RH24hdif<=10
   IAQ(i) = 0.8;
 elseif  T(i)<T_ave && T_ave-T(i)<=10 && T24hdif(i)<=2 && 15<=T_ave && T_ave<=25 &&
abs(RH_ave-RH(i))<=10 && RH24hdif<=10
   IAQ(i) = 0.6;
 elseif  T(i)>=T_ave && T(i)- T_ave<=5 && T24hdif(i)<=2 && 15<=T_ave && T_ave<=25 &&
abs(RH_ave-RH(i))<=10 && RH24hdif<=
   IAQ(i) = 0.6;
 elseif  25<RH(i) && RH(i)<75 && T(i)<=30
   IAQ(i) = 0.4;
 elseif  RH(i)<75 && T(i)<30
   IAQ(i) = 0.2;
 else
   IAQ(i) = 0;
 end
end
```

Figure 2.4. MATLAB code defining the IAQ-index based on ASHRAE.

2.2.5 IAQ-INDEX WITH STATISTICAL DATA

As we already mentioned in previous sections, the IAQ is not only affected by the absolute value of relevant environmental parameters. Their average values and fluctuations, either for a short period or linked to the seasonal transition, can have a severe impact on the degradation process of heritage objects. Therefore, taking into consideration a more consistent statistical approach to analyse the environmental data will result in a more reliable assessment of the IAQ. This approach was already successfully applied for indoor climate studies based on the ASHRAE standards by Martens, with extensive acceptation in the heritage community [28]. Considering this, we are presenting in this section some of the most relevant statistical characteristics of the environmental data and their influence in the IAQ-index.

Measurements Errors:

The most extreme values are filtered out to reduce the influence of instrumental errors or similar anomalies. To do this the valid data is taken in the range from 0.1 to 99.9 % of the entire data set.

Annual Average:

The annual average value is calculated by determining the mean value of an environmental parameter regularly measured over a year. If we consider that the parameter X was measured n times during a year, then the annual average ($\bar{X}$) would be defined by the following expression:

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X$$

Seasonal Fluctuations:

To calculate the seasonal fluctuations, we first calculate the running average value over a centred window of three months. Considering m the number of data points in a three-month window centred at the instant j, the expression to calculate the running average $X_r(j)$ is:

$$X_r(j) = \frac{1}{m}\sum_{z=j-m/2}^{j+m/2} X(z)$$

Once the running average is calculated for all the dataset, it is possible to determine the maximum seasonal rise and drop of the parameter under study. The seasonal rise is defined by the difference between the maximum value in the running average and the annual average: $X_{rise} = max(X_r) - \bar{X}$; while the seasonal drop is determined by the difference between the annual mean and the minimum running average: $X_{drop} = \bar{X} - min(X_r)$.

Short Fluctuations:

In section 2.2.4 we already presented the short fluctuations as the maximum fluctuation of the parameter in a short period (24 hours in our case) prior to moment j. Its value is determined by the difference between the maximum and minimum reached over the short period of interest:

$$\Delta X_{short}(j) = max[X(j-m), \dots, X(j)] - min[X(j-m), \dots, X(j)]$$

Impact on the IAQ-index:

Including these statistical characteristics in the interpretation of the quality criteria results in a different assessment of the IAQ-index. Despite maintaining the original structure of the Decision Tree Classifier, the statistical nature of the analysed magnitudes will yield different results when compared to the version presented in 2.2.4. In this new case, the absolute value of the magnitude will not be as relevant as before, since now the collective behaviour of the data points grouped in the same moving window will play a crucial role determining the running average of the corresponding instant. The acceptable short fluctuations now establish a bandwidth for allowed values above and below the curve of the running average, while in the previous case the bandwidth was centred on the corresponding absolute value of the measured magnitude. Furthermore, the maximum and minimum recommended seasonal changes are now defined by both the annual average and the seasonal allowed shifts [28].

Regardless of these differences in the IAQ-index evaluation, both versions of the model should concur in the classification of scenarios with higher degradations risk. In some cases, it will be possible to identify more extensive periods of risk with this second version, due to the impact of extremely dangerous periods included in the range of the moving average. However, these most critical periods will still correspond to those detected with the previous method. The statistical interpretation of the data does not affect the specific quality criteria defining IAQ-index=0, and consequently, a situation classified with IAQ-index=0 by the direct interpretation will always also be classified in the same way despite of including the statistical analysis of the data.

2.2.6 VISUALIZING THE IAQ-INDEX

Intuitive visualization of the IAQ-index is provided through a graphical representation based on colour codes. For this purpose, we use the reverse Jet colour map, comprising a range of 100 different colour combinations, individually assigned to discrete values of the IAQ-index with a resolution of 0.01 (See Figure 2.5). The colour red is assigned to the lowest IAQ values since it is intuitively coupled to danger [43].

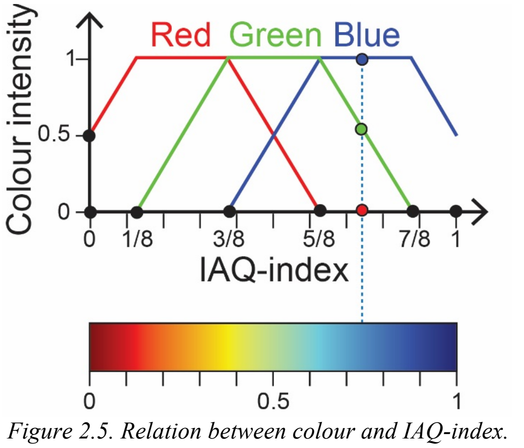


Figure 2.5. Relation between colour and IAQ-index.

2.3 RESULTS

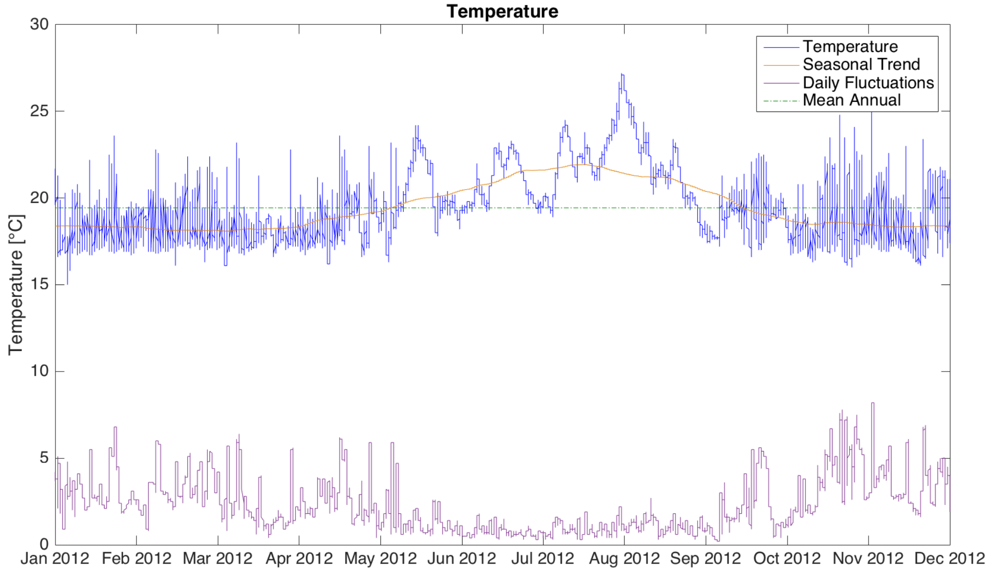
The behaviour of T and RH over time is presented in Figure 2.6 along with their corresponding seasonal trend, mean annual and daily fluctuations. The T oscillates from 15°C to 27.2°C with an annual average of 19.4°C, while RH goes from 18.2% to 76.8% and its annual average is 54.1%. In both cases, the short time fluctuations are notably large with a mean value of 2.4°C for T and a maximum value of 8.2°C, and 8.3% RH reaching up to 25.1%.

Despite the additional information about seasonal trend, mean annual and daily fluctuations, it is hard to understand how harmful the environment is by looking at the graphs. The graphs show considerable fluctuations so that the extremely harmful period in February where the climate system was broken is somewhat hidden in the harmless fluctuations (see the sudden drop in RH). In addition, in order to evaluate the aggressiveness of the environmental conditions it is necessary to simultaneously consider the results presented in both graphs. The individual behaviour of each parameter will directly influence the assessment of the IAQ. Having only one of the parameters studied surpassing the established thresholds is enough to classify a situation as a possible degradation risk condition.

The same data streams presented in Figure 2.6 can be summarized in any of the proposed IAQ-indices. The representation of the IAQ-index using a scale of colours is presented in Figure 2.6. In the case considering the ASHRAE set of thresholds we observe periods of high risk of degradation in February and during shorter periods of July and October. This high risk of degradation match with periods in Figure 2.1 where the T and/or RH exceed the threshold values established at the ASHRAE classes.

For example, during February RH drastically decreased below 25%, which is the limit established to prevent all high-risk extremes (Table 2.1). In July and October, RH exceeded 75% implying a dampness risk. This approach shows that non-experts are able to evaluate the air aggressiveness towards heritage collections. Once a harmful period is identified, heritage caretakers could go back to Figure 2.6 to understand the cause of the problem. This means, that the reading of the graphs in Figure 2.6 can be guided by the ones in Figure 2.7.

a)



b)

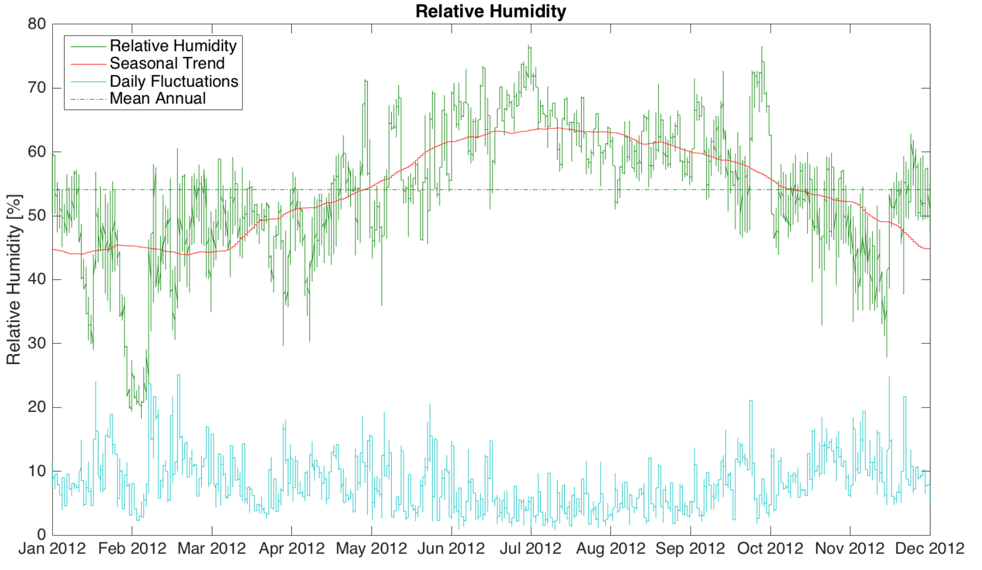


Figure 2.6. a) Data stream for the temperature over time together with the mean annual and seasonal trend and short time fluctuations. b) Data stream of the relative humidity over time with the mean annual and seasonal trend and short time fluctuations

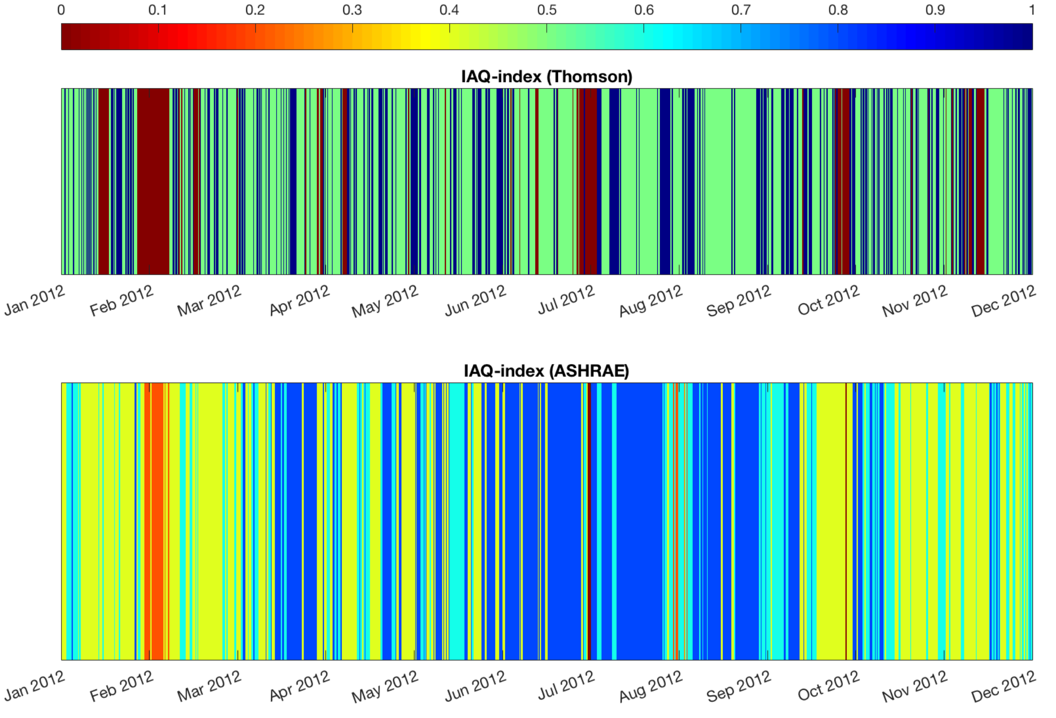


Figure 2.7. IAQ-index over time constructed with the ASHRAE and Thomson standards.

The results presented in Figure 2.7 clearly shows that both standards do not result in the same classification of the air aggressiveness. The IAQ-index calculated considering the Thomson standards shows more extended and frequent periods of risk. This was expected due to the use of narrower ranges of thresholds and disregard of the seasonal variations that demand an almost constant T in each season. The periods marked as dangerous with the IAQ-index using the ASHRAE standards are comprehended inside the regions of low IAQ-index when using the Thomson set of thresholds. This means that the standards determine differently the overall extent of air aggressiveness, although both of them identify similar short-time periods as dangerous.

Figure 2.8 presents the results obtained with the statistical characterisation of the environmental data. There are marked differences in the classification of the IAQ-index when compared to Figure 2.7. For the Thomson guidelines, there is a distinct shift in the classification of the periods of lower risk, while for ASHRAE there is a generally better classification of the indoor environment. However, there are also consistent similarities between the two sets of results. Like in the previous figure, the IAQ-index calculated applying Thomson standards shows larger and more frequent periods of risk. The index based on ASHRAE reflects a more positive depiction of the overall situation, with periods of higher risk comprehended inside the regions of low IAQ-index detected with Thomson guidelines. Furthermore, the periods of higher degradation risk remain the same in Figure 2.7 and 2.8, reflecting the expected consistent classification of the lower IAQ-index despite the introduction or not of the statistical characterisation of the data.

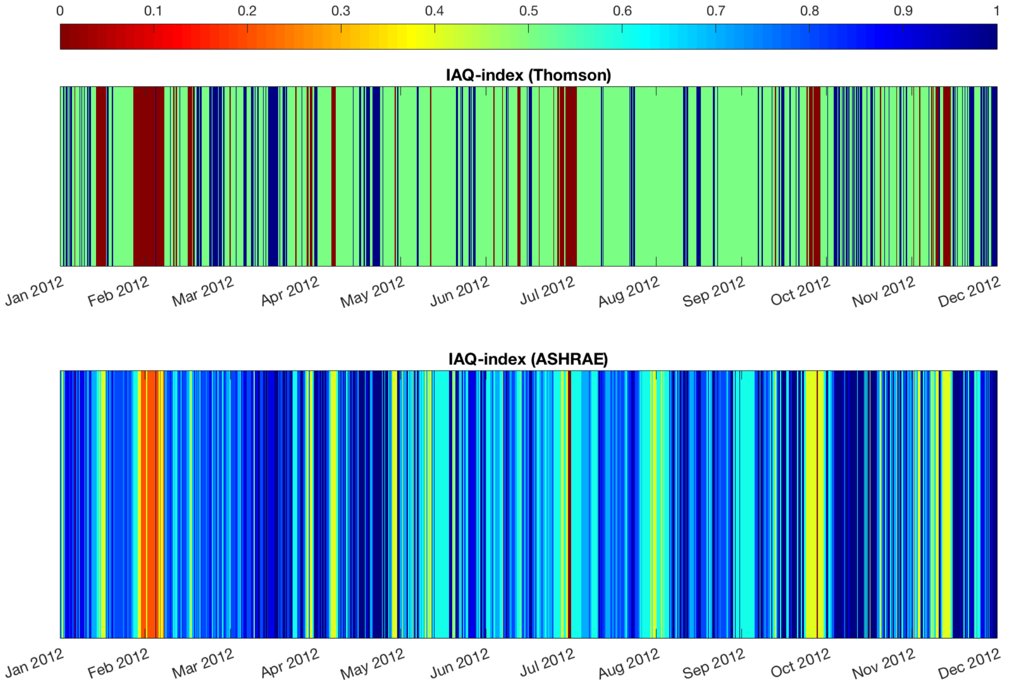


Figure 2.8. IAQ-index based on the statistical interpretation of the data for ASHRAE and Thomson standards.

2.4 DISCUSSION

The IAQ-index presented in this work offers the opportunity to easily identify periods inside large data sets where a clear risk of damage appeared. It can also be used to detect a tendency to approach to the safety limits before the actual risk becomes possible. The IAQ-index has the advantage of being comprehensible even for heritage caretakers that are specialized in creating optimal storage conditions but not in the analysis and interpretation of environmental measurements. However, the selection and interpretation of the thresholds has a significant impact in the final outcome, and could potentially mislead the results. For example, our implementation of the same guidelines yielded a considerably different evaluation of the lower risk periods depending on the statistical characterisation or not of the data. The good correspondence of the results for the evaluation of the higher risk validates the accuracy of the Decision Tree Classifiers; however, the marked differences between the rest of the assessment reflect how sensitive the method actually is to interpretation issues.

In the previous section we also showed how, independently of the statistical considerations, the application of the Thomson standards leads to conclude that the collection of interest was at risk during periods that were labelled as relatively safe under the ASHRAE standards. On the other hand, the implementation of the ASHRAE standards requires to acquire a full year of data before performing the analysis which limits one of the more interesting possibilities that the IAQ-index may offer: the opportunity to perform a real-time analysis and therefore detect the tendency to fall in situations involving high risk of degradation before they actually occur.

2.5 CONCLUSIONS

This first simplified version of the IAQ-index demonstrated that it is indeed possible to visualise IAQ assessments in an intuitive and actionable way. All the versions of this discrete index revealed the presence of a large series of smaller moments of inappropriate perseveration conditions, that would have been missed when average parameters would have been used. The application of an IAQ-index indeed simplifies the analysis of large volumes of data, making the IAQ assessment more accessible and less time consuming.

The use of Decision Tree Classifiers for translating the guidelines' textual relationships results in a consistent evaluation of the lowest periods of IAQ. However, subtler details in the interpretation of the quality criteria (like the statistical characterisation of the data) will lead to a different classification of the less extreme periods. The results obtained also exposed the differences in the IAQ-index evaluation depending on the guideline selection. This fact already highlights the impact of the threshold selection in the accuracy of the IAQ-index and highlights the necessity to implement and compare other guidelines. Furthermore, the direct interpretation of the Thomson and ASHRAE can only be applied in cases where is available a full year of environmental data. Short measuring campaigns and systematic in vivo analysis cannot be studied with this specific approach. However, a more flexible interpretation of these standards or the implementation of different guidelines can solve this issue.

Another limitation of the presented method is that only two environmental parameters, temperature and relative humidity, are considered. A more reliable IAQ-index must include as well other environmental parameters, such as light, ultraviolet radiation, particulate matter or reactive gases to provide a more accurate IAQ assessment.

CHAPTER 3

INDOOR AIR QUALITY ASSESSMENT ON BROAD INTERPRETATION OF GUIDELINES

Based on:

Mathematical Assessment of Indoor Air Quality Evolution for Preventive Cultural Heritage Conservation
Diana Leyva, Serge Demeyer, Olivier Schalm, Willemien Anaf
Submitted to Building and Environment, The International Journal of Building Science and its Applications

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ABSTRACT

In the previous chapter we presented the development of a first version of an IAQ-index based on the direct interpretation of the Thomson and ASHRAE standards. Despite of providing a more intuitive and actionable representation the IAQ assessment, the method involved some limitations, such as the necessity of a full year of measured data and the restricted number of environmental parameters considered. To tackle these, we now present a new continuous version of the IAQ-index, suitable for the analysis of short measuring campaigns and combining the data from four environmental parameters to assess the global environmental risk for a given collection as a function of time. We demonstrate on one realistic case how we use this index to visualise the evolution of the air quality, detect periods where the collection was at risk and identify the causal factors for the potential degradation.

3.1. INTRODUCTION

Preventive conservation is the most effective method in promoting the long-term preservation of cultural heritage [20]. The exposure of cultural heritage to the environment has a lasting impact on the degradation process and degradation rate of any material. Hence, controlling the indoor air quality (IAQ) is critical to avoid further damage to historic artefacts and works of art [44].

Considering that evidence-based decision making is fundamental for preventive conservation it would be interesting to detect and track potentially hazardous incidents in the history of a collection. However, collection caretakers are not experts in processing and interpreting large amounts of environmental data. The amount of data under analysis is affected by three factors (a) the number of environmental parameters under analysis; (b) the frequency of data input; (c) the length of the measuring campaign. Since the latter is the easiest to reduce, collection caretakers prefer short measurement campaigns revealing actionable insights in potentially hazardous situations.

Existing standards and guidelines can be used to convert the large amount of measurements into more meaningful information. Such approach has already been successfully implemented in the heritage community by Martens using a dynamic interpretation of the ASHRAE climate classes [12, 28]. Nevertheless, this method has its limitations. It only considers temperature and relative humidity, requires a full year of collected data and does not incorporate an analysis of the temporal evolution of the parameters.

We propose a versatile IAQ-index, combining all the parameters of interest into a single value that represents the degree of air aggressiveness for collections as a function of time. The calculation of this IAQ-index is based on existing standards while its evolution is visualised using colour bars. With the proposed approach, even non-experts would be able to quickly assess data streams for longer measuring periods and detect immediately when the environmental conditions become harmful. In this paper, we consider temperature, relative humidity, illuminance and ultraviolet radiation, although our approach can be expanded for other parameters such as particulate matter, and gaseous pollutants. The environmental guidelines selected for temperature and relative humidity were the Bizot Interim Guidelines for Hygroscopic Materials, while for illuminance and ultraviolet radiation the thresholds recommended to sensitive collections were considered [6, 45, 46].

3.2. MATERIALS AND METHODS

3.2.1. RELATED WORK

Environmental standards are not unknown to the cultural heritage conservation community. Sets of thresholds have already been applied for controlling temperature and relative humidity since the end of last century. In general, all these standards are essentially a large decision tree where the relationships between the parameters are complex and the definition of thresholds is critical.

One of the most recognized and applied standards was the Thomson standard [11]. The Thomson standard specifies two classes: one that assumes the presence of a heating, ventilation and air conditioning system (e.g., in large museums), the other to avoid major danger (e.g., in historic houses and churches). In both cases the classifying criteria comes from the simultaneous behaviour of temperature, relative humidity and their fluctuation. Thomson explicitly recommended that the thresholds should vary depending on the climate zone, seasonal variations, type of buildings. Unfortunately, this recommendation is often neglected and the standards are interpreted in a straightforward way. The most typical interpretation is detailed in Table 2.1.

Compared to the Thomson standard, the ASHRAE standards for 'Museums, Libraries, and Archives' (1999, with revisions in 2003, 2007 and 2011) represent a more up-to-date perspective on the topic [12]. As shown in Table 2.1, five different classes are defined based on the level of risk towards the collection, each considering complex relations between the values of temperature and relative humidity, their fluctuation and their seasonal depending trends. Despite of depicting a more flexible analysis compared with the Thomson standards, its level of complexity in the interdependencies of the analysed parameters increases considerably. An important limitation of the ASHRAE standard is the need for seasonal adjustments which requires a backlog of one year of data to calculate the seasonal fluctuations. Therefore, the ASHRAE standard cannot be used in shorter measuring campaigns aiming for an early detection of a potentially harmful situation.

More recently a new generation of simpler but still effective standards has been adopted by the heritage conservation community, known as the Bizot guidelines. This specific standard is presented as a response to the necessity of reducing the carbon footprints of heritage institutions while providing environmental conditions favourable for preventive preservation [47, 48]. However, the more relaxed nature of the proposed guidelines is contested among certain circles of specialists that consider its application will increase the degradation risk for their collections [49, 50]. In our case, the selection of the Bizot guidelines is mainly based in its considerable differences when compared to Thomson and ASHRAE and is intended to represent an example on the different possibilities found in the literature regarding the definition of standards. Instead of delimiting different classes as done in Thomson and ASHRAE, the Bizot standard presents a series of guidelines that minimize the risk of degradation, for many classes of objects containing hygroscopic material (such as canvas paintings, textiles, ethnographic objects or animal glue). The guidelines state that in such occasion, a stable relative humidity [41] is required in the range of 40–60% and a stable temperature in the range 16–25°C with fluctuations of no more than ±10% RH per 24 hours within this range. Contrary to the ASHRAE standard, the Bizot guidelines does not consider seasonal variations, resulting applicable in cases of shorter measuring campaigns.

3.2.2. CASE STUDY SETUP

To evaluate the effectiveness of the state-of-the-art assessment methods for indoor air quality, we analysed the conditions registered inside the Historical Gallery in the Royal Museum of the Armed Forces and of Military History, Brussels, Belgium. This gallery (Figure 3.1) is dedicated to the Belgian army from 1813 to 1914, containing hundreds of artworks of oil paintings on canvas, costumes, flags, weapons and instruments. The objects are placed in open display on the floor and the walls and in oaken display cases originating from the early 20th century.

Figure 3.1. Historical Gallery, Royal Museum of the Armed Forces and Military History.

In this investigation, four environmental parameters were continuously monitored with a measuring interval of 15 minutes. Commercial sensors were connected to a multi-purpose data logger DT 85 and the data was available online via a 4G network. The temperature and relative humidity were measured with a GMW90R sensor from the company Vaisala, while the illuminance and ultraviolet radiation with the sensors SKL310 and SKU421 from Skye company.

The measurements covered the period from January 21, 2016 up to February 22, 2016 and the data streams consisted of more than three thousand data points. The collection caretakers suspected a serious problem with temperature in this gallery, thus a one-month campaign during winter time was requested. Also, the collection consists of many organic materials, thus is very sensible to light. A short measuring campaign was selected on purpose to decide how urgent the situation was.

3.2.3. DEFINITION OF THE IAQ-INDEX

The IAQ-index is a value that varies from 0 (highest risk) to 1 (lowest risk). This implies that the measurements of temperature, relative humidity, illuminance and ultraviolet radiation must be converted into a single value.

To convert the data streams of temperature and relative humidity to their corresponding parameter-specific IAQ-value, we rely on the Bizot guidelines. Like in the previous chapter, we relay in the use of Decision Trees to represent the textual relations from the guidelines into the quality defining our IAQ index. They state that for many classes of objects containing hygroscopic material (such as canvas paintings, textiles, ethnographic objects) a stable temperature is required in the range 16-25°C and a stable relative humidity in the range of 40-60%, with fluctuations of no more than ±10% relative humidity per 24 hours within this range [12]. This means that temperature within the range of 16-25°C is associated with IAQ_T of 1 and outside that range with $IAQ_T = 0$. For relative humidity, the $IAQ_{RH} = 1$ when the fluctuations are lower than 10% and the relative humidity value lies within the range 40-60%. For illuminance and ultraviolet radiation, the IAQ-index, instead of a range of acceptable values there is only one threshold value above which there is a considerable risk of harming the collection, 50 lx for illuminance and 10 **μ**W/lm for ultraviolet radiation [45]. The use of multiple standards for the definition of the IAQ-index is one of the mayor differences presented in new version of our method. This can be represented as the union of multiple Decision Trees into a larger one, considerably increasing its complexity. As a final step of the new method, all the parameter-specific IAQ-values at a given time are converted into a single value (*the IAQ-index*) by taking the minimum (the highest risk) of all values.

Since the considered guidelines lack any type of subdivision for their classification, the resulting outcome will be a binary index, with a maximum value for the case where all the quality criteria were achieved or a minimum in case of any shortcomings. Such IAQ-index will report a very limited analysis, making impossible any predictive exploration since it would only detect a deviation of the ideal conditions to report the detection of the worst case scenario. To tackle this issue, we also propose in a broader interpretation of the guidelines for the construction of our new model. In this case, instead of representing the quality criteria relation by means of a Decision Tree Classifier we propose the use of a Regression Tree, where the classification will depend of continuous functions instead of discrete range of values. The implementation of this version of the model results in a more detailed description of the IAQ evolution, but also involves a less strict interpretation of the guidelines. Given that this new continuous index already requires further assumptions than in the previous cases, and that Bizot does not consider any seasonal influence, we are not including in this version the statistical characterization of the data. A general representation of the applied method can be found at Table 3.1.

To visualise the evolution of the IAQ-index through time we adopt a colour bar with a scale of colours varying from red to blue [23]. All the data streams processing, IAQ-index calculations and the graphics construction were performed using MATLAB R2015b.

3.3. RESULTS AND DISCUSSION

3.3.1. TRADITIONAL ASSESSMENT

The traditional assessment of the environmental data is based on the interpretation of regular profile graphs. Following this same approach, the behaviour of temperature, relative humidity, light and UV radiation over time is presented in Figure 3.2. The graphs show considerable fluctuations. The temperature oscillates from 17.72°C to 22.57°C, while relative humidity goes from 22.83% to 48.02% with a daily fluctuation reaching up to 19.64%. Light fluctuated from 0 to 292.4 lux and UV from 0 to 431.38 μW/lm. It is hard to understand directly from this standard how harmful the environment is. This can be facilitated by adding the thresholds as yardsticks in the graphs that demarcate the safe regions.

A direct comparison of graphs visualizing the trends of environmental parameters and the corresponding criteria is not always easy. For example, fluctuations of no more than ±10% relative humidity per 24 hours for every data point are complex to represent using yardsticks. In the case that 75% of the data points pass all imposed criteria, can the heritage caretaker consider the analysed location as safe for his collection or not? Should he perform corrective actions and, if yes, which ones? The traditional assessment leaves too many situations open to subjective interpretation. It fails to directly provide a standard way to assess every parameter, does not include the interrelationships of the parameters, and in the cases of the daily fluctuations requires lots of additional calculations.

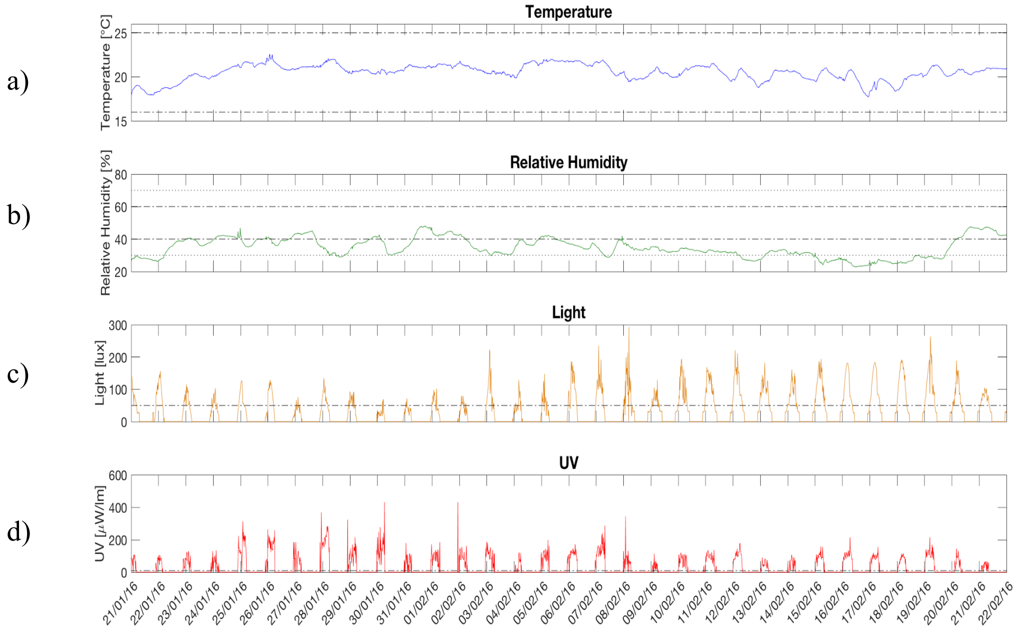

Figure 3.2. a) Data stream for the temperature over time, b) relative humidity, c) light and d) ultraviolet radiation.

3.3.2. ASSESSMENT VIA THE IAQ-INDEX

The same data streams presented in Figure 3.2 could be summarized in a single parameter: the IAQ-index. The representation of the IAQ-index using a colour scale is presented in Figure 3.3. In this case, we observe several periods of high risk in the course of the one month of measurements. These events of high risk, marked in red, usually are preceded by a transition from illuminance blue or green to yellow, representing the gradual decrement in the environmental conditions. Once a harmful period is identified, collection caretakers could go back to Figure 3.2 to understand the cause of the problem, directly analyse the parameter-specific components (Figure 3.4) for an easier interpretation, or study the measuring location on site in a dedicated way.

Table 3.1. Description of the relation between environmental parameters used to estimate indoor air quality and the corresponding quality judgement as described by IAQ-indices. The conditional statements are derived from the guidelines.

Quality Indicator	Quality judgement	Relation between quality indicator and quality judgement
$T(i)$: Temperature at moment i.	$IAQ_T(i)$: Corresponding quality judgement based on temperature only.	IF $T(i) \geq 16℃$ AND $T(i) \leq 25℃$ THEN $IAQ_T(i) = 1$ ELSE $IAQ_T(i) = 0$
$RH(i)$: Relative humidity at moment i. $RH_{24hdif}(i)$: Maximum fluctuation in RH in 24 hours prior to moment i.	$IAQ_{RH}(i)$: Corresponding quality judgement based on relative humidity.	IF $RH_{24hdif}(i) > 10\%$ THEN $IAQ_{RH}(i)=0$ ELSE IF $RH(i) \geq 40\%$ AND $RH(i) \leq 60\%$ THEN $IAQ_{RH}(i) = 1$; ELSE IF $RH(i) > 30\%$ AND $RH(i) < 40\%$ THEN $IAQ_{RH}(i) = 0.01*RH(i) - 3$ ELSE IF $RH(i) > 60\%$ AND $RH(i) < 70\%$ THEN $IAQ_{RH}(i) = -0.01*RH(i) + 7$; ELSE $IAQ_{RH}(i)=0$
$LUM(i)$: Illuminance at moment i.	$IAQ_{lum}(i)$: Corresponding quality judgement based on relative humidity.	IF $LUM(i) \leq 50$ lux THEN $IAQ_{lum}(i) = 1$; ELSE $IAQ_{lum}(i) = 0$;
$UV(i)$: Ultraviolet radiation at moment i.	$IAQ_{UV}(i)$: Corresponding quality judgement based on relative humidity.	IF $UV(i) \leq 10$ μW/lm THEN $IAQ_{UV}(i) = 1$; ELSE $IAQ_{UV}(i) = 0$;
	IAQ: Quality judgement by considering all quality indicators.	IAQ = Minimum of a set of elements (IAQ_T, IAQ_{RH}, IAQ_{lum}, IAQ_{UV})

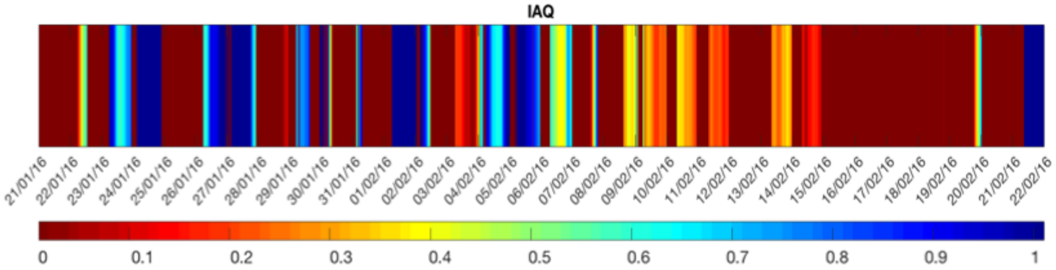

Figure 3.3. IAQ-index over time constructed with the Bizot Interim Guidelines for Hygroscopic Materials for temperature and relative humidity and the thresholds for illuminance and ultraviolet radiation recommended for general collections.

The results presented in Figure 3.4 clearly show that main responsible of the risk comes from the behaviour of relative humidity. In a lower degree the ultraviolet radiation also surpasses the recommended thresholds in several moments while, in contrast, illuminance and temperature reflect a more stable and safer behaviour.

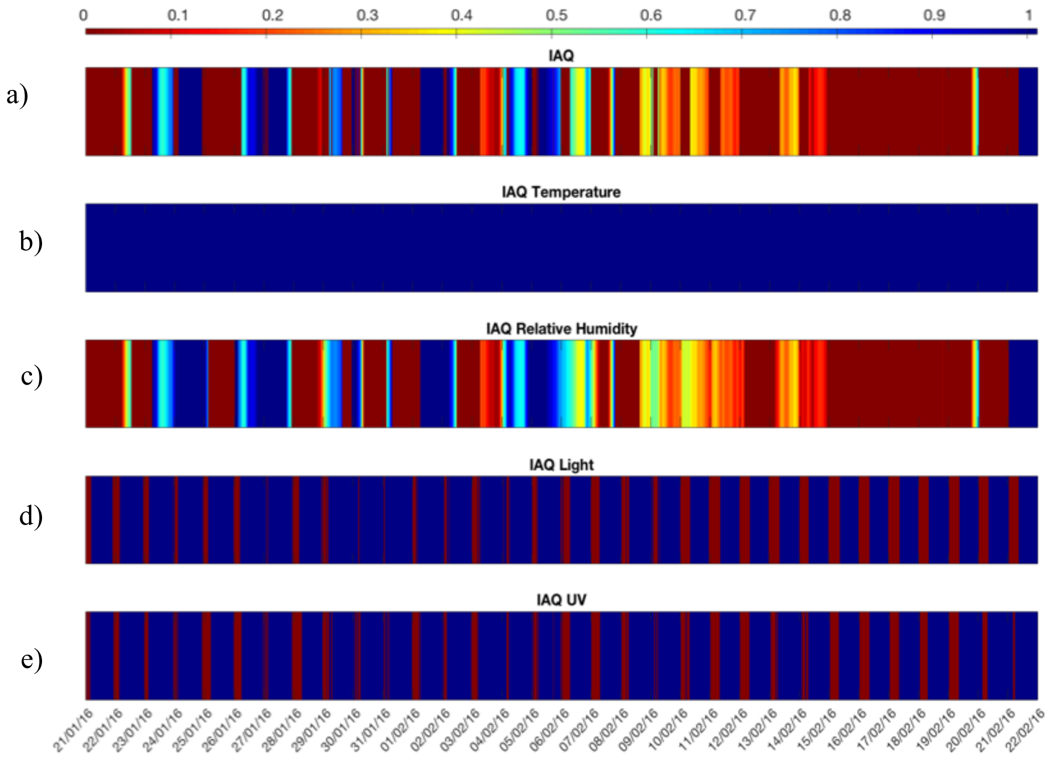

Figure 3.4. a) General IAQ-index and its different parameter-specific components, b) temperature, c) relative humidity, d) illuminance and e) ultraviolet radiation.

The IAQ-index presented in this work offers the opportunity to easily identify periods inside large data sets where a clear risk has appeared. The IAQ-index has the advantage of being comprehensible even for collection caretakers not specialised in analysing large data sets. From the colour bar they know when the environment became a risk for the collection, allowing them to identify the hazards responsible for these situations in a more dedicated way. By focussing on short measuring campaigns they can quickly assess the effect of recently applied mitigation actions, thus performing some cause-effect analysis. This approach does not focus on a pass or fail answer whether the overall environment is satisfactory; it rather allows collection caretakers to systematically improve the environmental conditions by correcting for risky situations that are identified over time.

3.3.3. THREATS TO VALIDITY

As with all empirical research, we identify those factors that may jeopardise the validity of our results and the actions we took to reduce or alleviate the risk. Consistent with the guidelines for case study research (see [51]), we organise them into four categories.

(a) Construct validity: do we measure what was intended?
The IAQ-index relies on externally defined thresholds to assess whether a given situation represents a risk for the collection. We relied on published standards (in our case the Bizot Guidelines). If needed it could be easily switch to other standards. The very act of defining a threshold implies the risk of false positives or false negatives, however by relying on external standards we minimise this risk.
Some of the simplifications made to translate the quality criteria of the guidelines into the IAQ-index definition can also introduce limitations to the validity of the model. That is the case, for example, of visible light and ultraviolet radiation, where we focus our analysis on absolute detection limits instead of dose functions. Previous studies demonstrate how dose functions characterise more accurately the influence of these two environmental parameters on heritage degradation [52]. However, the accurate calculation of the dose received by each object would need to be determined individually, analysing the characteristics and conservation history for every specific case. Considering that most of the institutions involved in our study deal with mixed collections and that there are precedents in the literature on the use of fixed detection limits, our analysis still results valid, but indeed rather general regarding the assessment of light and ultraviolet radiation damage.

(b) Internal validity: are there unknown factors which might affect the outcome of the analyses?
Once we discovered periods where the collection was at risk we tried to identify the causal factors for the potential degradation. We did this by interviewing staff members from the museum which helped us to interpret the fluctuations. Most of these changes could be attributed to a specific cause. Since we relied for this attribution on human judgement, it is possible that other causes might be responsible for these changes, however given the expertise of the museum staff we see this risk as small.

(c) External validity: to what extent is it possible to generalise the findings?
In our study, we analysed four data streams drawn from one measurement campaign in a single location lasting over 4 weeks. Obviously, it remains to be seen whether similar results would hold for other measurement campaigns. The construction of the IAQ-index itself is designed to combine multiple data-streams. However, we still have to actually

validate with sensors measuring material behaviour (wood expansion, metal coupons degradation, etc.) in controlled scenarios.

(d) Reliability: is the result dependent on the instruments and operators?
The measuring system is based on well-calibrated sensors. However, it is possible that visitors or co-workers touch the device, which might result in a slight deviation from the actual values. Manual readout of the monitoring system can disturb the ongoing measurements as well.

All calculations and visualisations involved in this case study have been created in Matlab. The code contains several unit tests and the integrated product has been tested over a period of two years with data from several measurement campaigns; thus the risk of faults in the scripts is small.

3.3.3. FUTURE WORK/POSSIBILITIES?

Additional advantages that can be explored in the future are the development of an early warning system because it is able to detect the increase in risk before it becomes dramatic. In principle, it should also be able to register the improvement of indoor air quality due to corrective actions.

3.4. CONCLUSIONS

The application of the IAQ-index proposed in this chapter simplifies the analysis of large volumes of data, making the indoor air quality assessment in a universal way and more accessible and less time consuming. The results presented demonstrate the possibility of easy detection of potentially hazardous situations, and the identification of the environmental parameter responsible. The presented study sets the basis for the development of an IAQ-index considering as well other environmental parameters, such as particulate matter and reactive gas concentrations and the future implementation of a user friendly software that will directly provide the information of which parameter is affecting the indoor air quality. We aim to develop a final tool that will provide the option of selecting standards and guidelines (e.g., Bizot, AIC Interim Guidelines endorsed by the Association of Art Museum Directors, ASHRAE), or even the option of choosing an own specific input. In this way, collection caretakers can evaluate their environmental data according to their own demands, which largely depend on the type and condition of the building and collection.

CHAPTER 4

IMPACT OF THE GUIDELINES SELECTION FOR INDOOR AIR QUALITY ASSESSMENTS IN CULTURAL HERITAGE PRESERVATION

Based on:
Impact of the guidelines selection for indoor air quality assessments in cultural heritage preservation *(Abstract)*
Diana Leyva Pernia, Willemien Anaf, Olivier Schalm, Serge Demeyer
In Book of Abstracts of IAQ Krakow 2018, 13th International Conference Indoor Air Quality in Heritage and Historic Environments, Krakow, Poland, October 10-12, 2018.

ABSTRACT
After introducing different IAQ-indices based on guidelines interpretation, we have observed discrepancies in the reported assessment. In general, these assessments rely on the comparison of measured environmental data and corresponding acceptable values defined by guidelines or norms. If two different sets of standards classify the same situation with different levels of risk, there will certainly be a discrepancy in their corresponding IAQ assessment. Nowadays, a significant number of different guidelines can be found in literature, and their recommendations do not necessarily concur. Would these differences be also noticeable in the IAQ assessment? How considerable might these variations be? We present in this chapter a study of the impact of the guideline selection in the outcomes of the IAQ assessment. This analysis is focused on five illustrative guidelines that direct their recommendations for temperature and relative humidity. We use datasets from two different measurements campaigns, one held in an exhibition room of a museum and the other held in a late gothic church, both in Belgium.

4.1 INTRODUCTION

It is well known that the environmental conditions have a profound impact on the degradation rate of materials. Consequently, the indoor air quality (IAQ) in a room directly affects the integrity of the objects contained inside [53]. IAQ results especially relevant in the preventive conservation of heritage, a field focussed in extending the life expectancy of cultural heritage by minimizing the alteration of any original features [14]. A good IAQ can decrease the degradation rate of the objects in a collection, prolong their life expectancy and lessen the need for restoration. In contrast, a poor IAQ accelerate degradation, and even result in the permanent damage or loss of some objects. Therefore, with an accurate IAQ assessment it is possible to detect and avoid situations that result in a higher risk of degradation or damage for the objects/materials of interest.

Nowadays most institutions concerned with heritage preservation will monitor, at least to some degree, the indoor environment at their installations. Multiple environmental parameters (such as temperature, relative humidity, illuminance, ultraviolet radiation, particulate matter, and various gaseous pollutants) can be easily monitored, and there is a growing range of devices developed for this specific purpose. These environmental measurements provide a first insight into the IAQ, but they generate overwhelming amounts of data that require further interpretation to obtain a direct IAQ assessment.

The IAQ assessment is most commonly performed by comparing measured environmental data and target values that define a certain acceptable range. Consequently, these target or acceptable values have a significant role in the outcome of the IAQ assessment and their accuracy will directly impact the accuracy of the assessment. Guidelines are usually applied to settle these acceptable values. However, a significant number of guidelines can be already found in the literature, most of them advising different recommendations for the same environmental parameters. Due to these variations, the assessment of the same environmental data set will describe different results depending on which recommendations are being followed. Since most of these studies are performed from a qualitative point of view, it is not evident how much assessment might vary depending on the guideline selection, and consequently, it is not clear their impact in the obtained results.

We present in this paper a case study that reflects how considerable can be the impact of the guideline selection in the outcomes of the IAQ assessment. To evaluate and compare this impact, we use a numerical IAQ-index that varies from 0 to 1 depending on how hazardous or safe the environment might be for heritage conservation. This method has been applied before for different guidelines and presents a quantitative analysis of the IAQ trough time [54, 55]. Our analysis is focused on five illustrative guidelines that direct their recommendations for temperature and relative humidity using datasets from different measurements campaigns.

4.2 MATERIALS AND METHODS

4.2.1. ENVIRONMENTAL GUIDELINES

From the extended list of recommended guidelines for heritage conservation we selected 5 different representative cases:

- The Thomson guidelines [11]:

  They propose two different classifications based on the behaviour of temperature and relative humidity. The class 1 would be appropriate for major national museums and for all important new museum buildings. It recommends keeping the temperature at 19 ± 1°C in winter, and at 24 ± 1°C during summer. For relative humidity they recommend 55 ± 5% (the level may be fixed higher or lower than 55%, but for mixed collections should be in the range 45-60%).

  The class 2 is aimed at avoiding major dangers whilst keeping costs and alteration to a minimum, by recommending a relative stable temperature and a relative humidity between 40-70% (more details in Table 2.1).

- The ASHRAE guidelines for museums and archives [12]:

  The ASHRAE guidelines propose five different classifications according to how safe would the environmental situation be for conservation purposes. The classification considers the dynamic behaviour of temperature and relative humidity, their interrelation, seasonal behaviour and short time fluctuations (more details in Table 2.1).

- The Bizot Interim Guidelines for Hygroscopic Materials [45]:

  For objects containing hygroscopic material (such as canvas paintings, textiles, ethnographic objects or animal glue) they require a stable relative humidity [41] in the range of 40–60% and a stable temperature in the range 16–25°C with fluctuations of no more than ±10% relative humidity per 24 hours within this range.

- The AICCM recommended Interim Temperature and Relative Humidity Guidelines for acceptable storage and display conditions of general collection material [45]:

  The temperature is recommended to remain in the interval of 15–25°C with allowable fluctuations of +/-4°C per 24 hr.

  In the case of the relative humidity, it should be between 45-55% with an allowable fluctuation of +/- 5% per 24 hr.

  Where storage and display environments experience seasonal drift, RH change to be managed gradually across a wider range limited to 40% – 60%.

- EN 15757:2010 Conservation of cultural property – Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials [56]:

  In case of an unstable relative humidity, lower and upper limits of target range of relative humidity fluctuations are determined as the 7th and 93th percentiles of the fluctuations recorded in monitoring period. If fluctuations follow Gaussian distribution, these limits correspond to -1.5 and + 1.5 of the standard deviation.

The guidelines provide a textual relationship between the level of risk (i.e., environmental states) and environmental parameters. Most of the guidelines use an interdependent relationship of the absolute value and their variations of several environmental parameters such as temperature and relative humidity. For example, the Thomson guideline specifies two classes: (1) a class that assumes the presence of a heating, ventilation and air conditioning system (e.g., in large museums), and (2) a class to avoid major danger (e.g., in historic houses and churches). In both cases the classifying criteria comes from the simultaneous behaviour of temperature, relative humidity and their fluctuation. Thomson explicitly recommended that the thresholds should vary depending on the climate zone, seasonal variations, type of buildings. Unfortunately, this recommendation is often neglected and the guidelines are interpreted in a straightforward way.

4.2.2. GENERAL METHOD FOR DETERMINING THE IAQ-INDEX

For every data point in the data stream, the corresponding IAQ-index is calculated. The IAQ-index does not only summarize all measurements that correspond with the data point, it also gives the corresponding judgement. This transformation is based on a specific guideline or norm where the textual descriptions has been converted into logical expressions. The guidelines provide criteria to classify the behaviour of some environmental parameters as hazardous or appropriate for conservation purposes. With that information, we define a numerical IAQ-index that would reach its minimum value (0) when the conditions would most likely lead to material damage or degradation and would get its maximum (1) when the environmental parameters reached values recommended for proper conservation.

The textual relationships must be formalized into conditional statements in order to evaluate the measuring points in a dataset. The major advantage of this approach is that the conditional statements can be applied to every measuring point in the data matrix so that the evolution of risk R (IAQ = 1 – R) over time can be visualised. In addition, the assessments are reproducible so that different moments in time can easily be compared with each other. As presented in Chapters 2 and 3, the formalization can be done by the use of either Classifier Trees obtaining a discrete IAQ-index (Chapter 2), or with Regression Trees resulting in a continuous index (Chapter 3).

Table 4.1The Thomson guidelines written as conditional statements.

Quality Indicator	Quality judgement	Relation between quality indicator and quality judgement
T(i): Temperature at moment i. T_{ave}: Average temperature. RH(i): Relative humidity at moment i.	IAQ(i): Corresponding general quality judgement.	IF 40%<=RH(i)<=70% AND T(i)<T_{ave} AND T(i) ≥ 19℃ ±1℃: THEN IAQT(i) = 1 ELSE IF 40%<=RH(i)<=70% AND T(i)>=T_{ave} AND T(i) ≥ 24℃ ±1℃: THEN IAQT(i) = 1 ELSE IF 40%<=RH(i)<=70%: THEN IAQT(i) = 0.5 ELSE IAQT(i) = 0

In the translation of the Thomson guidelines into conditional statements (see Table 4.1), only 3 environmental states are considered. This results in a discrete function where the IAQ only takes values of 0, 0.5 or 1, resulting in a discrete or "step-like" function where it is not possible to clearly appreciate the evolving transition in between states.

As presented in Chapter 3, the recommendations can be interpreted and applied in a more meaningful way by considering that the IAQ-index varies following some specific behaviour between these states. To accomplish this, we define a linear change in the level of risk between the quality categories. This continuous relationship defined for the

Thomson guidelines can be seen in Figure 4.1, and the new logical statements are presented in Table 4.2.

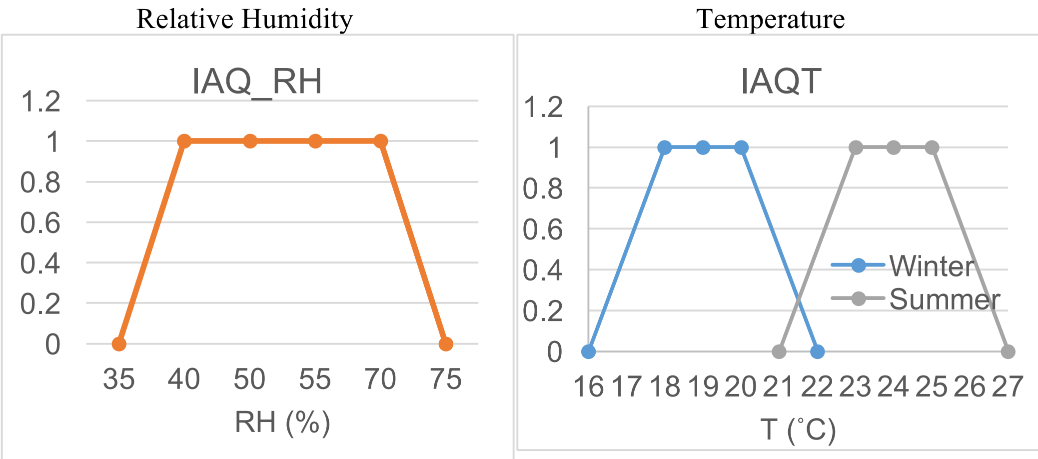

Figure 4.1. Continuous representation of the IAQ-index for relative humidity and temperature based on the Thomson guidelines.

The conversion of textual relationships into conditional statements can be also done for the ASHRAE, Bizot and AICCM guidelines as well. Of all translated standards, the ASHRAE was the most complicated one, since it 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. Boundary conditions for several frequency ranges are combined: (1) the average situation of the complete measuring period of at least 1 year, (2) the long-term fluctuations, and (3) short-term fluctuations. In addition, the target values are based on interdependent relationships of temperature and relationships.

Table 4.2. Conditional statements of Thomson standards for linear transition.

Quality Indicator	Quality judgement	Relation between quality indicator and quality judgement

T(i): Temperature at moment i.
 	
T_{ave}: Average temperature.
	IAQT(i): Corresponding quality judgement based on temperature only.	IF T(i)<T_{ave}:
		  IF 18ºC<=T(i)<=20ºC:
		    IAQT(i) = 100
		  ELSE IF 16ºC<=T(i)<18ºC:
		    IAQT(i) = 0.5*T(i)-8
		  ELSE IF 20ºC<T(i)<=22ºC:
		    IAQT(i) = (-0.5)*T(i)+11
		  ELSE:
		    IAQT(i) = 0
		ELSE IF T(i)>=T_{ave}:
		  IF 23ºC<=T(i)<=25ºC:
		    IAQT(i) = 100
		  ELSE IF 21ºC<=T(i)<23ºC:
		    IAQT(i) = 0.5*T(i)-10.5
		  ELSE IF 25ºC<T(i)<=27ºC:
		    IAQT(i) = (-0.5)*T(i)+13.5
		  ELSE:
		    IAQT(i) = 0

RH(i): Relative humidity at moment i.	IAQRH(i): Corresponding quality judgement based on relative humidity.	IF 40%<=RH(i)<=70%:
		  IAQRH(i) = 100
		ELSE IF 35%<=RH(i)<=40%:
		  IAQRH(i) = 0.5*RH(i)-7
		ELSE IF 70%<RH(i)<=75%:
		  IAQRH(i) = (-0.5)*RH(i)+15
		ELSE:
		  IAQRH(i) = 0

	IAQ(i): Corresponding general quality judgement.	IAQ(i) = Minimum of the set (IAQT(i), IAQRH(i))

In the case of the European Norm EN 15757:2010 it is necessary to take a different approach to translate it recommendations to logical statements. They recommend to determine a moving average within a three-month window and stablish a confidence bar based on this moving average ± 1.5 times the standard deviation. The interpretation of this recommendation only translates in a good IAQ-index (1) for the values inside this confidence bar, and a, inappropriate IAQ-index (0) for the values outside of it. These considerations only depend on the relative position of the data points regarding the confidence bar, and does not provide enough information to elaborate a continuous transition between the state of appropriate risk and the state of unacceptable risk. Therefore, we are only considering the discrete interpretation of this guideline.

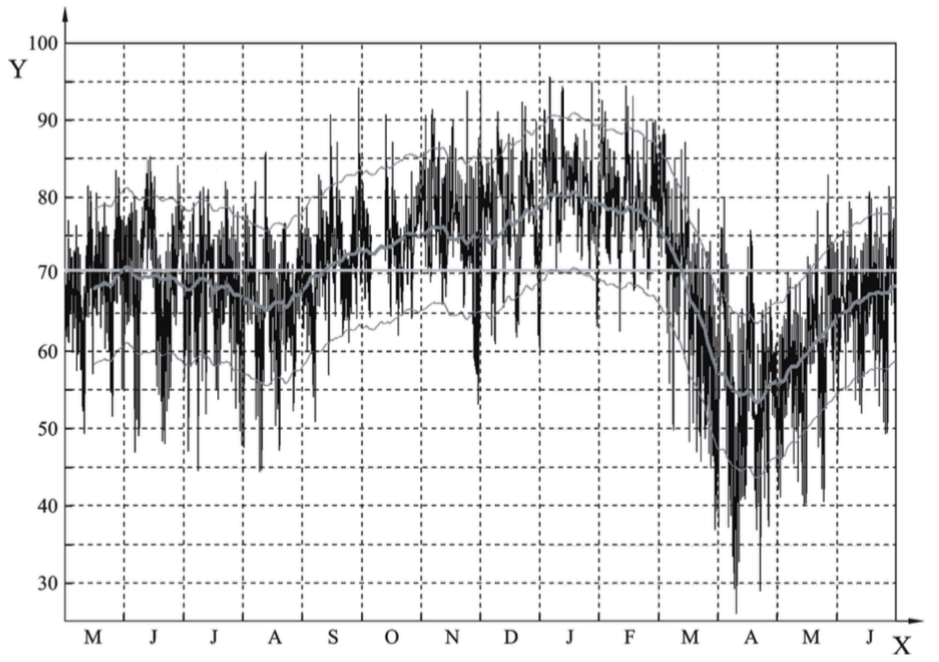

Figure 4.2. Representation of target values for relative humidity in a sample dataset [56].

4.3 RESULTS AND DISCUSSION

In this chapter we will be applying our assessment on the dataset generated from a measuring campaign held at Royal Museum of the Armed Forces and of the Military History, in Brussels, Belgium. The dataset is composed by measurements of temperature and relative humidity taken every 15 minutes over a period of approximately one year. The graphical representation of the dataset is shown in Figure 4.3. Due to technical issues with the collection of the data there is a gap in the data stream between the 24th of October 2017 and the 2nd of November of the same year.

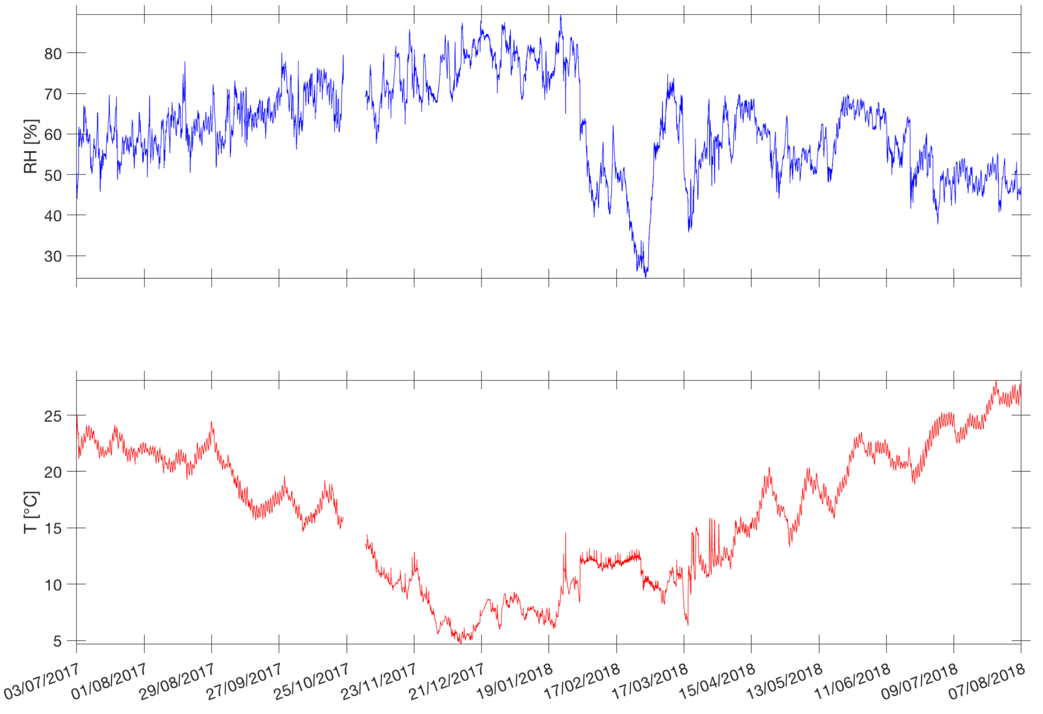

Figure 4.3. First dataset of temperature and relative humidity.

To illustrate the differences between the discrete and the continuous approach of our analysis we show the outcome of IAQ assessment using the two different interpretations of the Thomson guidelines in Figure 4.4. The first graph corresponds to the discrete interpretation, while the second corresponds to the continuous one.

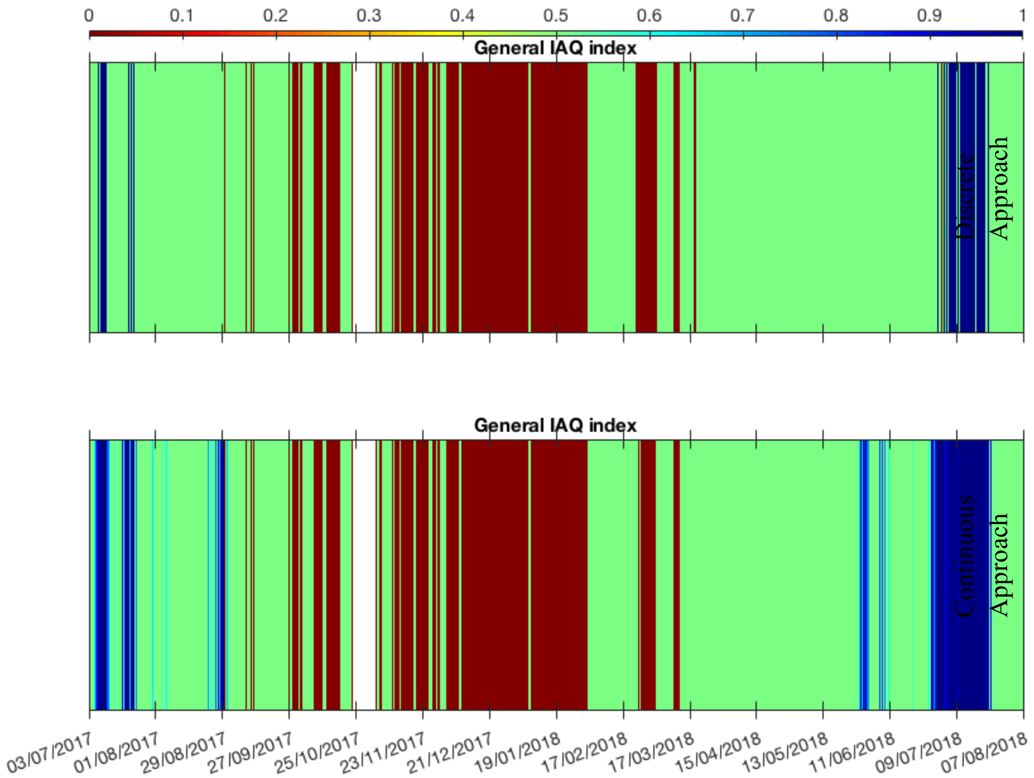

Figure 4.4. IAQ assessment by means of the discrete and continuous interpretation of the Thomson guidelines.

In general, both results show a very similar outcome, both classify most of the data points with similar values, and the extreme situations (IAQ-index=1 and IAQ-index=0) share the same classification in ~ 70% of the times. However, the second interpretation provides wider range of possible values that are mainly visible in the regions were the discrete approach wold transition from one state to the other. This behaviour is precisely one of the main advantages of the continuous interpretation. It provides more information regarding the evolution of the IAQ, allowing to detect an unwanted transition of the IAQ-index to lower values before reaching the actual state that would represent a higher risk of degradation. In preventive conservation this is considerable advantage, since the main focus relay in avoiding such risks.

Another interesting situation observed the firsts of June 2018 in case of the assessment performed with the continuous IAQ-index. In this case we detect a certain improvement of the IAQ that does not appear in the first assessment. Despite of not reaching the maximum IAQ-index this period shows a more appropriate environmental condition for conservation. This kind of behaviour is relevant in order to identify whether some specific mitigation actions performed in the analysed room were effective or not. It can confirm their degree of success despite of not reaching the maximum recommended values for temperature and relative humidity.

The results from the IAQ assessment applying the continuous interpretation for the Thomson, ASHRAE, Bizot and AICCM guidelines, and the discrete (and only) interpretation of the norm EN15757, are shown in Figure 4.5.

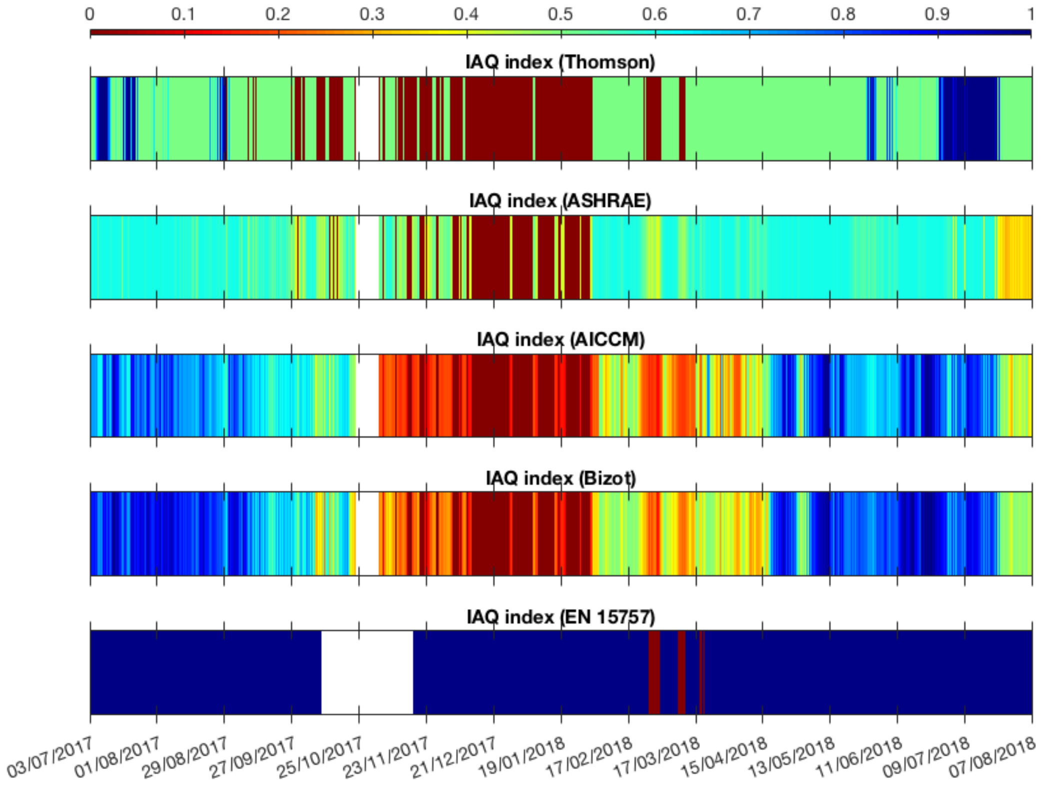

Figure 4.5. IAQ assessment based on the different guidelines.

In the Figure 4.5 we can directly observe how much the outcome of the IAQ assessment can vary for a same dataset depending on the guidelines selection. The first four assessments share some common characteristics despite of their differences while the assessment based on EN 15757 shows a completely different behaviour. This last assessment will describe an appropriate environment for conservation in the 86% of the situations despite of the actual values of the temperature and relative humidity. The result is an extremely positive depiction on situations that would classify as highly risky for degradation by the other four assessments, being the maximum difference in value of a 100% (reporting IAQ-index=1 for situations where the other four assessments report IAQ-index =0). An important restriction of applying this norm comes from the necessity of calculating the moving average in a three-month window of time. Any gaps or empty intervals on the data will affect the assessment of a longer period, as can be observed in Figure 4.5.

The assessments applying the Thomson, ASHRAE, AICCM and Bizot guidelines share a more consistent classification, but there are still notable differences in their assessment. The mean value of the IAQ-index through all the analysed period reflects this differences. Thomson guidelines application results in an average IAQ-index of 0.44, ASHRAE in

0.47, AICCM in 0.49, and Bizot in 0.53. The application of the Thomson guidelines depicts the most harmful situation out the four, which is consistent with the presence of more restrictive thresholds for both temperature and relative humidity. The assessment based on ASHRAE generally portrays a more favourable situation than Thomson, but it never reaches the maximum IAQ value. ASHRAE considers a more complicated relationship between the parameters and fluctuations for its classification and consequently more requirements most fulfilled to reach the maximum IAQ-index.

The more recent guidelines (AICCM and Bizot) provide the closest results in the assessment. The IAQ-indices obtained with them can differ in absolute value, but the transitions remain notably consistent in both cases. They also result in a more positive assessment compared to Thomson and ASHRAE, but not as positive as the norm EN15757.

This behaviour is consistent despite the dataset under study. Figure 4.6 presents a second dataset of approximately four months, obtained from a measuring campaign held at a late Gothic Church in the Belgian city of Aalst. During the measurements, we could record the environmental conditions during the period where a new heating system was set in use. This resulted in the temporal stabilisation of the temperature and relative humidity recorded in our data. The outcomes of our assessment for this dataset is presented in Figure 4.7.

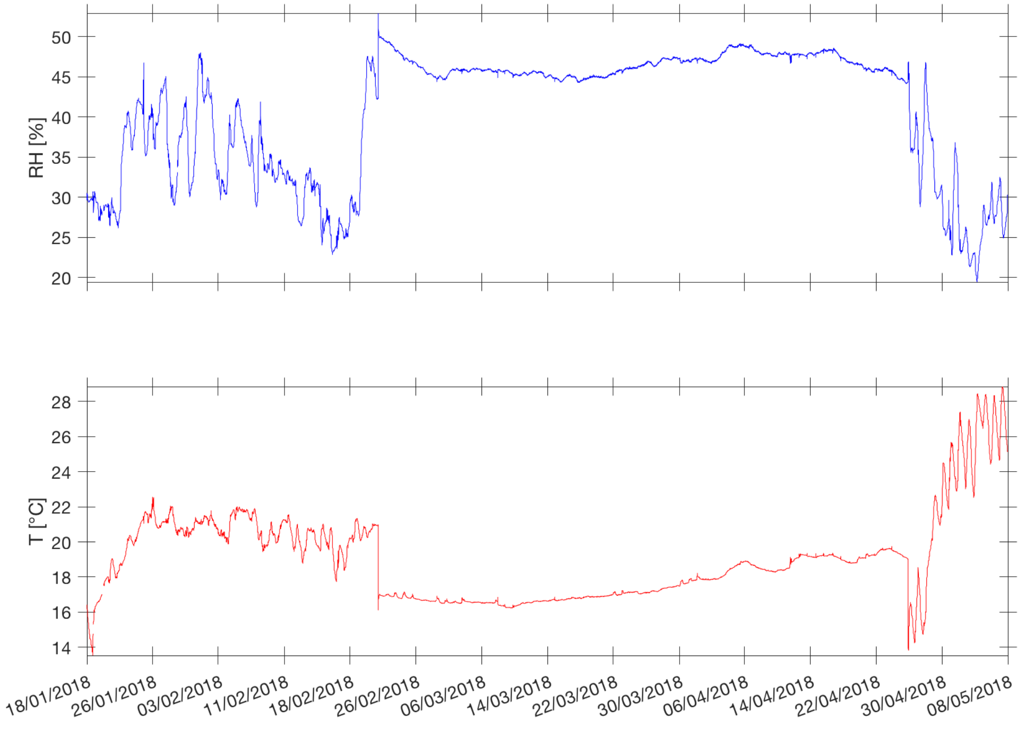

Figure 4.6. Dataset of temperature and relative humidity obtained at a church from the city of Aalst.

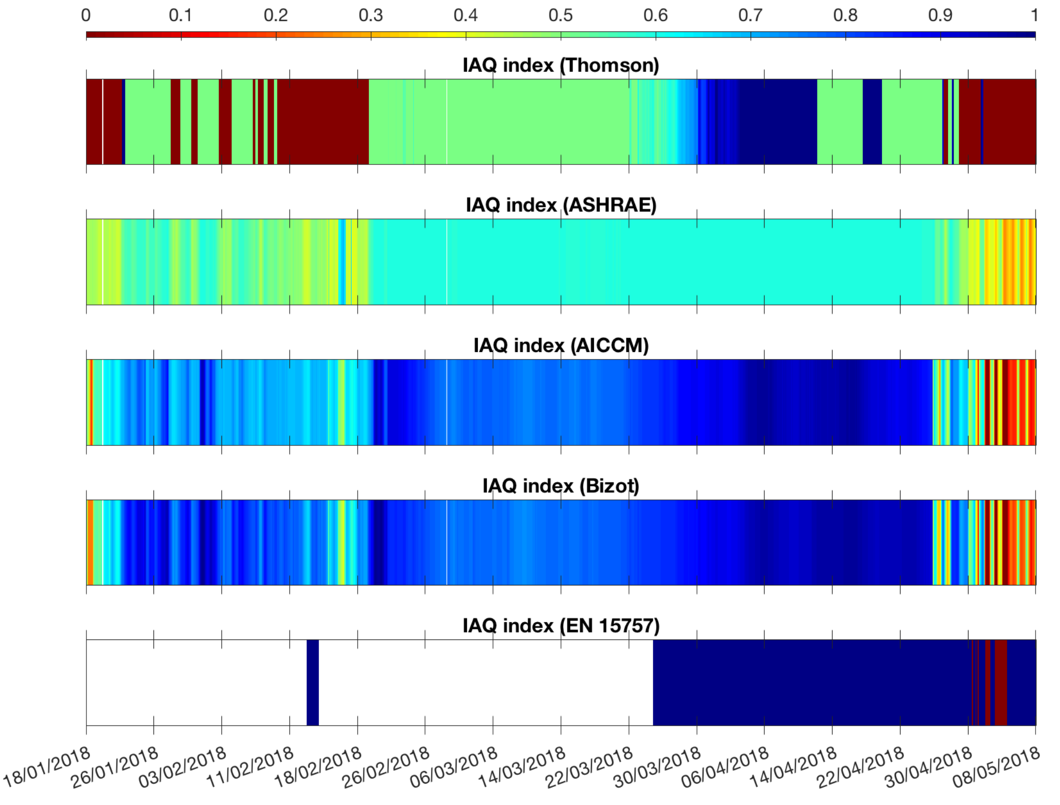

Figure 4.7. IAQ assessment of the dataset.

As in the previous case, the application of EN15757 provides a considerably more favourable outcome, with little resemblance to the other evaluations. It is also appreciable that for shorter measuring campaigns errors or gaps in the data will have a more massive impact during the assessment with this norm. At a first view, the second empty gap in the assessment with EN 15757 seems to be anomalous when compared with the rest of the evaluations. However, a zoomed visualisation of this period, shown in Figure 4.8, reflects that there are indeed smaller gaps in the data that are not directly noticeable when the results of the entire dataset are visualised.

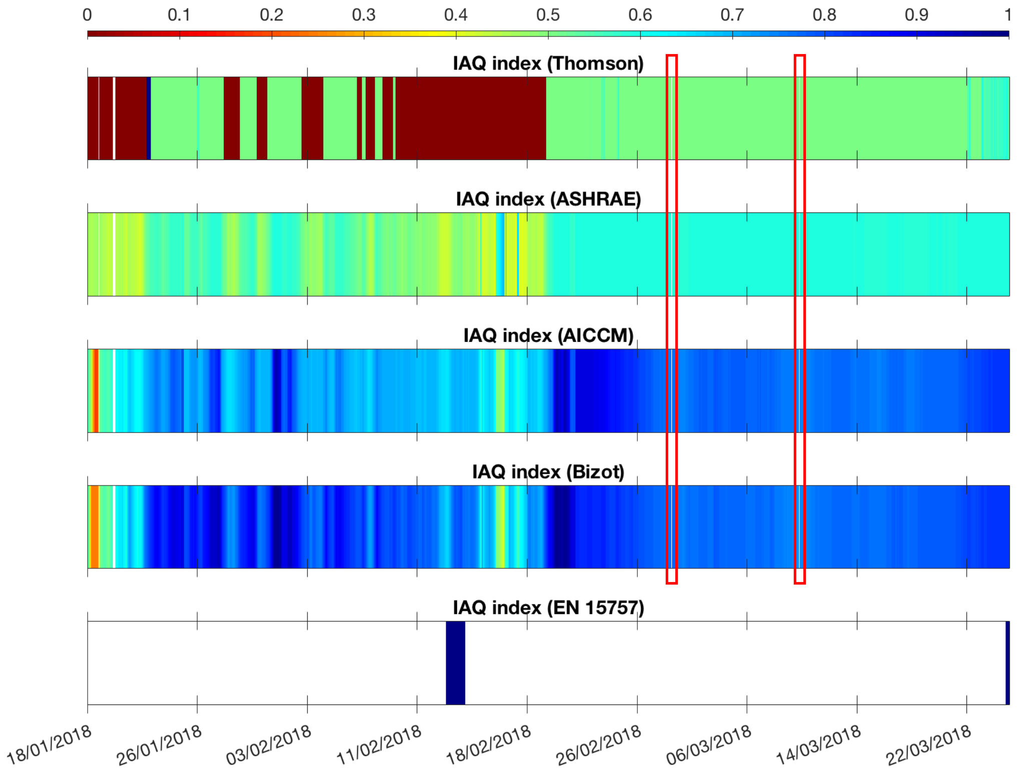

Figure 4.8. Zoomed sections of the results presented in Figure 4.7, with highlighted regions corresponding to gaps in the data.

For the other four cases, we have once again the less positive assessment with Thomson, with an average IAQ-index of 0.42. ASHRAE still results in a higher index (average of 0.55) but with less extreme classifications, and both AICCM and Bizot will share the more similar and positive results (corresponding averages of 0.75 and 0.78). Despite these similarities, the analysis of environmental conditions registered in this second dataset results in a more profound difference between the reported assessments. As an example, in the previous case, the average value of the Thomson and the Bizot assessments differed only in an approximately 15% while in this second case they vary in about a 40% of the value.

4.5 CONCLUSIONS

The direct representation of the IAQ by a numerical index provides the possibility of a straightforward interpretation of its behaviour. With the proposed method we were able to quantify the quality criteria of five different well-known guidelines and observe a reasonably consistent behaviour despite the characteristics of the environmental dataset analysed. However, the outcomes of the assessments reflect a considerable variation depending on the guideline selection.

There are regular differences in the results obtained with the different guidelines. In both case studies the application of Thomson guidelines resulted in lower IAQ averages, consistent with the fact that they are the most restrictive guidelines among the five studied. Bizot and AICCM provided very similar results, with a more positive depiction when compare to ASHRAE and Thomson. The results obtained from the application of EN 15757 were completely different from the other four guidelines. We observed situations where the analysis of the same situation resulted in complete opposite outcomes, either classified as the safer possible situation or as the worst possible scenario for heritage preservation. We do not aim to classify whether the recommendations of these guidelines might be correct or not but to present direct evidence of how their selection affects the IAQ assessment.

CHAPTER 5

STANDARDIZED INDOOR AIR QUALITY ASSESSMENTS, THE AIRCHECQ IAQ-INDEX

Based on:
Standardized indoor air quality assessments as a tool to prepare heritage guardians for changing preservation conditions due to climate change
Willemien Anaf, Diana Leyva Pernia, Olivier Schalm
In Geosciences, 8(8), 276.

ABSTRACT
The significant impact that the guideline selection has over the IAQ assessments undermines the reliability of a guideline-based IAQ-index. To support heritage guardians in the processing and evaluation of monitored data, we need to provide a standardised and more reliable method. With this in mind, we now focus on the development of new IAQ-index; this time based on the risk of degradation linked to multiple key risk indicators. This IAQ assessment enables the introduction of a more extensive set of environmental parameters. The current chapter describes the backbone of the IAQ-calculating algorithm. The algorithm is subsequently applied to a case study in which a mitigation action is implemented in a church.

5.1. INTRODUCTION

In this chapter we will introduce a standardized method that converts data streams collected with data loggers (i.e., the input) into a time series of IAQ-indices (i.e., the output). The index describes the overall air quality in relation to the preservation conditions of a specific material or object type. The use of air quality indices, both for indoor and outdoor situations, is already widely used in environmental studies from other fields, especially those related to health impact and human comfort [35, 57-60]. The IAQ-index that we propose for cultural heritage applications is material specific and focuses on the indoor environment. It can be calculated for each measured data point in time, in contrast to time-averaged evaluations. Plotting the IAQ-index over time by means of a line chart is a simple way to identify changes and trends in indoor air quality. It allows visualization of periods of elevated risk and the level of that risk and helps heritage guardians to identify hazards in a more focused way. Therefore, it offers a practical tool that supports decision-making towards the adaptation of the indoor environment to maintain certain preservation conditions despite climate change. Moreover, it can be used to objectively evaluate the effectiveness of a performed mitigation action.

The current chapter describes the development of the algorithm that calculates the IAQ-index from environmental measurements. The benefits of this approach are illustrated with a case study in which the effects of a mitigation action are shown.

5.2. BACKGROUND

A well accepted method to follow up the preservation conditions of a heritage collection is to monitor an objects preservation state by regular visual inspections. The disadvantage of this method is that the hazards cannot be identified until there is visible damage. An alternative approach that enables early warning is based on the calculation of degradation rates of heritage objects from environmental measurements. The prediction of expected damage requires thorough knowledge of the relationships between environmental parameters and degradation rates. However, for many materials, the exact degradation mechanisms that describe that relationship are not yet fully understood. Alternatively, degradation rates can be predicted by (accelerated) degradation experiments under well-controlled conditions. The relationships between environmental parameters and the degradation rate are then described by a best-fitting mathematical function. Dose–response functions illustrate this approach. They enable the prioritization of the agents of deterioration and the definition of damage thresholds [61-63]. An example of an algorithm based on such mathematical functions is the preservation metrics developed by the Image Permanence Institute [64]. 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. Thus, the above approaches appear to be impractical for a generalized evaluation of the preservation conditions. Over the last two decades, risk assessments for collections have made their appearance in the heritage sector [65-67]. Such assessments estimate the risk towards a collection by considering the ten agents of deterioration. They tackle the following questions [41]: What might happen? How likely is that? What will the consequences be? Such risk assessments are often time-consuming and require relevant expertise. In this contribution, we propose an alternative risk-based approach that focuses on the indoor air quality for heritage preservation. This approach requires less expertise and is based on several easily applied principles that are validated through practical experience and theory. The following paragraphs describe the approach.

5.2.1. THE CONCEPT OF KEY RISK INDICATORS

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 rates. However, that reality is too complex to estimate the risk that damage might occur. Instead, we simplified it by using a first simple principle: the degradation rate of any material is, to a large extent, driven by a limited number of environmental parameters. This set of parameters can be grouped in four categories that correspond to the following agents of deterioration: incorrect temperature, incorrect relative humidity, radiation and pollution (Figure 5.1).

The small set of environmental parameters that dominate the degradation rate of all (historic) materials can be considered to be markers, i.e., distinguishing and easily measurable features that give an objective indication of the preservation state in which a collection resides. Well-known examples are temperature, relative humidity, illuminance and UV-radiation. If the risks caused by these markers are known, the overall picture of the preservation conditions is known. For that reason, the markers can be used to introduce the concept of key risk indicators (KRIs) [68-70]. KRIs are independent parameters that estimate the threat that certain preservation conditions will harm the collection. They rely on the measurement of a marker and on a corresponding description of the alarming situation where enhanced risk for accelerated degradation might occur. The following list gives an overview of the 12 most critical KRIs (i.e., type of threats) identified from the literature: too high relative humidity [41], 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) (Figure 5.1).

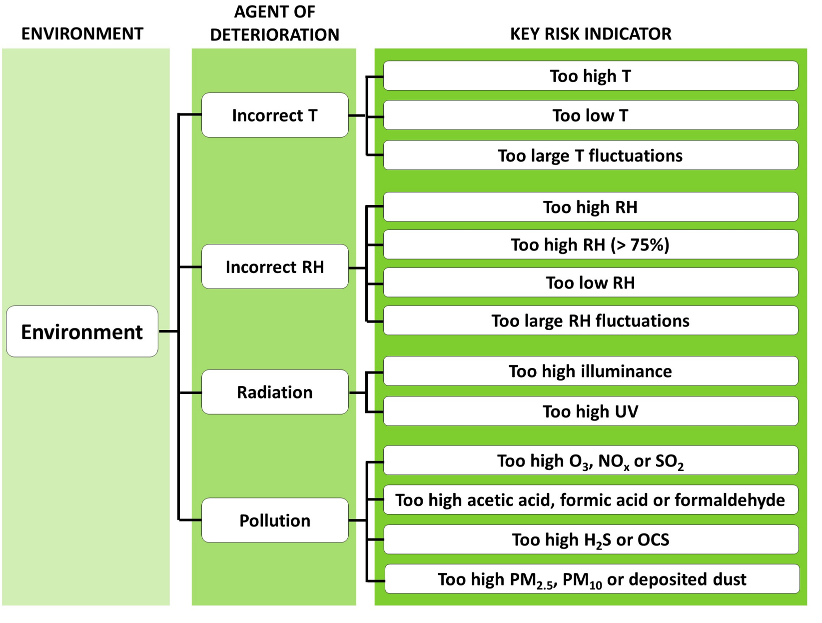

Figure 5.1. Schematic overview of the different levels by which the environmental appropriateness for heritage conservation are evaluated on. Abbreviations: RH, relative humidity; T, temperature; OCS, carbonyl sulfide.

5.2.2. QUANTIFYING THE KRIs

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 [71-73]. 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 its corresponding target value. Such target values or ranges of acceptable values 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. Based on previous literature, four types of conversion functions have been identified. They are described in the list below and visualised in Figure 5.2. 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 Figure 5.2, 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. In this contribution, one expert set these values and tested the results for consistency. The concept of calculating the level of risk with simplified conversion functions can be considered to be the second principle of the approach.

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 a limited risk of damage, while RH-values outside this recommended range are associated with higher 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 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 only a small risk of enhanced degradation, but that risk increases at higher intensities. At a certain intensity, 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). 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 [12]).

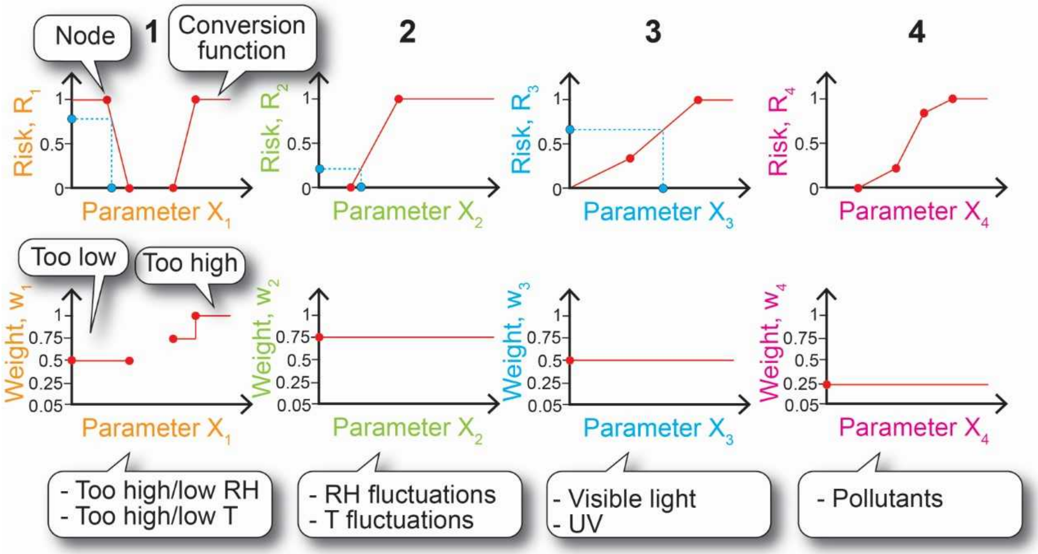

Figure 5.2. Conversion functions to calculate the level of risk that a marker is generating for a specific material or object type (upper part) and the way a weight is attributed to a key risk indicator (KRI) (lower part).

5.2.3. RISK PROFILE OF A MATERIAL

The first principle states that the degradation rate of historic materials is driven by a limited number of markers. However, one single 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 principle states that weighting factors can be used [23] to rank the importance of the different KRIs per 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 5.1 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 KRIs. First, the importance levels of the KRIs are ranked per material/object type (horizontal matrix direction). Five categories are allowed, and the same category could be attributed to several KRIs. The rankings are based on an extensive literature study, information from previous projects [74] and personal experience. Subsequently, the material/object sensitivity for each KRI was implemented using a five-category ranking as well (vertical matrix direction). To do so, the KRI importance within one material/object can change its ranking category, but the order of KRI importance within a material/object cannot change. Finally, the ranking categories are quantified by attributing a numerical score that reflects the impact of the KRI on the degradation: 0.05 (negligible), 0.25 (low), 0.5 (moderate), 0.75

(high) and 1 (extremely high). By using only five 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. The numerical scores are considered to be weighting factors.

In principle, the weighting factors 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 (Figure 5.2, 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%. Above this value, an elevated risk towards mold growth can be expected. This additional weighting factor is only valid for mold-sensitive materials. In the range where the risk is zero, the weight is not defined because w_i x R_i remains zero.

Table 5.1. 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.

For each material/object type, a spider graph can be plotted to visualise 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. Figure 5.3 gives an example for paintings, making the distinction between paintings on wood, canvas and copper.

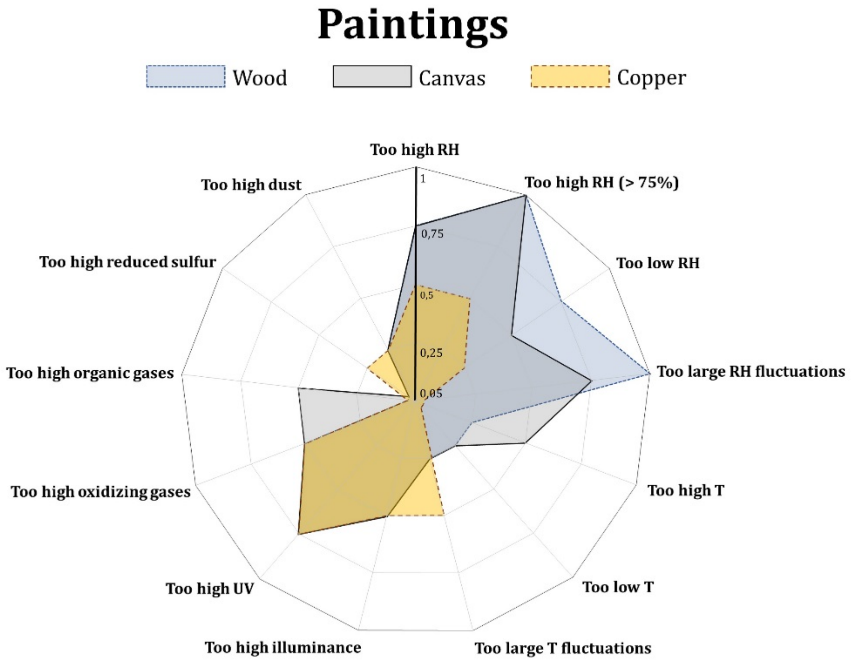

Figure 5.3. Spider plot with 13 dimensions to visualise the KRI importance for paintings on wood, canvas and copper. Five categories describe the impact on the degradation: negligible (0.05), low (0.25), moderate (0.5), high (0.75) and extremely high RH.

5.2.4. 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 for from a list of options. Then, the IAQ-index is calculated based in the implementation of a Regression Tree, similarly to the method presented in Chapter 3. The resulting algorithm follows six subsequent steps (Figure 5.4): (1) The heritage guardian pre-processes 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) Based on the material/object 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 $\{w_1 \times R_1, w_2 \times R_2, \ldots\}$). (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-indices. 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. [23] The behaviour of the IAQ-index over time can be visualised in line charts. Another visualization can be done by assigning a specific colour to each IAQ value using a colour map. This results in colour bars that depict the IAQ-index over time, allowing intuitive and user-friendly interpretation.

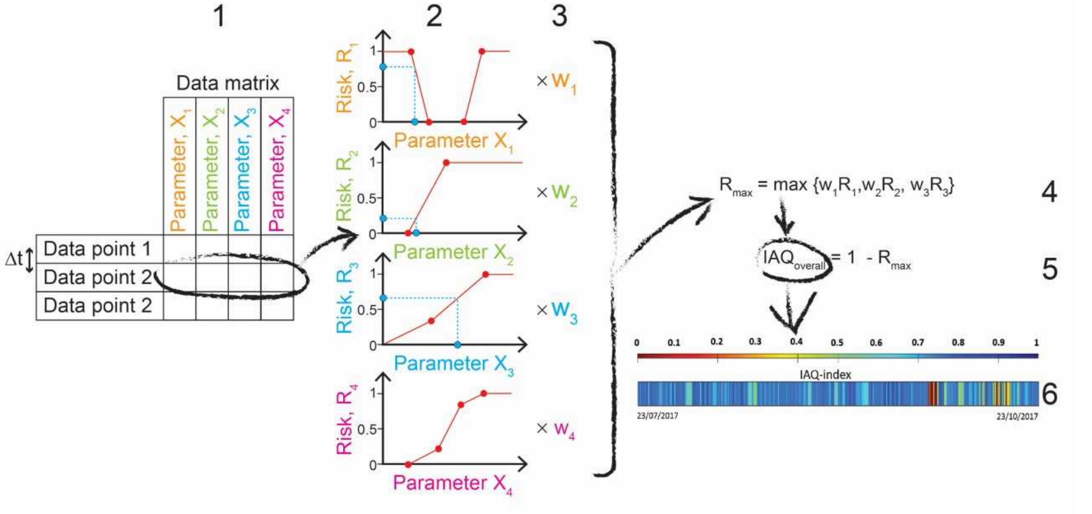

Figure 5.4. Schematic visualisation of the steps considered by the indoor air quality (IAQ) index algorithm.

5.3. MATERIALS AND METHODS

5.3.1. DATA ACQUISITION

An in-house developed multi-sensor tool measured a large number of markers. The monitoring tool consisted of a multi-purpose data logger (DataTaker DT85, Thermo Fischer Scientific, Scoresby Vic, Australia) to which a wide range of off-the-shelf sensors were coupled. The temperature and relative humidity were collected with a GMW90 (Vaisala, Helsinki, Finland). The intensity levels of visible and UV light were monitored with the upward positioned sensors SKL310 and SKU421, respectively (Skye Instruments, Llandrindod Wells, UK). Particulate matter was collected with a DC1100 Pro Air Quality Monitor (Dylos Corporation, CA, USA). The measured concentration in number of particles m^{-3} was converted into $\mu g\ m^{-3}$ using an empirical formula provided by the supplier. Concentrations of NO_2 and O_3 were collected with NO2-A43F and OX-A431 sensors (Alphasense, Essex, UK). The concentration of total volatile organic compounds (TVOC) was measured with a photo ionization detector with a 10.6 eV lamp (Vaisala, Helsinki, Finland), but the concentrations were too close to the detection limit to get a meaningful signal. For other markers, such as H_2S, no appropriate mid-price sensor could be found that was able to measure the (low) concentrations.

All sensors were read out in phase with a frequency of 15 min and saved by the data logger. Data was downloaded wirelessly using a 4G router.

5.3.2. DATA PROCESSING

The collected environmental data were stored in a data matrix. The rows consisted of the timestamp and the series of sensor readouts. The rows were denoted as the measuring points. The measured markers were organized as columns. The IAQ-index was calculated by following the procedure described above and using an in-house developed software written in MatLab R2017a (The MathWorks, Natick, MA, USA).

5.3.3. DATA VISUALIZATION

Data visualization makes large data sets understandable and helps to absorb the information in a constructive way. Therefore, even though the IAQ-index already summarizes the appropriateness of an environment based on several markers, an intuitive data visualization remains essential. The data should be visualised in a way such that it becomes useful and easy to understand by the end user, i.e., heritage guardians. It was decided to visualise the IAQ-index over time using colour bars. For this, the IAQ values were associated with the reverse jet colour map from the software package MatLab R2017a (The MathWorks, Natick, MA, USA). By associating the IAQ-index of each data point to a vertical coloured line, the time series was converted to a colour bar. A dark blue colour was assigned to an appropriate environment, while a red colour indicated an environment with elevated risk.

5.3.4. SAMPLING LOCATION

The application of the IAQ-index calculations was illustrated on a dataset collected in a late Gothic church in the centre of a small Belgian city. The church houses several canvas paintings, including a masterpiece of Rubens. Its other remarkable interior elements are a valuable organ, an early 17th century sacrament tower, several wooden statues, a wooden pulpit and metal candle holders. Environmental monitoring was performed at the organ loft at a height of around 7 m. Data collection started on 3 July 2017 and will continue until spring 2019. The current article focuses on a four-month period from 1 January 2018 to 30 April 2018. Within this period, a new heating system was started up in the church. The target temperature of the heating was set at 11 °C. When outdoor temperatures increase during the warmer seasons, the heating system is automatically switched off. For the IAQ-index calculations, we selected canvas paintings, restrained wood and copper as the material/object types of interest.

5.4. RESULTS

Figure 5.5 shows a traditional line chart for all measured markers in the church for the period, January to April 2018. At the beginning of January, temperatures in the church were below 10 °C, and correspondingly, high indoor humidity levels of around 80% were observed. On 25 January and 26 January, the newly installed heating system was tested.

The first test resulted in a remarkable peak in particulate matter. This was linked to the resuspension of deposited dust in the heating grids. After the tests, the temperature increased from about 9 °C to 11 °C while the RH dropped from somewhat higher than 80% to 75–78%. The heating system was effectively put into operation on 1 February, with a target temperature of 11 °C. This resulted in a sudden drop in RH to 60%. Until the end of February, the temperature remained constant, but the RH continued to drop. It should be noted that there was a cold snap during this period, marked with outdoor temperatures below the freezing point and an outdoor decreasing RH as well. The combination of the outdoor cold snap and the indoor heating resulted in a continued decrease in RH down to almost 25%. Therefore, it was decided to lower the temperature set point of the heating system on 27 February. In mid-March, a failure in the installation occurred, resulting in a temperature drop. Subsequently, after a short period of heating, the outdoor temperature rose, and the heating system did not switch on anymore.
The other markers—illuminance, UV-radiation, NO_2, O_3 and $PM_{2.5}$—showed the presence of numerous peaks. The peaks in the pollution-related markers could not be related to the heating system, except for one PM peak on 25 January. Illuminance and UV radiation mainly showed day–night cycles. Approaching spring, the UV levels tended to increase relative to the winter period.

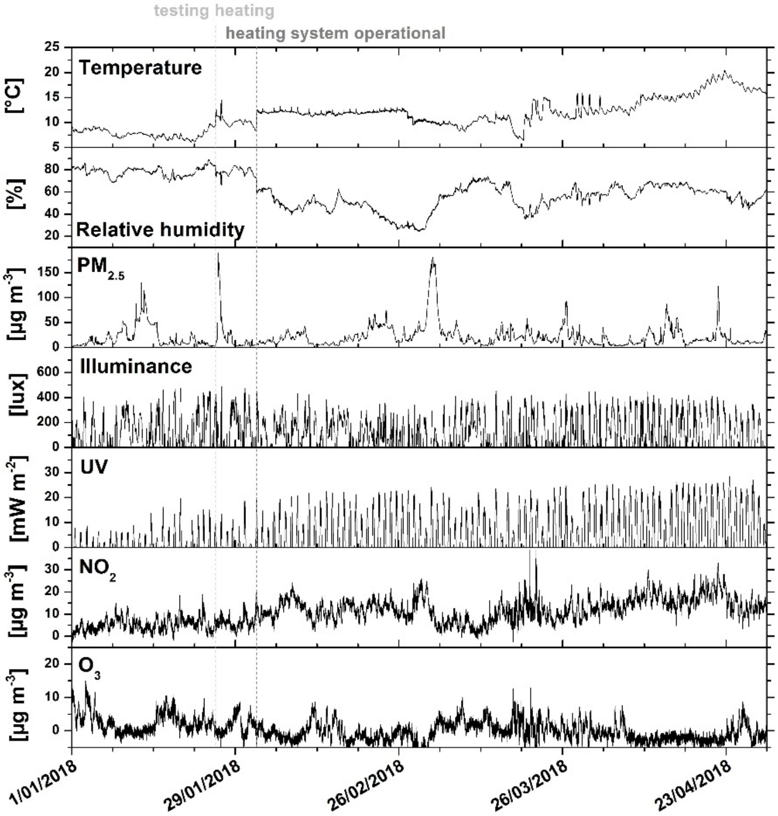

Figure 5.5. Scatter plot of the measured markers in the period, 1 January 2018 to 30 April 2018. The vertical dashed lines indicate the test period of the heating system and the moment at which the heating system became operational.

The graphs of all measured markers possess a wealth of information. However, when not familiar with data processing, the information can become overwhelming. The information output could be enhanced by adding yardsticks that denote the acceptable ranges as defined by guidelines. However, even with this information, heritage guardians could be lost in the data. To demonstrate the user-friendliness of the IAQ-index calculations, the algorithm was run for this dataset for canvas painting, restrained wood and copper (Figure 5.6). When hygroscopic materials, such as canvas paintings and wood, are exposed for a long time in certain humidity conditions, it is expected that they will acclimatize to these conditions [56]. Therefore, for these materials, general RH threshold values for Belgian churches were considered [75]. Other threshold values were mainly based on ASHRAE [12], CIE [76] and Finney [46].

When comparing the overall IAQ-index for these three material/object types, one quickly notices the correspondence between canvas painting and restrained wood, and the totally different outcome for copper. Indeed, canvas paintings and wood are both hygroscopic, while copper, as a metal, behaves in a different way. This results in a different sensitivity towards certain environments. For canvas paintings and restrained wood, a clear transition from a period with a high level of risk (dark red) towards more appropriate conditions (blue) can be observed around 1 February when the heating system was operational. After the heating system became operational, the IAQ-index became worse again for a certain period. This period was more pronounced for restrained wood (orange colour) compared to canvas painting (green to orange colour). For copper, there is a rather equal IAQ evaluation throughout the whole period, with an intermediate IAQ-index. To quantify the direct improvement of the start-up of the heating system, we considered the average IAQ-index of one week before and one week after the heating system became operational. 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 ΔIAQ between the weeks before and after the commissioning of the heating system equalled 0.6, 0.5 and 0.0 for canvas painting, restrained wood and copper, respectively.

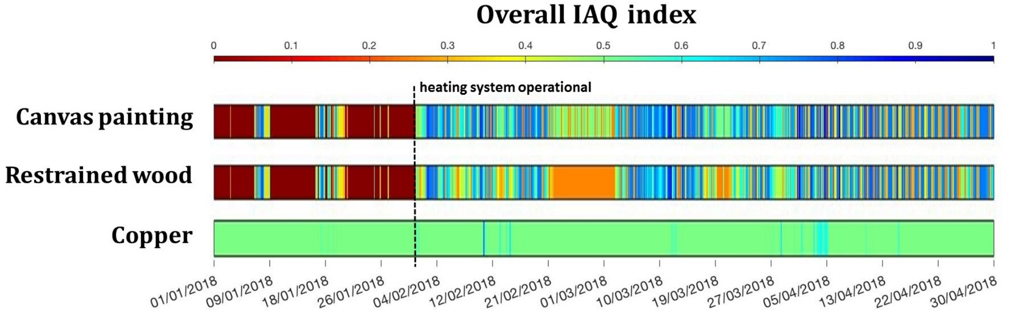

Figure 5.6. Overall IAQ-indices for canvas painting, restrained wood and copper over a period of 4 months. The dashed line indicates the moment at which the heating system came into operation.

The overall IAQ-index gives a visual summary of the environmental appropriateness based on all (measured) KRIs. It compresses all information from the multiple environmental parameters of a data point into one single index. Based on the marker-specific IAQ-indices

(1-R_i), the marker(s) that cause the undesired situation can be identified. Figure 5.7 shows an overview of all marker-specific IAQ-indices for restrained wood and copper, which are also visualised in colour bars. For restrained wood, it is easily visible that the characteristic pattern in the overall IAQ-index was mainly caused by a too high/too low RH. Temperature values and PM concentrations also exceeded the threshold levels, but these are estimated to have a lower impact on the general degradation rate of the collection.

For copper, the situation is more complex. The most striking undesired periods appeared for both a too high/too low RH and for too high concentrations of $PM_{2.5}$ (dark red). However, the overall IAQ-index depicts colours in the greenish range, corresponding to IAQ-indices of around 0.5. The translation of the marker-specific IAQ-indices to the overall IAQ-index seems counter-intuitive. This is due to following reason. Copper is not considered to be a highly sensitive material when compared to other material types such as, for example, paper. Therefore, the highest weighting factor attributed to any marker for copper is 0.5. This means that only half of the colour scale for the overall IAQ-index is used. In this specific case, both RH and PM exceeded the thresholds. The weighting factor for both markers equalled 0.5. Since the IAQ-index is calculated as the maximum of ($w_1 \times R_1$, $w_2 \times R_2$, ..., $w_n \times R_n$), almost the whole period had an overall IAQ-index of 0.5. In addition, our approach evaluated the preservation conditions with several independent KRIs. Synergetic effects, if any, were not considered, for example, the increased degradation rate of dust particles in humid conditions. Therefore, the start-up of the heating system is not visible in the colour bar of the overall IAQ-index but is reflected in the marker-specific indices and, especially, in the colour bar related to a too high/too low RH. This effect is a limitation of the algorithm: the choice of incorporating the sensitivity of materials relative to each other results in a loss of information. However, by evaluating the combination of the overall and the marker-specific IAQ-indices, the information can still be made available.

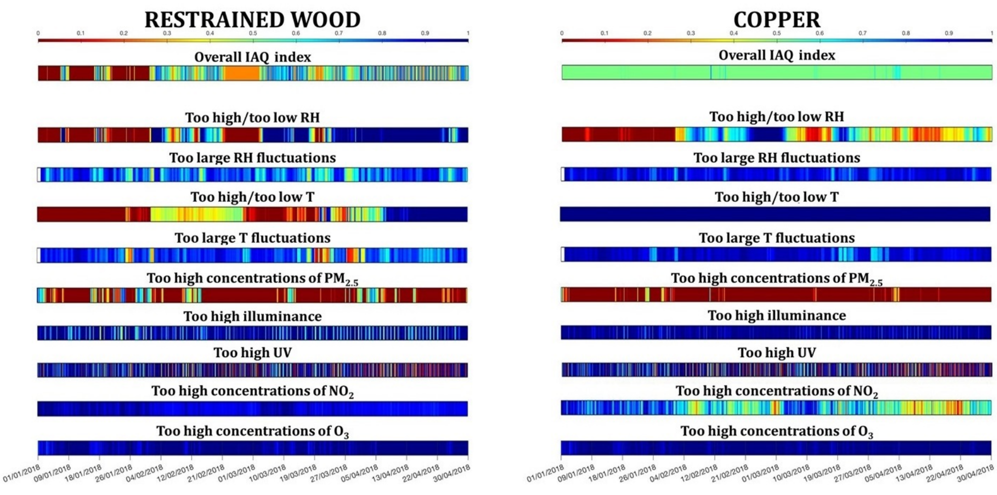

Figure 5.7. Overview of the parameter-specific risks for restrained wood (left) and copper (right).

5.5. DISCUSSION

Although several personal/human decisions (e.g., selection and interpretation of standards and guidelines, definition of weighting factors, etc.) are introduced in the algorithm, the algorithm itself is a standardized procedure that leads to reproducible and quantitative judgement of the IAQ. This standardized evaluator enables the conversion of measurements into judgements. These judgements help the heritage guardian analyse the preservation conditions and identify the hazards that are endangering his collection. 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. It is important to have measurements of all relevant KRIs for that 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.

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. With this approach, the slow change in hazard occurrence as a result of climate change will automatically be compensated for. The overall IAQ-index can be used to detect periods of elevated risk. By looking at the marker specific IAQ-indices 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 algorithm can already be applied on short datasets and does not require a minimum of at least one year of data as an input. Therefore, it allows the environment to be followed up in real-time. When the preservation conditions start to become worse, one can quickly undertake action before (irreversible) damage occurs. In this way, the IAQ-index serves as an early warning.

Despite the advantages and the user-friendliness of our approach, there are also some points of concern that should be considered. Our analysis is mainly focussed in the detection of potential mechanical damage, with little or none direct reference to chemical damage. As mentioned in Chapter 1, section 1.3.3, we are not basing our analysis in the direct influence of the degradation mechanisms, of which we have only limited information for regarding an also limited group of specific materials.

Another limitation of or method has already been described by the visualization of the overall IAQ-index of copper where the ranking of the different KRIs based on their impact on one material and the ranking the KRI based on the impact of a series of materials resulted in a limitation in the visualization of all required information. Also, the following remarks should be considered when using the algorithm:

The intuition of the developer affects the definition of the standardized evaluator. The proposed principles do not perfectly reflect the complex reality and require some expert intuition. However, they work well enough to make several evaluations. The principles can be refined at a later stage, and the IAQ-indices of data from the past can be recalculated. Thus, the standardized evaluator generates reproducible and quantitative evaluations, but the scale is not absolute.

The exact degradation rate remains unknown. Although the IAQ-indices give good insight into the periods with elevated risk, the initial question, “How fast do materials degrade?”, is not answered. However, the IAQ algorithm supports the formulation of that answer by estimating the enhanced risk for degradation. This already helps heritage guardians to make decisions.

Restricted options for material choice. The algorithm offers a list of 35 materials and object types to select. The list covers a wide range of heritage materials and objects that is representative of heritage collections. When using the 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 to be unique objects. Also the conservation state is important, since deterioration rates may vary during ageing [56], and conservation–restoration treatments can suddenly change the fragility of an object. Such refinements are not implemented in the algorithm which considers materials and objects at a statistical level (i.e., average materials and objects with an average behaviour).

Synergistic effects. The IAQ-index does not consider synergistic effects because it uses independent KRIs to estimate the risk of elevated degradation and not degradation mechanisms. Several synergistic effects are well known, e.g., lead corrosion is highly promoted in the presence of organic acids and high humidity [77, 78]. Since synergistic effects are not considered, periods of elevated risk could be somewhat underestimated. This could happen when the ranking of the KRIs as described by the weights is affected. However, changes in ranking are only expected with strong synergistic effects. Even though the overall IAQ-index could be underestimated in cases of such strong synergistic effects, the marker-specific indices will still show the periods of elevated risk.

Evolving standards and guidelines. 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 [79]. It is also expected that more accurate thresholds will become available for pollution levels. Therefore, to keep the algorithm up-to-date, the values that determine the conversion functions should be revised on a regular basis. Once revised, data from the past can be recalculated and re-evaluated considering the updated threshold values. This allows an evaluation of the progress in the IAQ despite changes in the ‘standardized evaluator’, i.e., the algorithm.

5.6. CONCLUSIONS

This IAQ-index estimates the indoor air quality in a standardized way. The proposed algorithm is a versatile tool that enables the introduction of a set of environmental parameters that goes beyond temperature and relative humidity. The introduction of an overall IAQ-index and its visualization in colour bars simplifies the analysis and interpretation of large data streams and a wide range of parameters that can be measured simultaneously. This offers heritage guardians a practical tool that helps them understand their indoor air quality. If more in-depth information is required, the user can consult the marker-specific IAQ-indices, or the original line graphs. The evaluation of such graphs becomes easier with the help of the IAQ-indices. This saves time and facilitates decision-making to improve the indoor air quality and to adapt the heritage institute to a changing climate.

All periods in time are evaluated in exactly the same way, resulting in a comparative risk of damage to heritage collections over time. Even if the following generations decide to adapt the algorithm, the data from the past can easily be re-evaluated and new comparative risks can be obtained. The comparative risk output also allows heritage guardians to quantify the effectiveness of mitigation actions and demonstrates that the effectiveness is not necessarily the same for all material/object types.

CHAPTER 6

A DATA MINING APPROACH FOR INDOOR AIR ASSESSMENT: AN ALTERNATIVE TOOL FOR CULTURAL HERITAGE CONSERVATION

Based on:

A data mining approach for indoor air assessment: an alternative tool for cultural heritage conservation

Diana Leyva Pernia, Serge Demeyer, Olivier Schalm, Willemien Anaf

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ABSTRACT.

As we demonstrated in Chapter 4, the IAQ assessment based on the interpretation of guidelines can yield on very different outcomes depending on the guideline selection. To tackle this issue, we proposed to apply the AIRCHECQ IAQ-index based on KRIs instead. However, it is inevitable this method will eventually become also outdated due to our still incomplete knowledge of heritage degradation. Considering these, we explore in this section the use of data mining as an alternative method for the IAQ assessment in heritage studies. Data mining can provide knowledge from vast volumes of heterogeneous data, through high-speed processing, detection, and analysis. Here we present its application to identify the dynamics and patterns affecting the indoor air quality in a realistic case. Using data from a measuring campaign held at a late Gothic church in Belgium, we show that inappropriate periods can be identified without using standards. Besides, different types of periods can be identified by studying the relation between multiple parameters. For that we use the k-means clustering method, interpreting the results with both visual and statistical tools.

6.1. INTRODUCTION

Several studies have already demonstrated how the exposure to an aggressive environment has a significant impact on the degradation process and degradation rate of cultural heritage objects [23]. Based on these findings heritage guardians and institutions have now an increasing interest in managing the indoor air quality and provide stable environmental conditions to minimize, as much as possible, the occurrence of further damage to historical or valuable artefacts on their collections. However, monitoring and evaluating relevant environmental data is a challenging task for most heritage guardians, mainly due to the considerable amount of information generated, and the uncertainties behind the selection of the acceptable environmental values.

Continuous indoor air quality monitoring implies the collection of vast amounts of data that can quickly become overwhelming for specialists with limited experience in data science. This is aggravated when an increasing number of environmental parameters are analysed. Temperature and relative humidity are the most common parameters monitored by the heritage community, but other parameters such as visible light, UV radiation or pollution also have a remarkable influence on the degradation rate of most objects. With the currently available technology these parameters can be monitored as well, and they should be considered to achieve an accurate assessment [24].

Traditional assessments usually rely on the comparison of measured environmental parameters with their corresponding acceptable values. Unfortunately, the target values are not precisely known, and they depend on variables such as the material type, preservation state, etc. This entails a strong dependency on the selected guidelines that define acceptable environmental values, and will be reflected in the accuracy of the analysis [55, 80].

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. In our specific context we focus on interesting patterns or atypical behaviours [81]. A similar approach has already been successfully implemented in indoor environment quality assessment for human health and comfort [82]. However, the application of this method for a comprehensive environmental characterization is still uncommon in the field of cultural heritage studies.

We present here our results from the implementation of two different data mining methods: (1) Filtering data for recognizing inappropriate periods in the absence of standards or guidelines; (2) Clustering data points according to their similarity in general behaviour for identifying dynamics or patterns affecting the indoor air quality in a specific case study.

6.2. MATERIALS AND METHODS

6.2.1. CASE STUDY

To evaluate the viability of our approach, we analysed the data gathered from 23/07/2017 to 23/10/2017 in a measuring campaign held at a late Gothic church in the centre of a small Belgian city. The environmental information was collected with an innovative multi-sensor tool that registered every 15 minutes the values of temperature, relative humidity, illuminance, particulate matter (PM), nitrogen dioxide (NO_2) and ozone (O_3) concentrations among other parameters [24]. This resulted in a data matrix of 8928 measuring points (matrix rows) and 7 measurements per point including the above mentioned parameters (matrix columns). In addition, every measuring point was labelled with a timestamp and the corresponding weekday number in which the measurements were performed (e.g., Monday = 1).

6.2.2. IDENTIFYING PERIODS OF ELEVATED RISK BY FILTERING DATA

Our method for the identification of periods of elevated risk is based on three main suppositions.

1. A stable climate is more conducive for heritage conservation, especially in the case of temperature and relative humidity acting over hygroscopic materials [23].
2. Keeping the light exposure and the concentration of pollutants as low as reasonable achievable minimises the risk of material degradation [83].
3. Short-time fluctuations will not necessarily affect all objects, since the reaction time of the piece must be shorter that the fluctuation in order to have a potential impact on its conservation state. [84]

Considering the third supposition, we start the analysis by filtering out the short-time fluctuations. There are several classes of filtering methods, but the most widely used apply statistical measures over moving windows [23]. The mean value is often used as the statistical measure for the data in the window. Consequently, a moving mean is calculated creating series of averages of different subsets as the window shifts over the full data set.

Moving means are ordinarily used to smooth out short-term fluctuations and highlight longer-term trends or cycles in time series data. In our case, the use of the moving mean method filters out the fluctuations caused by the day and night variations exposing the regular seasonal variations or the anomalous behaviour that occurred during periods of elevated risk.

Considering now the first and second suppositions we can establish that the periods where the filtered data presented the higher fluctuations were the periods most likely to be linked to an elevated risk of degradation. For temperature and relative humidity, the relevant fluctuations can be found above or below the mean value, while for the rest of the environmental parameters, only the fluctuations above the mean would be noteworthy.

The general algorithm can be formalized in the following steps:

1. The short time fluctuations are smoothed out by the calculation a moving average inside a 24-hour window.

$$X_s(t) = \frac{1}{n} \sum_{i=t-n/2}^{t+n/2} X(i)$$

   Where $X_s(t)$ is the smoothed value of the magnitude X in the instant t, and n is the number of data points inside the 24-hour window. With this, we reduce the relevance of the day/night fluctuations, focusing already on more atypical deviations.

2. The average value of the dataset is calculated and all the data points within a range of ± one standard deviation are filtered out. The remaining data points will conserve only the information regarding their deviation from the upper or lower limits of the filtered region.

$$\begin{gathered} If\ \ X_s(t) \in [\bar{X} - sd, \bar{X} + sd]: \\ \Delta X(t) = 0 \\ Else\ if\ \ X_s(t) > \bar{X} + sd: \\ \Delta X(t) = X_s(t) - (\bar{X} + sd) \\ Else: \\ \Delta X(t) = X_s(t) - (\bar{X} - sd) \end{gathered}$$

   Where $X_s(t)$ is the smoothed value of the magnitude X in the instant t, $\bar{X}$ is the average value of X, sd is the standard deviation, and $\Delta X(t)$ is the new value of the filtered dataset for the point corresponding the instant t, reflecting the magnitude of its deviation.

3. As a final step ΔX is normalised to facilitate the comparison with other environmental parameters.

$$\Delta X_N(t) = \Delta X(t)/\max\left(|\Delta X|\right)$$

6.2.3. CLUSTERING DATA, K-MEANS CLUSTERING

Clustering is an unsupervised learning method that assigns labels to objects in unlabelled data that can be implemented by different types of algorithms [23]. For our research, we selected the k-means clustering, a data-partitioning algorithm based on iterative minimization of the sum-of-squares criterion [23].

Clustering validation was performed with two different methods: The Davies-Bouldin index, and Silhouette value. The Davies-Bouldin criterion is essentially a ratio of within-cluster and between-cluster distances. Based on its analysis the optimal clustering solution has the smallest Davies-Bouldin index value [85]. The Silhouette value is a measure of how similar a point is to points in its own cluster when compared to points in other clusters [86]. This value ranges from -1 to +1, where a high silhouette value indicates that the point is well-matched to its cluster and poorly-matched to neighbouring clusters.

6.3. RESULTS AND DISCUSSION

The complete data set studied is presented in Figure 6.1. As mentioned in the previous section, seven different environmental parameters were monitored every 15 minutes during 93 days, resulting in data streams of 8928 elements each. This data set cannot be regarded as considerably large when compared to a typical climate characterization campaign that should cover, at least, one full year of data. However, it is more than enough to hinder a prelaminar assessment through visual inspection. There are certainly patterns in the data, but there is too much information to get a clear grasp of them. One characteristic that all the parameters share is the unremitting presence of short time fluctuations, mainly related to the day-night cycle.

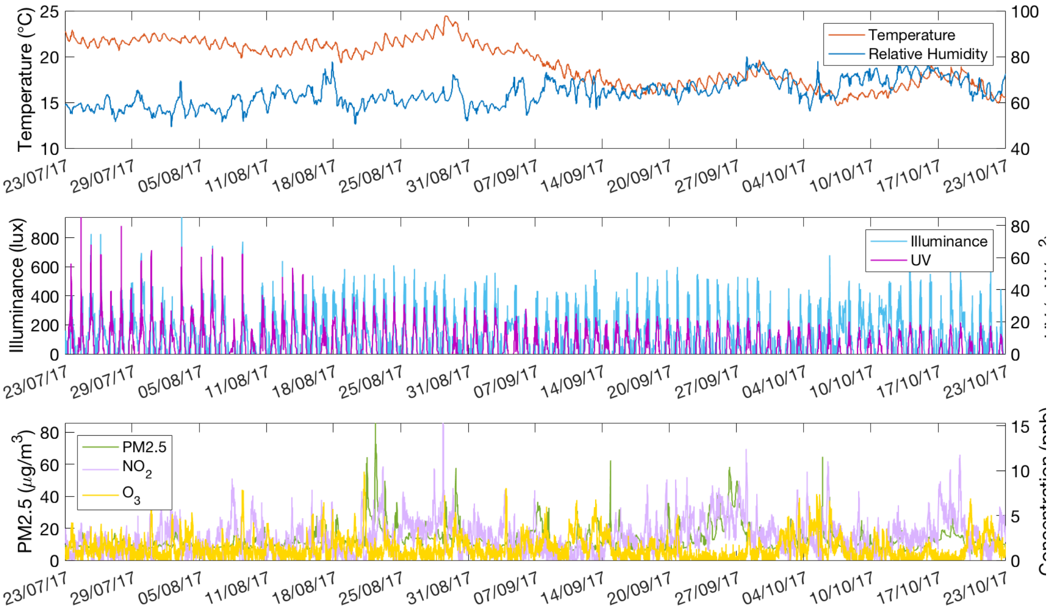
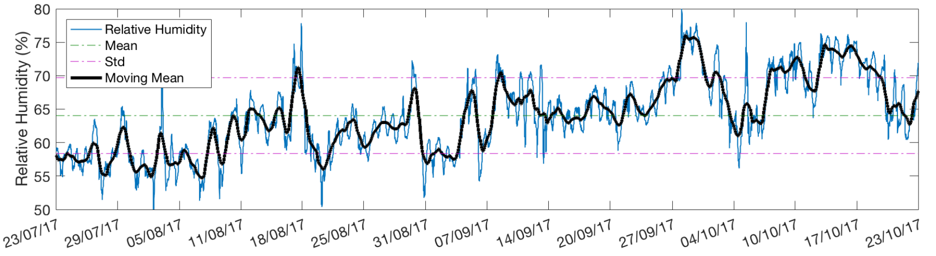


Figure 6.1. Environmental data registered for temperature, relative humidity, illuminance, ultraviolet radiation, particulate matter (PM2.5), NO2 and O3 concentration.

In order to filter out the daily fluctuations we calculated the moving mean of the parameters with a symmetric window of 96 data points, which covers a period of 24 hours in the time scale of our case study. The result of its application on the case of relative humidity is presented in Figure 6.2 (a). In this figure we plotted the measured data points for relative humidity, the mean value over the complete period analysed, the confidence bars delimited by the standard deviation (std) and the correspondent moving mean. By filtering higher frequency fluctuations, the moving mean shows now a gradual, but still appreciable overall increment during the studied period, which match the expectations for the seasonal transition from summer to autumn.

(a)



(b)

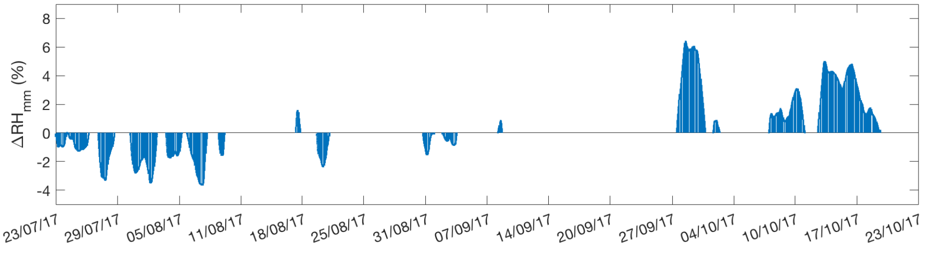


Figure 6.2. (a) Data registered for relative humidity, its mean value over the time analysed, confidence bar of ± the standard deviation, and moving mean for a symmetrical window of 24 hours. (b) Difference between the values of the moving mean outside of the confidence bar.

In Figure 6.2(a) we can notice periods where the moving mean reached extreme values crossing the confidence bar. These periods are the most deviated from the typical behaviour, and consequently, more likely to be linked to unusual events or even to potentially dangerous occurrences. The magnitude of the difference between these points and the standard deviation can be used as a metric to characterize their anomaly. Plotting this magnitude would filter out the periods where the environmental parameter exhibits a standard behaviour, and therefore, directly guiding the analysis to periods of elevated risk. This analysis is illustrated in Figure 6.2(b), where the difference between the values of the moving mean outside of the confidence bar and the standard deviation (ΔRH_{mm}) are plotted as a function of time.

This analysis facilitates the detection of extreme periods and can be implemented for all the environmental parameters on our dataset. Figure 6.3 shows the normalised values of these differences between the moving means and the corresponding confidence bars (y-axis) as a function of time for all parameters. The normalization was performed to establish an unbiased comparison unrelated to the measuring units of the parameters. For each case, the higher the difference value, the more atypical is the corresponding period. Due to the significant amount of data filtered out, it is still possible to identify the atypical episodes clearly, even when showing the information of all the parameters in the same graph.

It is possible to find certain similarities between the outcome of this method and the already proposed assessment of the IAQ-index. However, the coincidence will be more dependent on the values and overall behaviour of the studied dataset than on the selection of any specific guideline. Figure 6.4 presents the evaluation of the IAQ-index applying the interpretation proposed in Chapter 4 of two different sets of guidelines: The Thomson and the Bizot standards. In either of the presented cases, it is possible to settle a direct and constant equivalence in the obtained assessments. In the case of Bizot, only the region around the end of August would be equally classified as a risk for degradation. On the other hand, in the assessment with Thomson, we find periods of elevated risk around the 18 of August, that are not identified as relevant periods in our filtered data. The strong dependency of this assessment with the specific characteristics of the analysed dataset does not guarantee that any coincidence in the outcomes will be consistently found in other case studies.

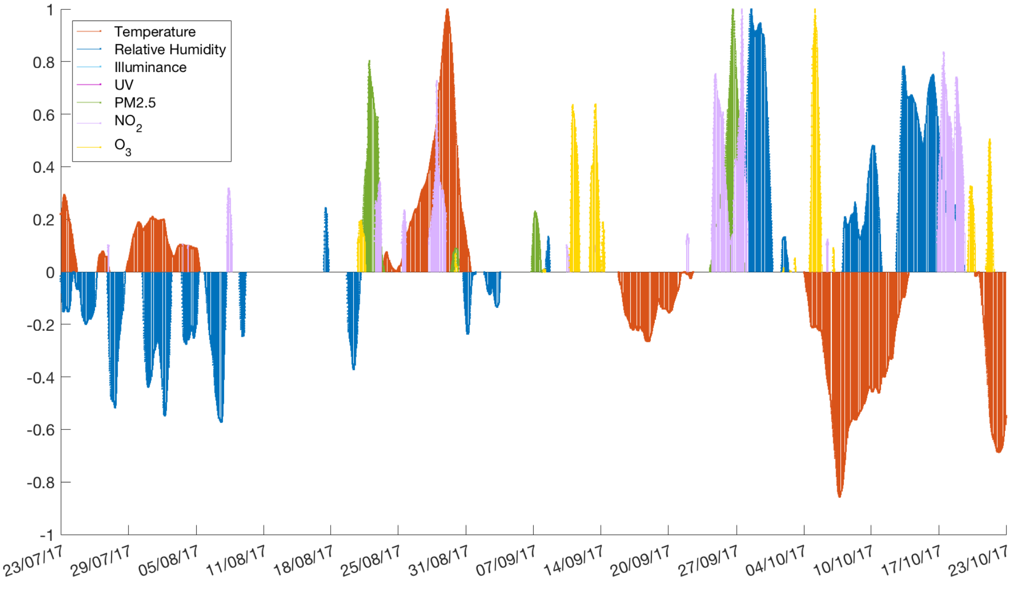


Figure 6.3. Normalised differences between the moving means of each environmental parameter and the corresponding confidence bars, identifying atypical periods.

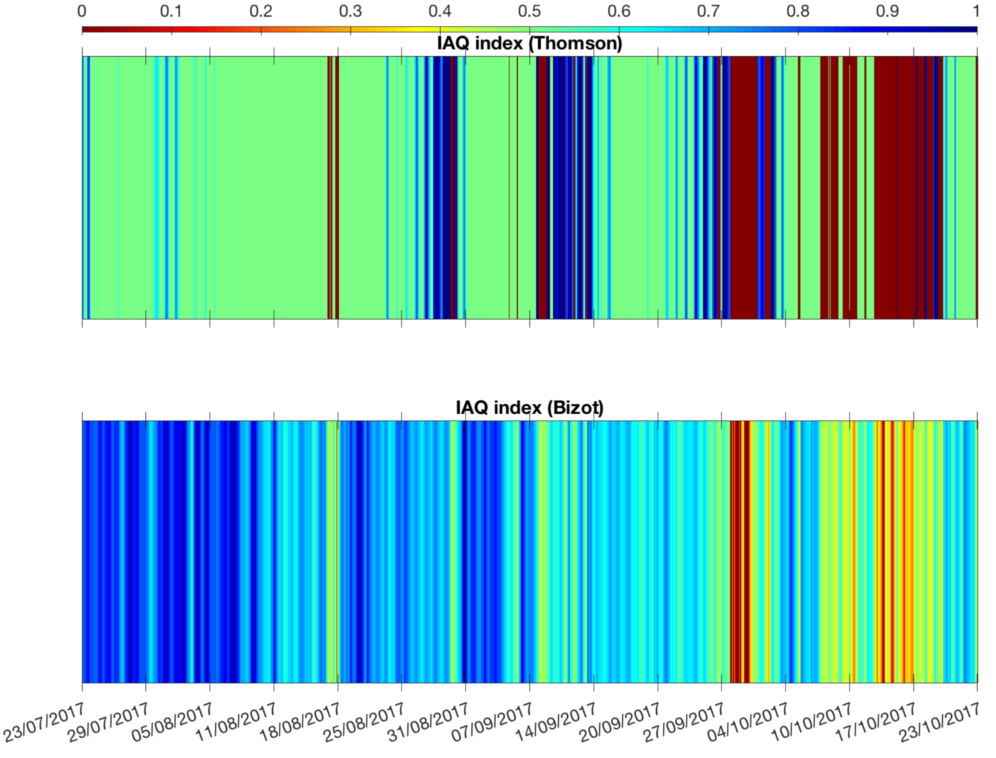


Figure 6.4. Evaluation of the IAQ-index with the Thomson and Bizot guidelines

Table 6.1. Cluster interpretation and corresponding data.

		Day	Temperature (ºC)	RH (%)	Illuminance (lux)	UV (mW/m^2)	Pm2.5 ($\mu g/m^3$)	NO_2 (ppb)	O_3 (ppb)
Cluster 1	min	1	19.153	51.436	0.000	0.000	5.153	0.000	0.000
	max	7	24.282	74.018	357.674	22.470	64.358	15.323	7.999
	mean	**3.862**	**21.244**	**61.026**	**40.040**	**1.935**	**12.406**	**2.754**	**1.165**
Cluster 2	min	1	14.646	56.147	0.000	0.000	2.973	0.000	0.000
	max	7	21.237	79.006	680.531	25.351	64.605	11.779	7.358
	mean	**4.045**	**17.205**	**65.755**	**236.407**	**8.743**	**14.333**	**2.355**	**1.613**
Cluster 3	min	1	14.647	60.476	0.000	0.000	4.024	0.000	0.000
	max	7	20.950	80.067	279.758	18.022	62.399	12.423	7.389
	mean	**4.063**	**17.008**	**69.350**	**30.157**	**1.148**	**11.937**	**3.086**	**1.146**
Cluster 4	min	1	18.163	49.346	0.000	0.000	6.164	0.000	0.000
	max	7	24.462	74.655	942.825	85.150	85.777	10.240	9.895
	mean	**4.088**	**21.646**	**59.063**	**284.142**	**17.988**	**12.891**	**1.461**	**1.614**

For the implementation of the k-means clustering method, we analysed the entire data matrix of environmental data collected. Each column was normalised by rescaling in the range from 0 to 1 before applying the clustering method to avoid assigning artificial weights to the data. The clustering algorithm was implemented for k values from 2 to 15, each done in 5 separated runs. The resulting 13 cluster distributions were evaluated using the Davies-Bouldin and Silhouette criteria, and a detailed inspection of their characteristics. Based on these, we selected k=4 as the most relevant distribution for classifying our data set.

The data interpretation of each cluster is presented in Table 1. We found two sets of patterns that provide physical meaning to the cluster distribution. One pattern is defined by the presence of lower values of illuminance and ultraviolet radiation (clusters 1 and 3) or higher values of these two environmental parameters (clusters 2 and 4). The other pattern is set by the anti-correlation of temperature and relative humidity. Clusters 1 and 4 hold higher temperature and lower relative humidity (summer), while clusters 2 and 3 are the opposite (autumn).

Plotting the temporal distribution of the 4 clusters, Figure 6.5(a), confirms our hypothesis on the seasonal influence. Comparing the graphs in Figure 6.5(a) and 6.5(b) we can confirm that clusters 1 and 4 comprehend the periods where the temperature was above the mean value, while the temperatures in clusters 2 and 3 where below the average. From Figure 6.5(a) we can also conclude that the distribution based on the illuminance and UV levels does not exactly reflect the day-night variations. The number of days during the analysed period does not match the number of repetitions of the clusters, therefore the difference comes from the distribution of brighter days (clusters 2 and 4) and nights or darker days (clusters 1 and 3).

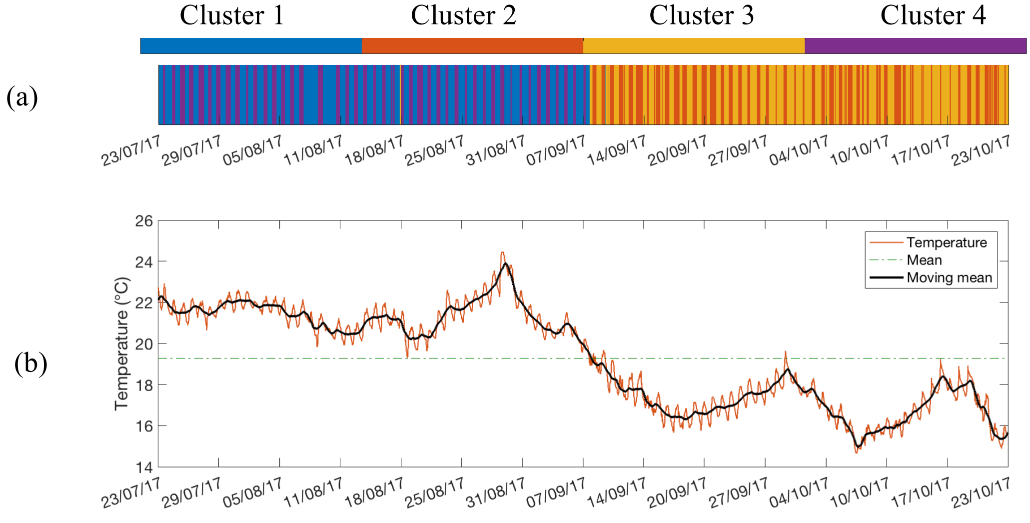


Figure 6.5. (a) Cluster distribution over time and (b) temperature distribution for comparison.

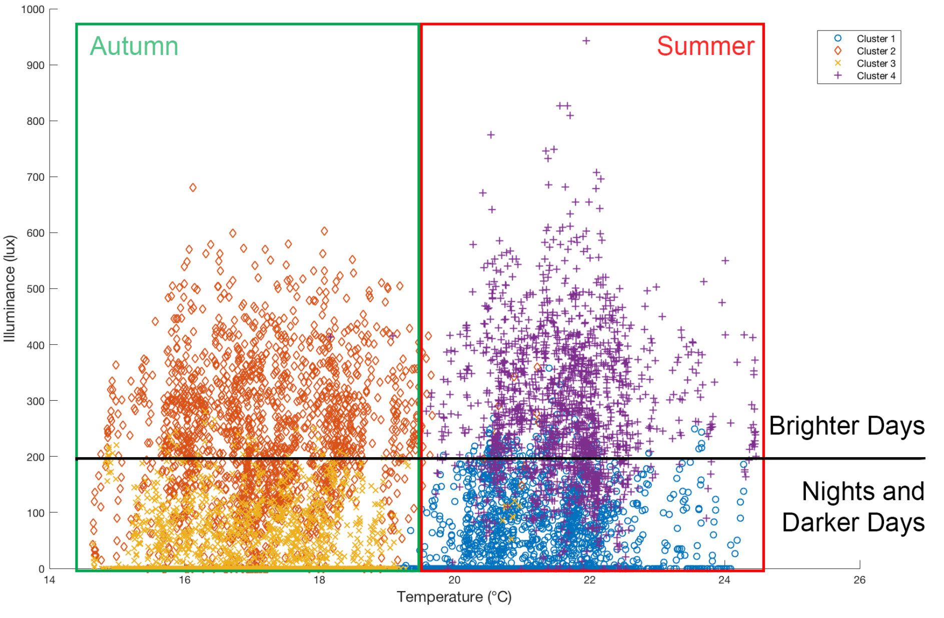


Figure 6.6. Cluster distribution for the plane temperature vs illuminance.

These distributions are also recognisable by plotting the clusters in the plane of temperature and illuminance (Figure 6.6). In this graph the clusters can be found in 4 different quadrants representing nights and darker days of summer (cluster 1), brighter days of summer (cluster 4), brighter days of autumn (cluster 2), and nights and darker days of the same season (cluster 3); confirming our previous interpretation.

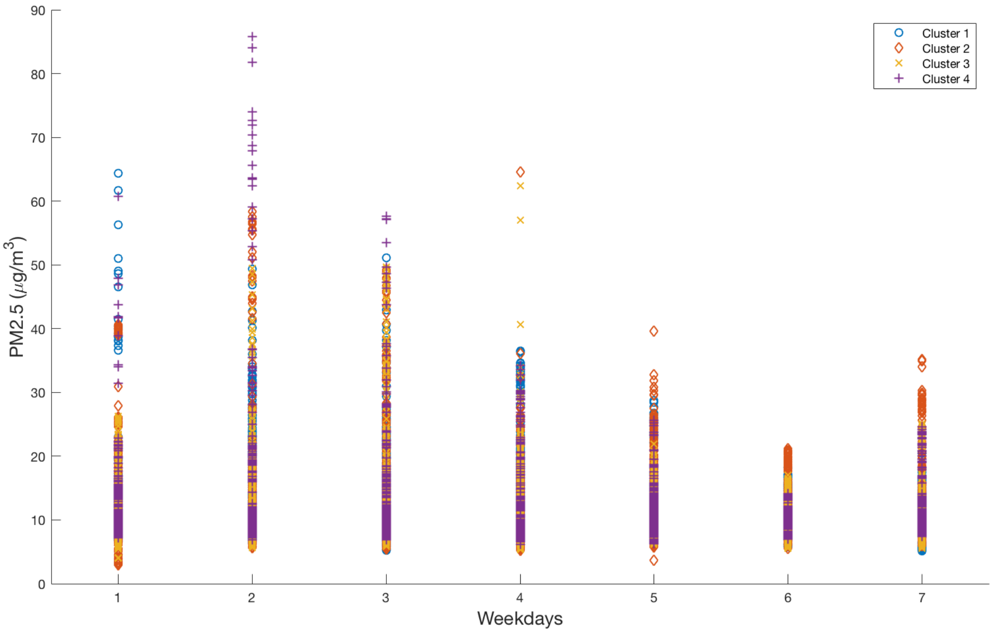


Figure 6.7. Cluster distribution regarding particulate matter and corresponding weekdays.

The analysis of the cluster distributions over different axes combinations can provide information about patterns in the environmental conditions. An example of this is presented in Figure 6.7, where we plot the behaviour of particulate matter for each cluster as a function of the weekday number. In this figure is observed that, independently of the season, the lowest values of particulate matter were reached during the weekends, especially on Saturdays. In contrast, the higher concentrations, linked to periods of elevated risk, were reached on Tuesdays during brighter summer days (cluster 4). The source of this increment in the particulate matter concentration is most likely related to the construction works going on during the period. However, we cannot discard the influence of other sources, such as heavier traffic on workdays compared to weekends; or different internal sources, like a larger number of visitants during summer holidays. Nevertheless, being able to identify that this particular behaviour is connected to specific weather conditions can facilitate the selection of mitigation actions and alert heritage guardians about the potential risk during periods with similar characteristics.

6.4. CONCLUSIONS

This study revealed that, on the basis of three simple suppositions, it is possible to identify periods of elevated risk without the use of any specific guideline. The proposed approach detects periods of sudden change that deviates from the standard behaviour and filters out the information concerning stable periods. Despite this, the method would fail for periods of constant inappropriate environmental conditions. Regardless of the actual value measured, the method will only report as anomalous the data points deviating from the typical behaviour, resulting in a potential misinterpretation of the inherent risk of degradation. Despite the stability of the environment, certain environmental conditions will lead to degradations damage (i.e., relative humidity above 75% will lead to mould grow). For that reason, we consider it as a complementary method, and not a substitution, to the use of norms or guidelines. However, in the cases where the application of direct guidelines is not a viable option, heritage guardians could still use our method to propose mitigation actions that would reduce the risk of degradation during the most extreme periods.

Our study also showed that the extended data matrix of environmental measurements does contain different types of patterns superposed on top of each other. By using clustering techniques, such patterns become easier to detect and interpret, facilitating the study of potential hazards.

CHAPTER 7

USER-FRIENDLY SOFTWARE FOR IAQ ASSESSMENT IN HERITAGE CONSERVATION

Based on:
Indoor air quality assessment in heritage conservation: development of a user-friendly software. *(Extended abstract)*
Diana Leyva Pernia, Serge Demeyer, Olivier Schalm, Willemien Anaf
In Proceedings of YOCOCU 2018, VI International Conference Youth in Conservation of Cultural Heritage, Matera, Italy, 23-26 May, 2018.

ABSTRACT
In order to give heritage guardians access to the assessment methods resulting from our research, we now present the development of a user-friendly software. The software allows an intuitive interpretation of environmental data and guides heritage guardians in environmental appropriateness assessments. The software-based data analysis tool combines and summarises monitored data of multiple environmental parameters into one versatile IAQ-index. The calculation of the IAQ-index is based on KRIs analysis and is material dependent. Its evolution over time is visualised using colour bars.

7.1. INTRODUCTION

The environment has a profound impact on heritage conservation [11-13]. That is why heritage guardians often perform environmental monitoring by continuously measuring temperature and relative humidity. However, heritage guardians are often lost in the data analysis and interpretation [13, 32]. Continuous measurements can be as frequent as one intake every minute, generating considerable large data streams in a very short period of time [30, 31]. On top of that, not only temperature and relative humidity are crucial environmental parameters: also visible light, ultraviolet radiation and pollutants should be considered harmful [87, 88]. Due to quickly evolving technology, it is expected that in near future, inexpensive sensors will be available that enable a more complete indoor air quality monitoring in heritage environments. This will lead to even larger data streams that still need to be further interpreted to assess the indoor air quality (IAQ).

In principle, the IAQ can be evaluated intuitively through our senses. However, this approach is very personal and results in common variations between stakeholders. To guide the heritage caretaker in indoor air quality judgements, the Belgian AIRCHECQ-project is developing a user-friendly software-based tool with an intuitive visualization of environmental datasets. The software estimates the IAQ on the basis of a rational method. A time-dependent IAQ-index quickly indicates the periods where the collection might be at risk. Such periods could be investigated in detail to detect the parameter(s) responsible for the inappropriate preservation conditions. The introduction of a summarizing IAQ-index is a fairly new concept in cultural heritage applications [35, 55]. The proposed index is a relative number that indicates periods of harmful environmental conditions. It can be used in evidence-based decision making, e.g., to select an appropriate mitigation action, or to evaluate an implemented one. Through the use of colour bars, the rational IAQ-index becomes accessible in an intuitive way. Such intuitive visualization has the advantage that IAQ information becomes accessible to heritage guardians with no expertise in environmental science or data processing. Moreover, it minimizes erroneous interpretations or conflicting opinions. In addition, the colour bars can be considered as a common language between stakeholders. Access to more information and improved communication ensure that heritage guardians are able to make better decisions.

7.2. MATERIALS AND METHODS

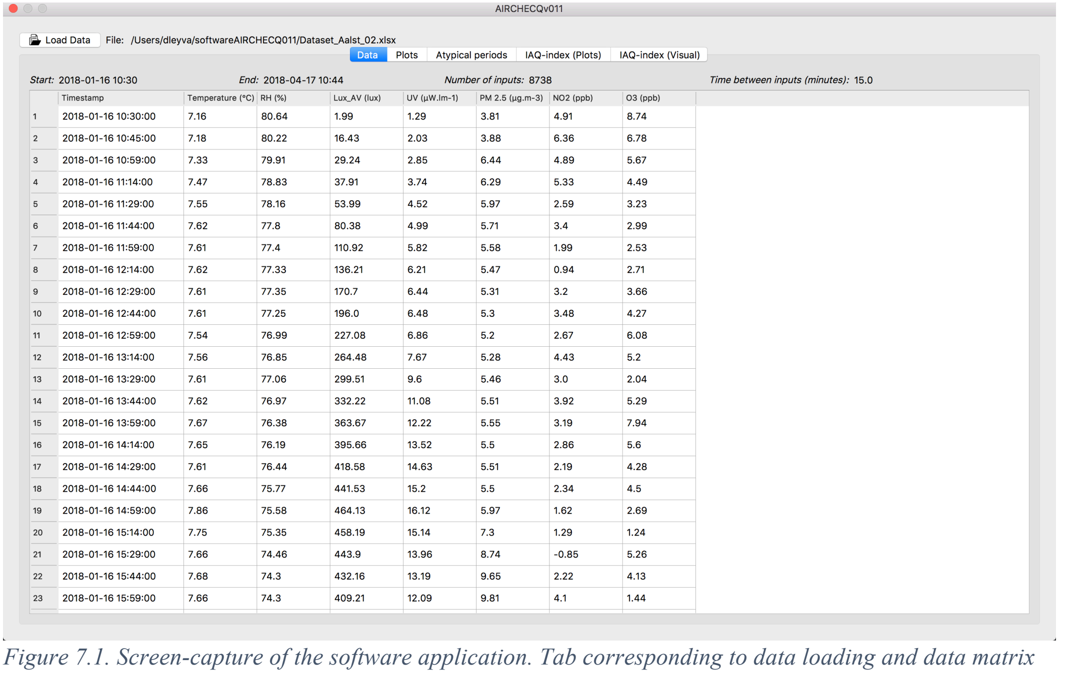
The first requirement to use our tool is having access to environmental data streams. To illustrate the software tool, we use a dataset collected in the 'Historic Gallery' of the Royal Military Museum, War Heritage Institute, Brussels. A huge and diverse collection is exhibited in the Historic Gallery, with costumes, headgears, flags, medals, weapons, cannonry etc. Two important material categories are textile and metal. In the current study, we focus more specifically on vegetable fibbers (e.g., cotton, linen) and iron.

Temperature and relative humidity were collected with a GMW90 (Vaisala, Finland). Illumination and UV radiation were monitored with a Hanwell ML4000UV/LUX (IMC group, Letchworth, Hertfordshire, UK). Particulate matter was collected with a DC1100 Pro Air Quality Monitor (Dylos Corporation, CA, USA). Data was collected every 15 minutes between 13/09/2016 and 10/10/2016.

The end user imports collected environmental data, and specifies a material of interest. Subsequently, the software calculates an indoor air quality index (IAQ-index). The IAQ-index is a single value between 0 to 1 that represents the degree of environment aggressiveness as a function of time. It considers the material-dependent target values and the relative importance of the key indicators. It is a relative number that does not quantify the deterioration rate or estimate the lifetime of materials. The evolution of the IAQ-index over time is visualised using colour bars. The initial draft of the software was built in Matlab R2017a, but the latest version was developed in Python 3.6 in order to make a free-access stand-alone application. We will focus in the description of this latest version: a software application of 1268 lines of Python code, available for macOs and Microsof Windows.

The software's backbone is based on a material-dependent input. A general set of 12 environmental key performance indicators has been defined, i.e., high relative humidity, low relative humidity, relative humidity fluctuations, high temperature, low temperature, temperature fluctuations, visible light, ultraviolet radiation, oxidizing gases, organic gases, sulphur reducing gases and deposited dust. For each key indicator, material-specific target values have been set based on standards, guidelines and expert experience. When the target values are met, the environment is considered as appropriate for that key indicator. The further away from the target values, the less appropriate the environmental conditions are. Since each material has its specific environmental sensitivity, material dependent weighing factors have been set to determine the relative importance of each key indicator. The weighing factors estimate the impact of each key indicator on the degradation and thus the preservation conditions of a material.

The graphical user interface was developed with the use of PyQt5 and Matplotlib libraries, resulting in an interactive software application with five distinctive tabs or areas where the end user can access the different functionalities provided. The first tab is devoted to loading the data streams from an external file and providing a table-based visualisation of the obtained data matrix (Figure 7.1).



	Timestamp	Temperature (°C)	RH (%)	Lux_AV (lux)	UV (µW.lm-1)	PM 2.5 (µg.m-3)	NO2 (ppb)	O3 (ppb)
1	2018-01-16 10:30:00	7.16	80.64	1.99	1.29	3.81	4.91	8.74
2	2018-01-16 10:45:00	7.18	80.22	16.43	2.03	3.88	6.36	6.78
3	2018-01-16 10:59:00	7.33	79.91	29.24	2.85	6.44	4.89	5.67
4	2018-01-16 11:14:00	7.47	78.83	37.91	3.74	6.29	5.33	4.49
5	2018-01-16 11:29:00	7.55	78.16	53.99	4.52	5.97	2.59	3.23
6	2018-01-16 11:44:00	7.62	77.8	80.38	4.99	5.71	3.4	2.99
7	2018-01-16 11:59:00	7.61	77.4	110.92	5.82	5.58	1.99	2.53
8	2018-01-16 12:14:00	7.62	77.33	136.21	6.21	5.47	0.94	2.71
9	2018-01-16 12:29:00	7.61	77.35	170.7	6.44	5.31	3.2	3.66
10	2018-01-16 12:44:00	7.61	77.25	196.0	6.48	5.3	3.48	4.27
11	2018-01-16 12:59:00	7.54	76.99	227.08	6.86	5.2	2.67	6.08
12	2018-01-16 13:14:00	7.56	76.85	264.48	7.67	5.28	4.43	5.2
13	2018-01-16 13:29:00	7.61	77.06	299.51	9.6	5.46	3.0	2.04
14	2018-01-16 13:44:00	7.62	76.97	332.22	11.08	5.51	3.92	5.29
15	2018-01-16 13:59:00	7.67	76.38	363.67	12.22	5.55	3.19	7.94
16	2018-01-16 14:14:00	7.65	76.19	395.66	13.52	5.5	2.86	5.6
17	2018-01-16 14:29:00	7.61	76.44	418.58	14.63	5.51	2.19	4.28
18	2018-01-16 14:44:00	7.66	75.77	441.53	15.2	5.5	2.34	4.5
19	2018-01-16 14:59:00	7.86	75.58	464.13	16.12	5.97	1.62	2.69
20	2018-01-16 15:14:00	7.75	75.35	458.19	15.14	7.3	1.29	1.24
21	2018-01-16 15:29:00	7.66	74.46	443.9	13.96	8.74	-0.85	5.26
22	2018-01-16 15:44:00	7.68	74.3	432.16	13.19	9.65	2.22	4.13
23	2018-01-16 15:59:00	7.66	74.3	409.21	12.09	9.81	4.1	1.44

Figure 7.1. Screen-capture of the software application. Tab corresponding to data loading and data matrix visualisation.

In the second tab the user can generate and export the direct visual representations of the data streams under investigation. These representations can be either line graphs of each environmental parameter's evolution (Figure 7.2), or scatter plots reflecting the relations between two of the measured parameters (Figure 7.3). The third tab provides information related the presence of atypical periods in the data streams applying the method introduced in chapter 6 (Figure 7.4).

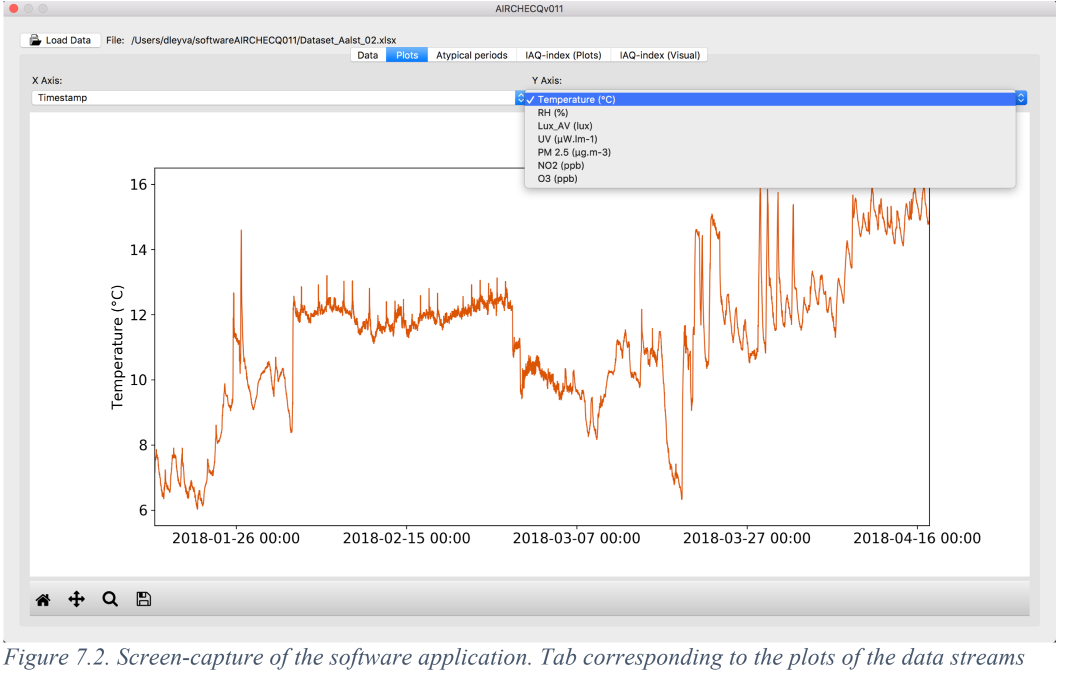


Figure 7.2. Screen-capture of the software application. Tab corresponding to the plots of the data streams (line graphs).

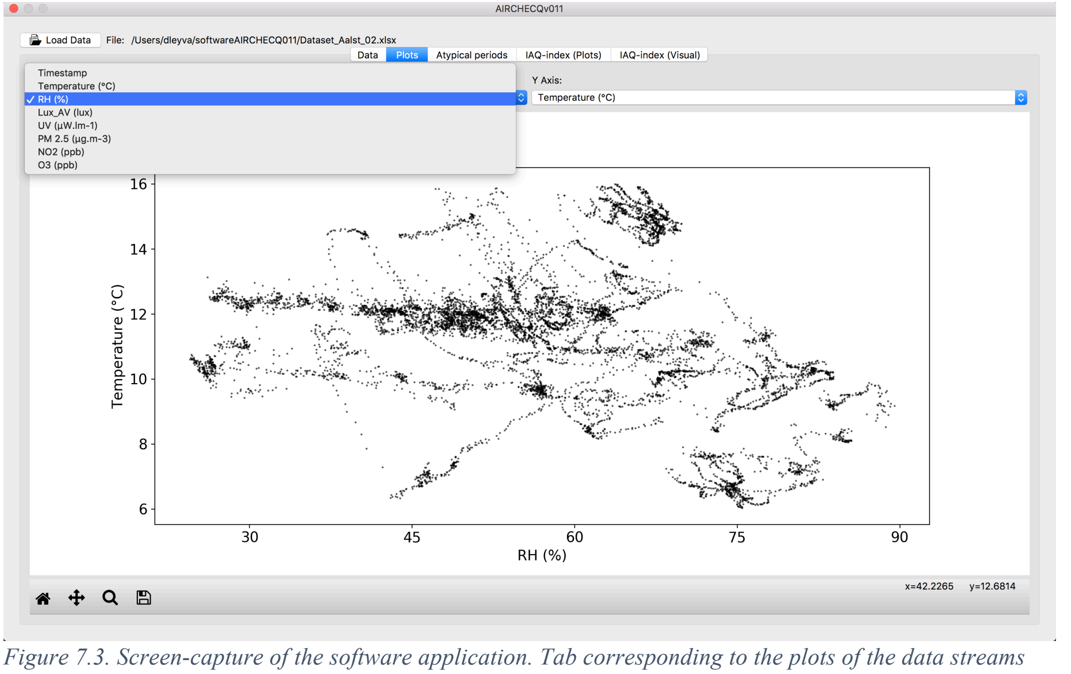


Figure 7.3. Screen-capture of the software application. Tab corresponding to the plots of the data streams (scatter plot).

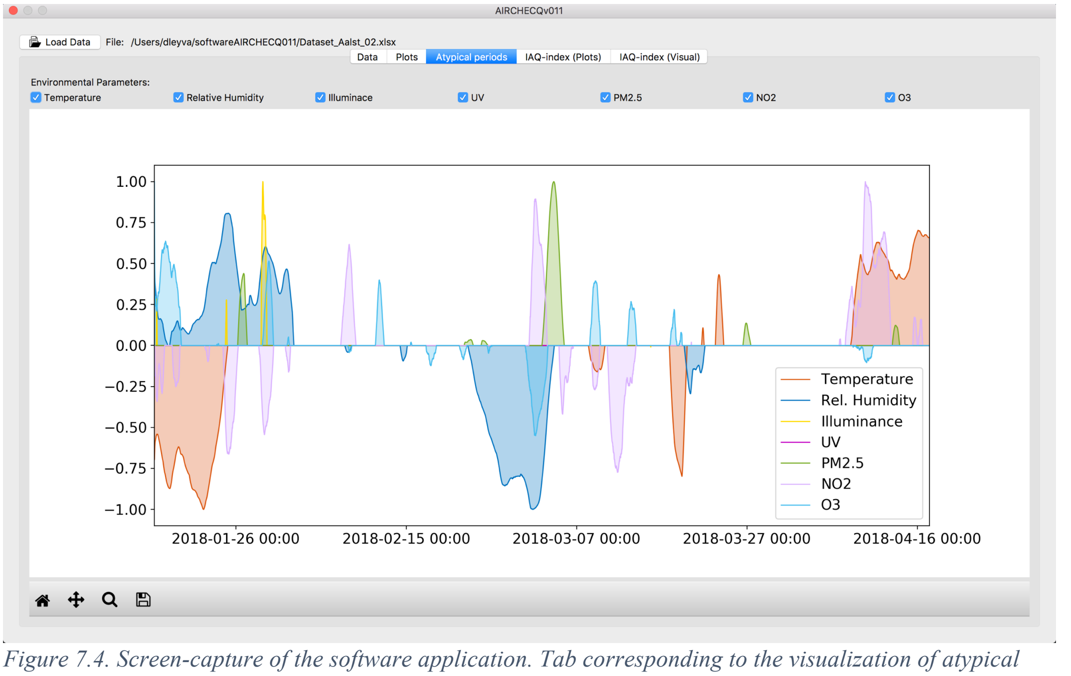


Figure 7.4. Screen-capture of the software application. Tab corresponding to the visualization of atypical periods.

The information regarding the material-specific IAQ-index is available in the fourth and fifth tabs. In the fourth tab (Figure 7.5) the end user can generate the line graphs for the numerical representation of the general IAQ-index, or the parameter-specific indices. This can be done for each one of the materials presented in the table 5.1. The visual representation of these indices can be generated in the fifth and final tab (Figure 7.6). In this case there is also the possibility of selecting the colour maps for the IAQ-index representation. The user can select on option out of a list of five different colour maps available in Matplotlib libraries: Jet (reversed), Green-Yellow-Red, Viridis, Hot and Grey.

All the graphs generated with the software can be zoomed in, zoomed out, navigated, reset to its original stated, or exported by means of the elements available the common tool bar.

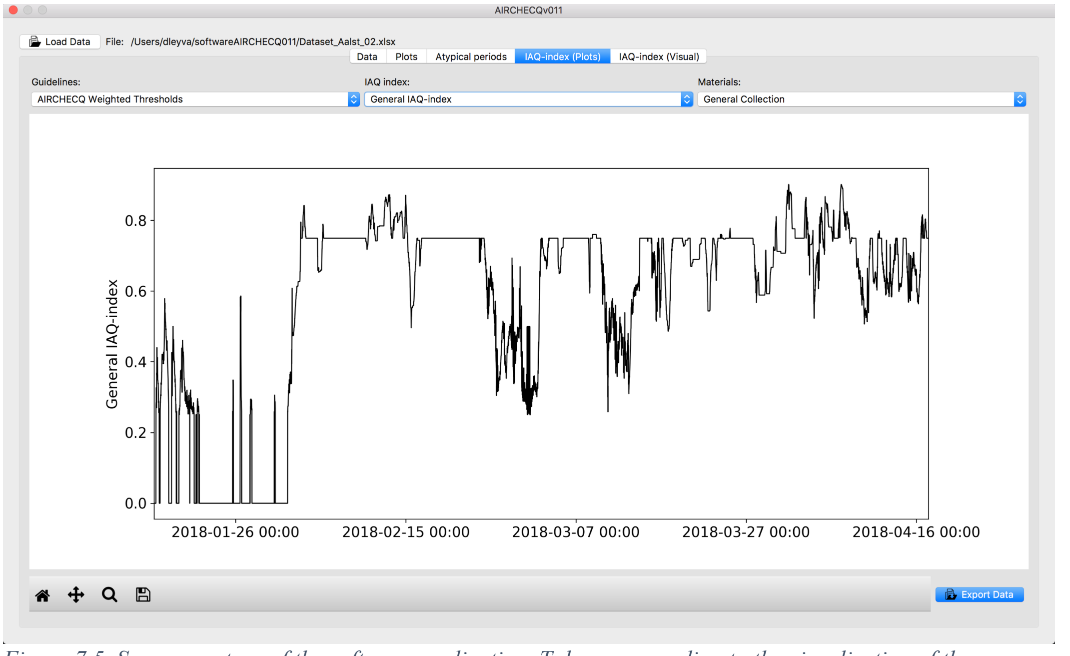


Figure 7.5. Screen-capture of the software application. Tab corresponding to the visualization of the numerical value of the IAQ-index.

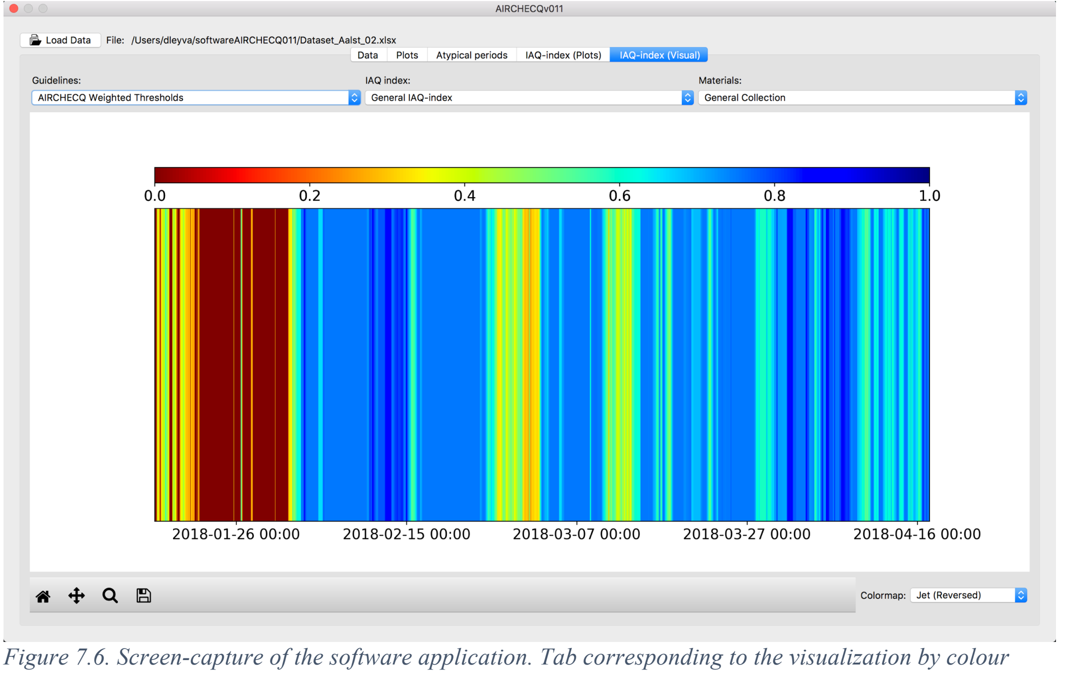


Figure 7.6. Screen-capture of the software application. Tab corresponding to the visualization by colour bars of the IAQ-index.

This version of the software was presented in the second AIRCHECQ Worksop (22 of October of 2018, Antwerp, Belgium) to a group of approximately 20 potential end users from different Flemish institutions. During the experimental session of the workshop, the participants tested the software with real data streams from their own institutions, or from some of our measuring campaigns. At the end of the session we performed a small survey to evaluate the overall user experience, where the participants answered the following questions:

1. Was the software user-friendly? *(Yes, No, I don't know)*
2. Does the software have practical applicability in your institution? *(Yes, No, I don't know)*
3. Does the software offer you added value in comparison with existing data interpretation? *(Yes, No, I don't know)*
4. Does the numerical value IAQ-index provides added value? *(Yes, No, I don't know)*
5. Which colour map was the most intuitive? *(Jet (Reversed), Green-Yellow-Red, Viridis, Hot, Grey)*
6. Platform preference? *(Stand-alone application, Web application, No preference)*

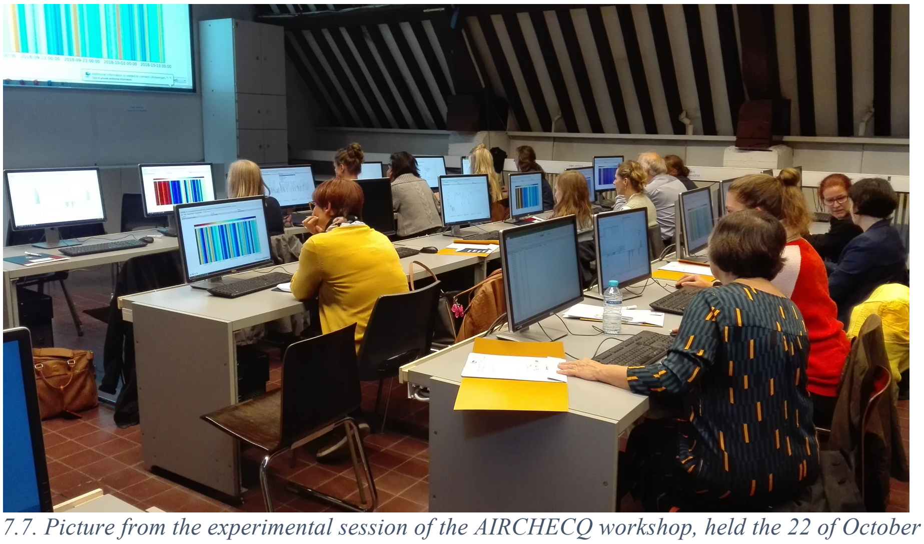


Figure 7.7. Picture from the experimental session of the AIRCHECQ workshop, held the 22 of October of 2018 in Antwerp, Belgium.

7.3. RESULTS AND DISCUSSION

Figure 7.8 shows line graphs for the different measured parameters over time generated for the analysed data streams. From such graphs we can observe the individual behaviour of each environmental parameter, however, it is hard to quickly judge how good the preservation conditions are for a certain material. Figure 7.9 shows the IAQ-indices of the same dataset visualised in colour bars, for both iron and vegetable fibbers. Blue periods are appropriate, while orange to red colours indicate periods where the collection might be at risk. With this visual summary, it quickly becomes clear that the conservation conditions in the Historic Gallery are generally more appropriate for iron compared to vegetable fibbers.

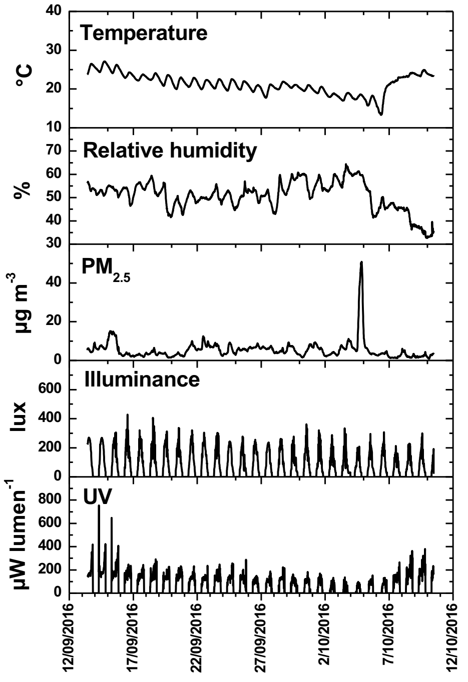


Figure 7.8. Graphical visualization of the monitored data radiation.

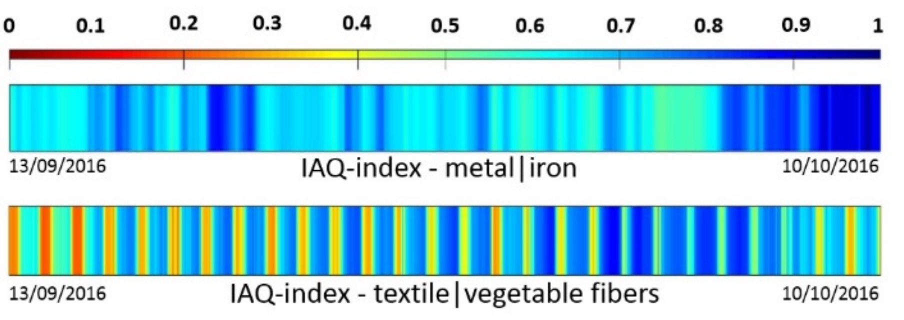


Figure 7.9. IAQ-index for both iron and vegetable fibbers.

For the vegetable fibbers, a clear periodic event is present. The origin of such events can easily be determined by looking at the individual parameters, which are also visualised in colour bars. Figures 7.10 and 7.11 show such colour bars for iron and vegetable fibbers, respectively. For iron, humidity and dust particles are the environmental parameters that impact the IAQ-index. For vegetable fibbers, more different parameters influence the IAQ-outcome. Temperature, light and ultraviolet radiation have the worst conditions. The periodic events that are visible in the IAQ-index, is due to day and night cycles of light irradiation.

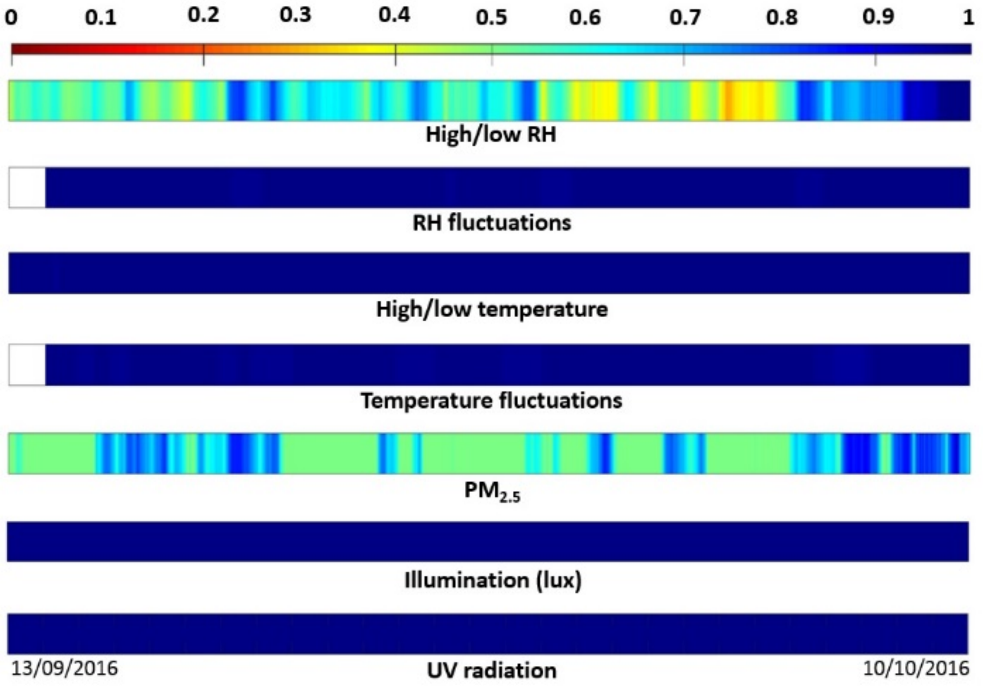


Figure 7.10. Colour bars of the individual parameters for iron.

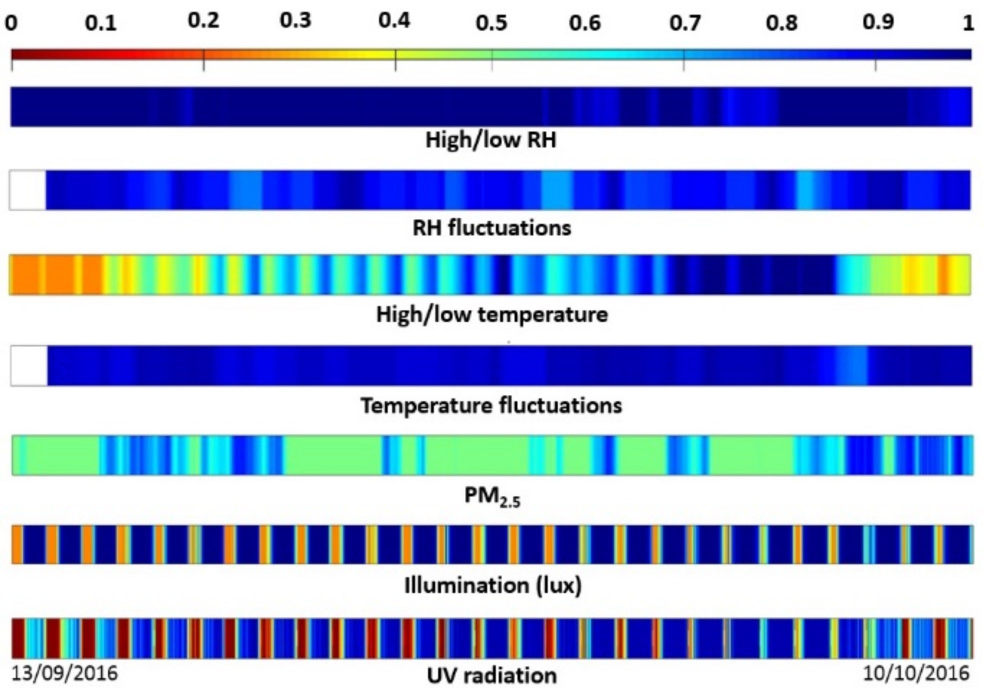


Figure 7.11. Colour bars of the individual parameters for vegetable fibbers.

To appropriately use the software tool, all relevant environmental parameters for the material of interest should be monitored. If not, this could result in false results. For example, radiation is an important parameter for vegetable fibbers, and textile in general.

If this parameter wouldn't have been included in the IAQ-index calculations, the harmful daily irradiation events would have been ignored, resulting in a false sense of confidence.

The survey carried out at AIRCHECQ workshop portrays a rather positive user experience. The 100 % percent of the replies to question 1 classified the software as user-friendly, a 93 % confirmed practical applicability in their institutions, 92% considered that the presented approach provided added value when compared to existing data interpretations, and approximately the 78 % found added value in the numerical representation of the IAQ-index (Figure 7.12).

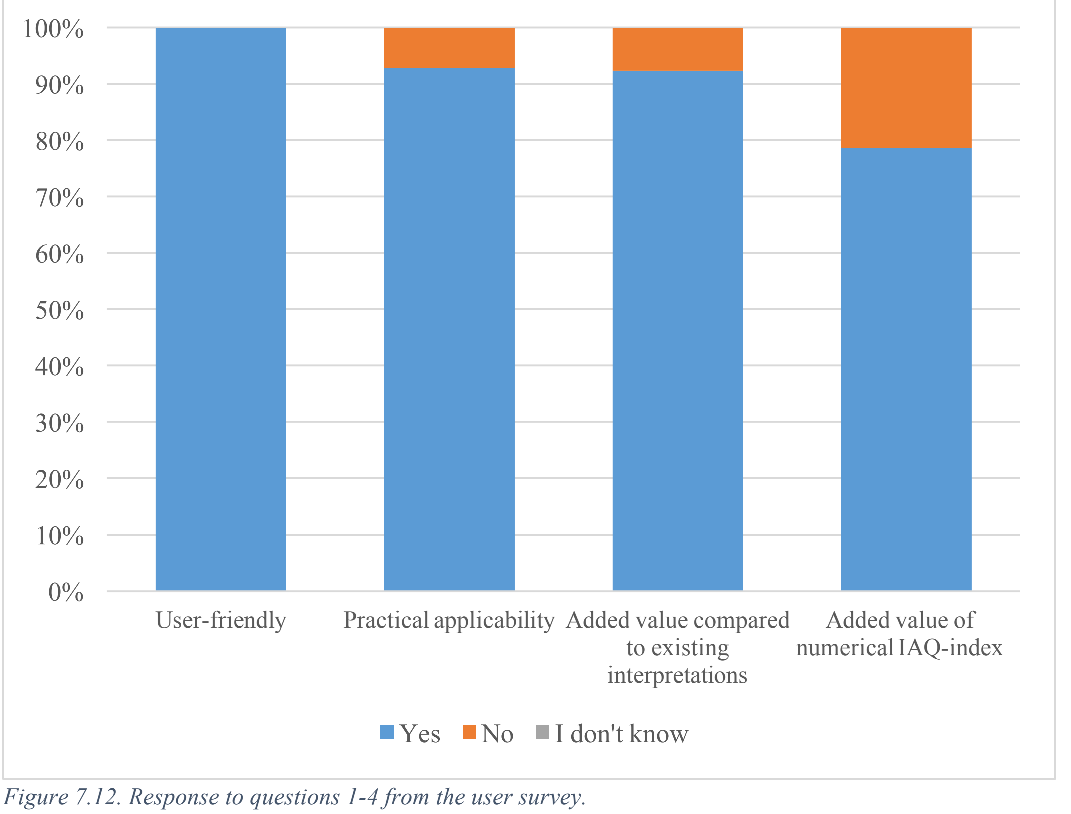


Figure 7.12. Response to questions 1-4 from the user survey.

Regarding to the perception of the users about the available colour maps, 59 % found the reversed Jet colour map as the most intuitive, 23 % preferred the Green-Yellow-Red transition, 6 % selected Viridis, 12 % Hot and 0 % found the Grey colour map intuitive. For the last question regarding platform preference for the software, 57 % of the answers chose the stand-alone application format, 29 % had no preference and only a 14 % would rather use a web application.

A web application can provide several advantages: they do not require updating and all the data and settings will be accessible on multiple devices. However, a stand-alone application provides the advantage of a more controlled and private handling of the data, since the information never leaves the user's local device. Some institutions consider their environmental data as sensitive information, therefore, is reasonable to expect a preference for a more secure approach to the management of such data. All the surveyed users tested the software with multiple data streams, and some of them could also analyse their own legacy data.

7.4. CONCLUSIONS

The software-supported calculation of an IAQ-index highly simplifies the analysis and interpretation of large data streams. Data visualization by using colour bars makes the output intuitive, and heritage guardians can easily use it as a support for their indoor air quality judgements. The software is considered user-friendly and, despite the room for improvement, it has received a positive reception in the local heritage community.

CHAPTER 8

CONCLUSIONS

The IAQ assessment has a significant impact on heritage conservation. Correctly managing the IAQ is vital to minimize further damage to historical artifacts and works of art; therefore, it is crucial for heritage guardians to assess it and keep track of its evolution correctly. Despite its potential impact, the traditional assessment of the indoor air quality still represents a challenge for most collection guardians. This approach typically relays on the comparison of considerable large amounts of measured environmental parameters and corresponding acceptable values. However, the information about these the acceptable values and relative importance of the different environmental parameters turns out to be contradictory, and usually focus on the general qualitative behaviour during a specific period.

In this thesis, we provided a direct method to assess, quantify and visualise the IAQ. By implementing the presented method, we were able to offer a comprehensive assessment, and an intuitive and consistent representation of the quality criteria characterizing the IAQ.

8.1 SUMMARY OF CONTRIBUTIONS

IAQ-index and Standards:
We propose the assessment of the IAQ through a unique numerical index to transform environmental data into quality judgments. This direct representation of the IAQ provides the possibility of a straightforward interpretation of its behaviour. Its implementation simplifies the analysis of large volumes of data, making the IAQ assessment more accessible and less time consuming. The results presented demonstrate the possibility of easy detection of potentially hazardous situations, while still allowing the identification of the environmental parameter responsible.

We first based our analysis in the quality criteria proposed by different guidelines or norms already recognised by the heritage community. With this approach, we were able to incorporate the influence of multiple environmental parameters on heritage degradation into the IAQ-index. This was done by covering multiple combinations, from the most typical cases like temperature and relative humidity to a more inclusive version also including illuminance, ultraviolet radiation, particulate matter or pollutant gases.

Using this method, we were able to explore the variations in the assessment outcome caused by the different recommendations considered in the environmental guidelines for heritage conservation. We were able to quantify the quality criteria of five different well-known guidelines and observe a reasonably consistent behaviour despite the characteristics of the environmental dataset analysed. The outcome of the assessments reflects a considerable variation depending either on the guideline selection, or interpretation of the data (i.e., statistical characterization of the data); reaching in some extreme cases completely opposite classifications.

IAQ-index and Weighted Thresholds:
In order to tackle this dependency and estimates the IAQ in a standardized way, we proposed an assessment based multiple material-specific criteria. This method considers on the influence of Key Risk Indicators and is based on the use of conversion functions to calculate the level of degradation risk for a specific material or object type. The introduction of an overall IAQ-index and its visualization in colour bars simplifies the analysis and interpretation of large data streams and a wide range of parameters that can be measured simultaneously.

Data Mining:
We were also able to explore the possibilities of a threshold-free analysis using Big Data related techniques. With this approach we could detect periods of sudden change that deviates from the standard behaviour, while filtering out the information regarding stable periods. Despite is independence on threshold values or guidelines, the method would fail for periods of constant inappropriate environmental conditions. For that reason, it is proposed as complementary method, and not a substitution, to the use of norms or guidelines. We could also determine that the extended datasets of environmental measurements do contain different types of patterns superposed on top of each other. By using clustering techniques, such patterns become easier to detect and interpret, facilitating the study of potential hazards.

Software:
As a final step we were able to provide a user-friendly software to support the calculation of the IAQ-index. This offers heritage guardians a practical tool that helps them understand their indoor air quality. It highly simplifies the analysis and interpretation of large data streams by means of an intuitive visualization based on colour codes, and heritage guardians can easily use it as a support for their indoor air quality judgements. The tool has been presented in different venues (international and national workshops) with a very positive reception from the heritage community.

8.2 OUTLOOK

The improvement of our knowledge on material degradation caused by environmental conditions, the necessity of less energy-intensive preventive measures and the very case-specific requirements for individual heritage conservation will keep evolving our judgements on IAQ assessment. Our main goal with this thesis was to provide the heritage community with a practical method to already assess and understand their indoor air quality. However, it should be expected that this interpretation will require further revision and expansion. For example, the inclusion of other pollutant agents, like volatile organic compounds, could provide a more accurate IAQ assessment, since these compounds are closely link to multiple chemical reactions resulting in heritage degradation [89]. Another possibility could be including further material specific considerations for a more personalized analysis.

There are also multiple possibilities of growth in the area of Big Data based applications for IAQ assessment. We could still explore multiple machine learning algorithms, employed for either data classification or prediction. Unsupervised deep learning methods, like the application of convolutional neural networks, could already be applied in our specific field. However, it requires the use of accurately labelled data, which we do not have available.

Regarding to the presented software, we expect to improve it over future iterations based mainly on user's feedback and possible evolution of our assessment methods.

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