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Indoor environmental quality index for conservation environments: The importance of including particulate matter

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A B S T R A C T

It is commonly known that the conservation state of works of arts exhibited inside museums is strongly influenced by the indoor environmental quality (IEQ). Heritage institutions traditionally record and evaluate their IEQ by monitoring temperature, relative humidity, and -more rarely-light. However, smart use of technology enables monitoring other parameters that give a more complete insight in environmental 'air aggressiveness'. One of this parameters is particulate matter (PM) and especially its concentration, size distribution and chemical composition. In this work, we present a selection of data sets which were obtained in a measuring campaign performed in the War Heritage Institute in Brussels, Belgium. A continuous monitoring of PM concentration with a light scattering based particle counter was performed. In addition the daily mass concentration and size distribution of airborne PM was monitored by means of Harvard impactors. The chemical composition of sampled PM was inferred from the results of XRF and IC analysis. The insights from these datasets are combined with the results of traditional environmental monitoring (temperature, relative humidity and light intensity), and assessed against the recommended guidelines for conservation environments. By using an integrated approach based on the calculation of an IEQ-index, we present a straightforward methodology to evaluate and visualize the IEQ including also continuous PM monitoring. It is clear from the results of this study how including PM in IEQ analysis allows to identify potential risks for museum collections that remain invisible when only traditional parameters are considered.

1. Introduction

In order to protect and conserve the relics of human history, it is important to address the environmental factors that may cause damage to museum collections and cultural heritage in general. Consequently, continuous indoor environmental quality (IEQ) measurements are a prerequisite to evaluate best practices in an exhibition or storage environment.

Currently, the continuous evaluation of conservation environments is usually based on physical parameters only, such as temperature, relative humidity and the intensity of visible (Vis) and ultraviolet (UV) light [1–9]. It is generally accepted that these parameters pose the largest threat towards hygroscopic and light sensitive objects, influencing also the conservation of general collections [10]. Several commercial systems are available on the market to monitor these physical parameters. However, deterioration is also influenced by gaseous pollutants and particulate matter (PM) [11–16]. A large number of studies taking into account the average levels of these pollutants in conservation environments has been published through the years [17–28]. However, only in few cases a continuous monitoring was performed [29–32]. This can be explained for gaseous pollutants by the lack of suitable sensors for a continuous and sensitive monitoring. The

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commercially available sensors for common pollutants such as O_3, NO_2, SO_2, H_2S, formaldehyde and acetic acid [33–42] are usually created for industrial applications and present limit of detections higher than the recommended levels in conservation environments [43]. On the other hand, PM can rather easily be continuously monitored using airborne particle counters based on light scattering principles. Both precise and accurate sensors created for clean rooms monitoring and inexpensive sensors for home or office applications exist [44–46]. However, these systems are not yet employed to their full potential in cultural heritage.

In this article, a system is presented that enables the continuous monitoring of temperature (°C), relative humidity (%), illuminance of visible light (lux), UV light intensity (mW/m^2) and PM concentration (number of particles/m^3) in a simultaneous and synchronous way. Extended measuring campaigns were performed at two locations in the former Royal Museum of the Armed Forces and of Military History, or shorter Royal Military Museum, in Brussels, Belgium. The Royal Military Museum is integrated in the War Heritage Institute (WHI) since May 1st, 2017 [47]. Since the risk associated with the presence of airborne PM in conservation environments strongly depends on the concentration and aerodynamic dimension of the particles [27,48], but also on their chemical composition [13,14,49–51], the continuous monitoring is supplemented by an in depth chemical analysis of PM. The total mass concentration and chemical composition of fine (PM_1, $PM_{2.5}$) and coarse particles (PM_{10}) is analyzed. This qualitative and quantitative analysis of PM allows to register sudden changes of the indoor environmental quality which are invisible with physical parameters. The available guidelines for conservation environments are then used to calculate an IEQ-index [52] by combining the information of temperature, relative humidity and light exposure with that of PM. No univocal guideline has been found in literature prescribing an optimal PM concentration for conservation environments expressed in number of particles per unit volume. A mass per unit volume threshold is therefore considered and converted into number of particles/m^3 values on the basis of site-specific empirical correlations. Taking into account the extreme variety of objects exposed in the museum, the ASHRAE maximum limit for general collection of 10 $\mu g/m^3$ for $PM_{2.5}$ is applied [1].

This article discusses in detail how and why continuous PM data should be included in indoor environmental quality studies. The versatile methodology discussed can be applied to the monitoring of environmental quality in any type of indoor conservation environment. When the main concern is directed towards objects or materials with more specific needs, potentially dangerous conditions can be promptly recognized by simply changing the threshold values applied in the calculation of the IEQ-index.

2. Materials and methods

2.1. Sampling locations and campaigns

The Royal Military Museum is located in the Parc du Cinquantenaire area in the city center of Brussels in Belgium (50°50′29.4″N 4°23′31.6″E). The building dates from the end of the 19th century. The collections of the Royal Military Museum, now integral part of the War Heritage Institute (WHI), illustrate ten centuries of military history ranging from medieval times up until this day. The more than 125,000 objects include amongst others uniforms and headgear, edged weapons and firearms but also paintings and sculptures, medals and music instruments. The museum building even houses airplanes, armored vehicles and artillery. The collections consist of an extremely wide range of materials. The museum occupies five large exhibition galleries covering approximately 40,000 m^2.

First, measurements were performed in one location from April 11 to April 24 in 2016, followed by a period in a second place from April 25 to May 9 in 2016. The first location is the central storage facility situated underground (further indicated as ‘storage’), the second location is the Historic Gallery, situated at the ground level of the Army museum and further indicated in the text as ‘gallery’ (Fig. 1).

The collection stored in the storage is a mixed collection, including paintings, textiles, leather, metal, stone and ceramic objects. The measuring equipment was located in the central alley of the storage. This space is equipped with a HVAC-system with two different types of filters (TL7U600 class F7 and TM9U600 class F9, AL-KO KOBER SE, Germany) to control environmental conditions and PM levels. The storage is located above a highway tunnel and indirectly connected to it through a shared emergency exit. This connection could negatively affect the IEQ in this environment, potentially causing high levels of gaseous pollutants and particulate matter.

The gallery was inaugurated in 1923 and is dedicated to the Belgian army between 1831 and 1914. It houses a collection consisting of hundreds of oil paintings on canvas, uniforms, flags, weapons and musical instruments. The gallery has a large roof with a skylight that enables direct sunlight entering (Fig. 1), causing a severe temperature increase on sunny days. In winter period the gallery is heated but no cooling nor humidity control are installed. This strongly influences the thermo-hygrometric conditions for the collection. The gallery is not equipped with an air filtering system, which also might affect the PM levels. The objects are exhibited on the walls and in oaken display cases originating from the early 20th century. This type of display cases has a high air exchange rate, allowing infiltration of dust [53,54].

The very different environmental conditions in the two locations do not allow to obtain an overview of the conservation conditions in the whole museum, but represent an ideal context for testing the methodology discussed in this work. The “controlled” environment in the storage and the “uncontrolled’ environment in the gallery, in fact, ideally represent the two extremes of the possible range of conditions that can be found in this conservation environment.

2.2. Monitoring of environmental parameters (temperature, relative humidity, Vis and UV light, CO_2)

The monitoring of environmental parameters was performed with a frequency of 15 min during the sampling campaigns. For simplicity, and to underline the difference between these monitoring techniques and other PM sampling methods used, this “semi-continuous” monitoring will be referred to as “continuous” throughout the rest of this article. Well-calibrated, commercial off-the-shelf sensors were connected to a multi-purpose data logger (DataTaker DT85, Thermo Fischer scientific, Australia) [55]. Data was available online using a 4G network. Temperature, relative humidity and carbon dioxide (CO_2) were measured with a GMW90 sensor (Vaisala, Finland) [56], while the intensity of visible and UV light were measured with the sensors SKL310 [57] and SKU421 [58] (Skye Instruments, UK). For the light sensors, the orientation and distance from the light source have a substantial impact on the intensity. The sensors were placed in a vertical position to simulate vertically stored objects (e.g., paintings). To monitor the real light exposure, the sensors should be placed next to the object of interest. The monitoring unit and its sensors were placed on a table at a height of 1.10 m. This corresponds with the average height of the lower edge of exhibited paintings [59].