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New generation monitoring devices for heritage guardians to detect multiple events and hazards

O Schalm[1,2], W Anaf[1,3], J Callier[3,4] and D Leyva Pernia[5,6]
[1] Conservation Studies, University of Antwerp, Blindestraat 9, B-2000 Antwerp, Belgium
[2] Antwerp Maritime Academy, Noordkasteel Oost 6, B-2030 Antwerp, Belgium
[3] War Heritage Institute, Renaissancelaan 30, B-1000 Brussels, Belgium
[4] Royal Museum of Fine Arts of Belgium, Museumstraat 9, B-1000 Brussels, Belgium
[5] Computer Science, University of Antwerp, Middelheimlaan 1, B-2020 Antwerp, Belgium
[6] Department of Physics, CEADEN, 502, Calle 30, 11300 Havana, Cuba

E-mail: olivier.schalm@uantwerpen.be

Abstract. Environmental parameters such as temperature, relative humidity, visible light, UV radiation and pollution influence the deterioration rate of heritage items. To judge on the environmental appropriateness for heritage conservation, it is therefore important to monitor the environment. Often, an incomplete set of environmental parameters is measured, or sporadic or time-averaged measurements are performed. As a result, a wide range of undesirable situations and hazards remain unnoticed. This might lead to an underestimation of environmental dangers (i.e., inaccurate judgement) or to inappropriate mitigation measures (i.e., inaccurate decision making).

We present an innovative and user-friendly monitoring device that simultaneously and continuously measures (1) environmental parameters and (2) material behavior. An extended combination of off-the-shelf sensors for temperature, relative humidity, air speed, CO_2, NO_2, O_3 and particulate matter are connected to a multipurpose datalogger. In-house developed sensors for the shrinkage and expansion behavior of wood, as well as sensors for metal corrosion rates are connected to the same datalogger. Such extended monitoring shows the identification of a wider range of undesirable situations, and it facilitates the search for correlations between such situations and the sources that cause them, i.e., the hazards.

1. Introduction

Scientific studies on heritage degradation and preventive conservation often focus on the (mathematical) relation between the object's degradation rate and its environment [1]. Although precise relations vary from object to object, an average relation could be assumed. This means that monitoring the environment gives substantial information on the degradation rate of heritage objects. Usually, the environmental appropriateness is estimated from temperature and relative humidity measurements. However, it is known

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that many other parameters such as visible light, UV radiation or pollution affect the degradation rate as well. Since many relevant parameters remain invisible with the commonly used monitoring systems, underestimation of environmental dangers might occur.

Studies in preventive conservation often fit within a well-defined framework of risk management [2]. Although risk refers to the future, examples of past damage are considered as they illustrate what might happen in future. The risk approach supposes that the accumulation of harm is governed by a sequence of randomly occurring incidents. Up to the authors' knowledge, the application of that approach on environmental data streams has not been used to its full potential. To apply the approach on environmental data streams, 3 types of undesirable situations are distinguished: dangerous occurrences, events and incidents. All three concepts define periods with elevated risk but with increasing risk level.

- **Dangerous occurrence:** Reportable period with elevated though limited risk for accelerated accumulation of harm;
- **Event:** Reportable period where at least 1 environmental parameter exceeds the corresponding guideline and where the risk for accelerated accumulation of harm is significant;
- **Incident:** Reportable period where the environmental conditions induce harm to at least 1 object.

Periods with elevated risk might remain invisible when only temperature and relative humidity are monitored. For example, housekeeping or moving actions in a museum environment may cause a sudden rise in particulate matter (PM). NO_2 and black carbon concentrations may significantly increase inside buildings due to traffic rush hours. In order to detect periods of elevated risk, a multi-sensor tool that combines off-the-shelf sensors for temperature, relative humidity, light, UV radiation, CO_2, NO_2, O_3, particulate matter, air speed, and human activity is developed. To directly monitor material behavior, in-house developed sensors for the shrinkage and expansion behavior of wood surfaces, as well as sensors for metal corrosion rates were incorporated in the monitoring system. The possibilities of the multi-sensor tool to identify undesirable situations are explored with a pilot study. By identifying undesirable situations, actions could be taken to avoid hazards to occur in future. The hazard is the potential source of harm that causes the period of elevated risk.

2. Materials and method

2.1 Sampling location

Monitoring has been performed in a late Gothic church in the center of a small Belgian city. The multi-sensor tool was located at the organ loft at a height of around 7 meter. Data collection started on 03/07/2017 and will continue until the summer of 2018 in order to collect one year of data. For the current article, the period from 23/07/2017 to 23/10/2017 was selected, including the transition from summer to autumn. This period was dominated by the installation of a new 'cold air' heating system. This means that there was no heating, that doors were regularly open and that the construction works generated dust. All precious objects of art were protected behind plastic foils with openings covered with Tyvek®.

2.2 Multi-sensor tool

The multi-sensor tool's backbone is a multi-purpose data logger (DataTaker DT85, Thermo Fischer scientific, Australia) to which sensors for a wide range of environmental parameters are connected. The total cost of the multi-sensor device was around 7000. Data of temperature (T), relative humidity (RH) and CO_2 were collected with a GMW90 (Vaisala, Finland). The intensity of visible and UV light were monitored with the upward positioned sensors SKL310 and SKU421, respectively (Skye Instruments, UK). Air speed was measured with a HD403TS omni-directional hotwire sensor (Delta Ohm, Soest, The Netherlands). Concentrations of NO_2 and O_3 were collected with NO2-A43F and OX-A431 sensors from Alphasense (Essex, UK). Particulate matter was collected with a DC1100 Pro Air Quality Monitor (Dylos Corporation, CA, USA). The measured concentration in number of particles m^{-3} has been converted into $\mu g\ m^{-3}$ using an empirical formula provided by the supplier. Human activity was measured with a passive infrared motion sensor with a detection range of 10 m (Panasonic Electric Works, Osaka, Japan).

Besides the environmental parameters, the behavior of two materials was monitored as well. The shrinkage and swelling of the surface of a cube of 16th century oak with a volume of 10 dm^3 was monitored by adhering a PFLW-30-11 strain gauge on the wood using the corresponding PS adhesive (TML, Tokyo). The wood originates from a beam of a historic house and was dated by means of dendrochronology. The beam was not in its original position anymore, but kept in the basement of the house. A small piece was sacrificed to be used as a sensor. The metal corrosion sensor is an atmospheric electrical resistance (ER) probe Model 610 consisting of Ag with a thickness of 250 nm (Cosasco Corrosion Monitoring and Chemical Management Systems, Santa Fe Springs, CA, USA). The resistance of this sensitive probe increases with progressing corrosion [3]. The wood and silver sensors were directly attached to the data logger using a Wheatstone bridge.

All sensors were read out in phase with a frequency of 1 minute, and 15 minute averages were saved by the data logger. The air speed sensor is the exception, for which the maximum speed within each 15 minutes time interval is stored. Data could be downloaded wirelessly using a 4G router.

2.3 Data processing

The stored data consists of a matrix of measuring points that are organized as rows. Each measuring point consists of the timestamp and the series of sensor readouts. The parameters measured are organized as columns. In-house developed software written in MATLAB combines the readouts of the different environmental parameters from the same measuring point and converts them in an overall indoor air quality index (IAQ-index). The IAQ index is calculated by (1) comparing each measured parameter with published target values, and (2) considering the importance of each measured parameter, since not all parameters endanger a collection to the same extent. The time dependency of the IAQ-index is visualized in a color bar. For this, the IAQ-values are associated to the jet color map used in MATLAB. A dark blue color is assigned to an appropriate environment, while a red color indicates an environment with elevated risk. More information about this data processing can be found elsewhere [4].

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3. Results

All environmental data are plotted as scatter plots where measuring points are connected with lines (Figure 1a, with Figure1b a one week detail). Dangerous occurrences, events and incidents could be identified as sharp peaks that arise on top of a relatively constant background level. This is clear for all plotted parameters except for temperature and relative humidity. For the latter parameters, undesirable situations are more difficult to identify. This is mainly due to the fact that the fluctuations of ambient temperature and relative humidity cannot be described as a deviation from a baseline. For all other environmental parameters deviations could be considered as deviations from a baseline (e.g., a perfect dark situation for visible light, average CO_2 concentration on earth of around 400 ppm).

At certain moments, remarkable peaks are identified in the parameter-specific plots. Such an exemplary undesirable situation is the one on Sunday 20th August. On this day, a remarkable increase in CO_2 is observed (Figure 1b). This peak attracts attention due to its height and width. Therefore, this period is studied into detail. Information was collected on what happened that day. The church was open to the public and attracted around 1350 visitors. In the same time frame, an elevated air displacement was detected by the air speed sensor. In combination with the high visitors' amount, it is hypothesized that open church doors highly increase the air speed. At the same time, a reduction in RH of almost 10% occurred. This RH-drop was also recorded with other monitoring systems present in the church. This is counterintuitive when large numbers of people are present in the same building. Due to the open doors, outdoor influence was expected. However, daily averaged outdoor RH-values indicate a higher outdoor level compared to the indoor levels for this specific day. The indoor level of illumination is high until 11:00 PM. This is much later compared to sunset, and indicates the use of additional artificial illumination. Despite the large visitor number, hardly any rise in particulate matter is observed. The case study demonstrates that many more dangerous occurrences (e.g., several peaks in wind speed) can be seen in the graphs. Some of these occurrences would remain unnoticed when only temperature and relative humidity information is available. With the known periods in which they appear and the known parameters where sudden increase occur, substantial information is available to search for additional hazards in a targeted way.

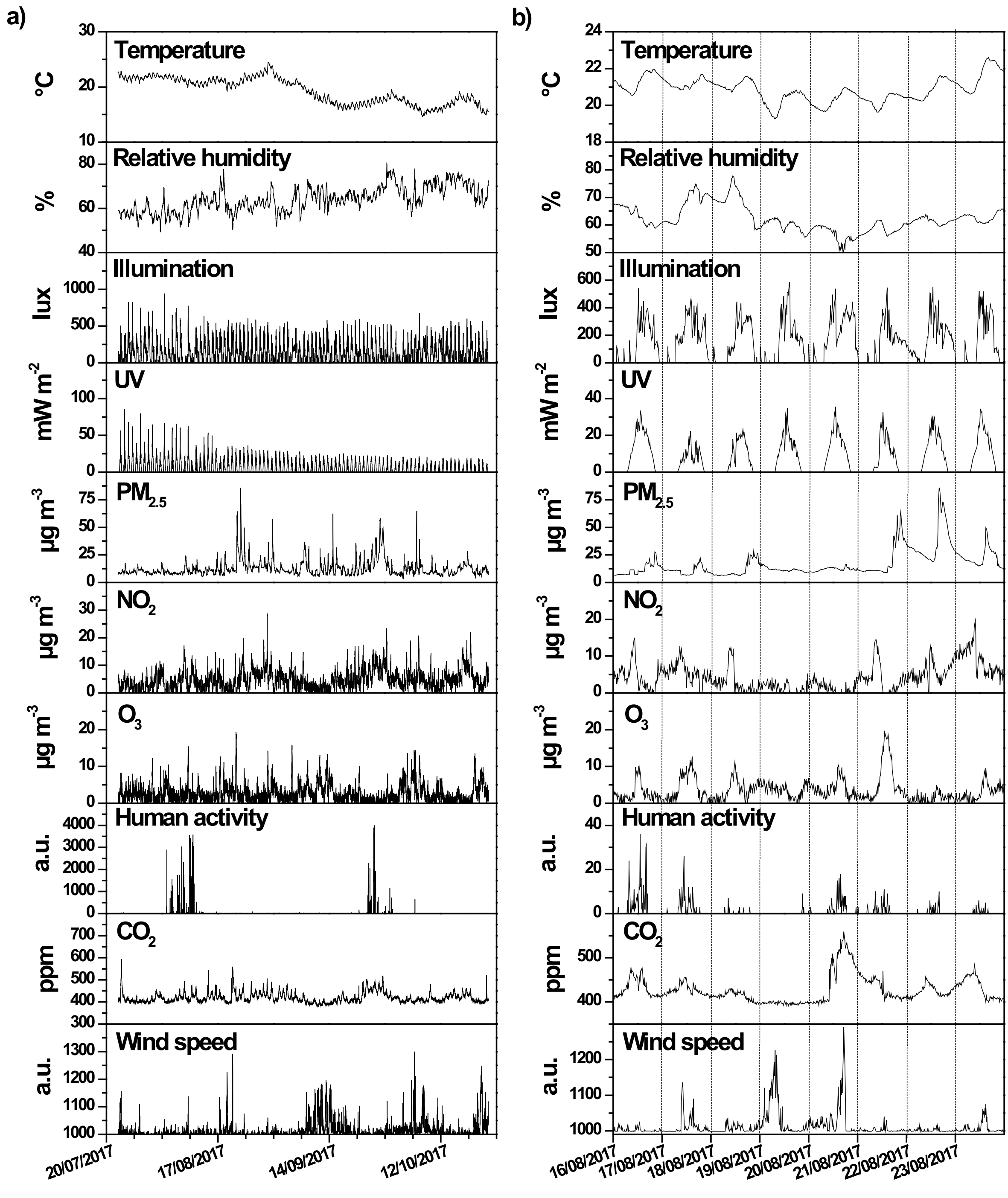

Figure 1. (a) Plots of environmental data over time from a period of 3 months (between 23/07/2017 and 23/10/2017); (b) One week detail (between Wednesday 16/08/2017 and Wednesday 23/08/2017).

As demonstrated in the example of the public day, periods with elevated risk could be visually identified in the parameter-specific plots, i.e., peaks on top of a background. Such periods could often be related to specific hazards. Not every peak has the same height. A clear example are the peaks in particulate matter in Figure 1b. On 16th, 17th and 18th August, small peaks appear, whereas on 21st, 22nd and 23th the PM-peaks are remarkably larger. This implies a difference in risk magnitude.

To guide the heritage guardians in detecting undesirable situations, in-house developed software generates color bars that visualize the dataset. Events are defined based on thresholds. When a period deviates from the thresholds, that period is colored in shades from cyan, yellow to red. Thus, all colors except of blue should be considered as events. The more the color reaches the red hues, the larger the level of risk. Figure 2 shows the result for a general collection, i.e., a mixed collection without any particularly sensitive objects. The overall conditions are classified in the blue color range, which means they could be considered as acceptable. However, several shorter periods show orange to red colors and should be checked in detail. The events in the current dataset are mainly due to inappropriate RH-conditions. The red periods in the IAQ-index reflect periods where the RH-levels exceed 75%. The cyan/greenish periods mainly reflect daily RH-fluctuations larger than 10%. This data processing and corresponding visualization demonstrates that the precise moments when events take place could be easily identified and the main parameter responsible for elevated risk could be found as well.

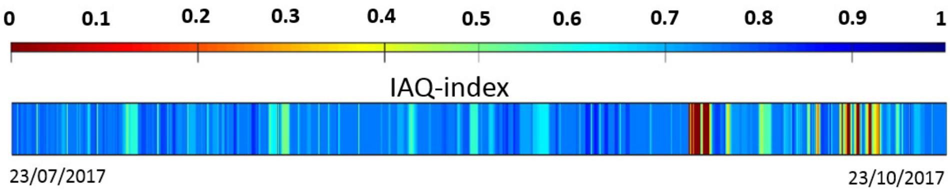

Figure 2. Summary of the environmental data collected in the period 23/07/2017 to 23/10/2017. The IAQ-index visualizes the environmental appropriateness for a general collection. Dark blue colors indicate appropriate conditions, while red colors are periods with significant environmental risks.

The data streams of the environmental parameters give meaningful information about the environmental dangers to which the heritage collection is exposed to. However, synergetic effects remain difficult to evaluate on the basis of the parameter-specific plots. This could be covered by directly monitor the material behavior. The wood and silver sensors monitor the material behavior of two totally different materials. Wood is hygroscopic and therefore sensitive to changes in RH. Silver, on the other hand, is mainly sensitive to pollution, and more specifically to sulfide reducing compounds.

The behavior of both material sensors is illustrated in Figure 3. Fig 3a shows the overview of the whole sampling period, while Figure 3b represents a detail of the same week as depicted in Figure 1b. The material behavior demonstrates that degradation of materials should not be considered as a constant over time. The fast response of the wood surface has a clear correlation with the relative humidity. The overall increase in wood strain is related to the overall increase in RH. The latter is less clear in the RH-plot due to the large fluctuations on top of an increasing trend. However, both parameters have a linear correlation coefficient

R^2 of 0.75. The short drop in RH during the open day (20th August) is not reflected in the wood behavior, which means that the four-hour lasting drop in RH is too short for the wood surface to react.

The silver sensor is subjected to progressing corrosion, but the corrosion rate is not constant. This is reflected in different slopes. For example, in September, the slope and thus the silver corrosion rate is lower compared to the summer months July and August. In October, the corrosion rate increases again. From the zoom in Figure 3b, it becomes clear that certain peaks in the silver corrosion signal correspond to RH levels, e.g., on the 21th August. This could be explained by an increase in surface conductivity at increasing RH levels. This means that the sensor read out is affected by the relative humidity. On the 20th August, there is no clear relation with the RH. Therefore, the number of visitors on that day had a (limited) impact on the silver corrosion rate.

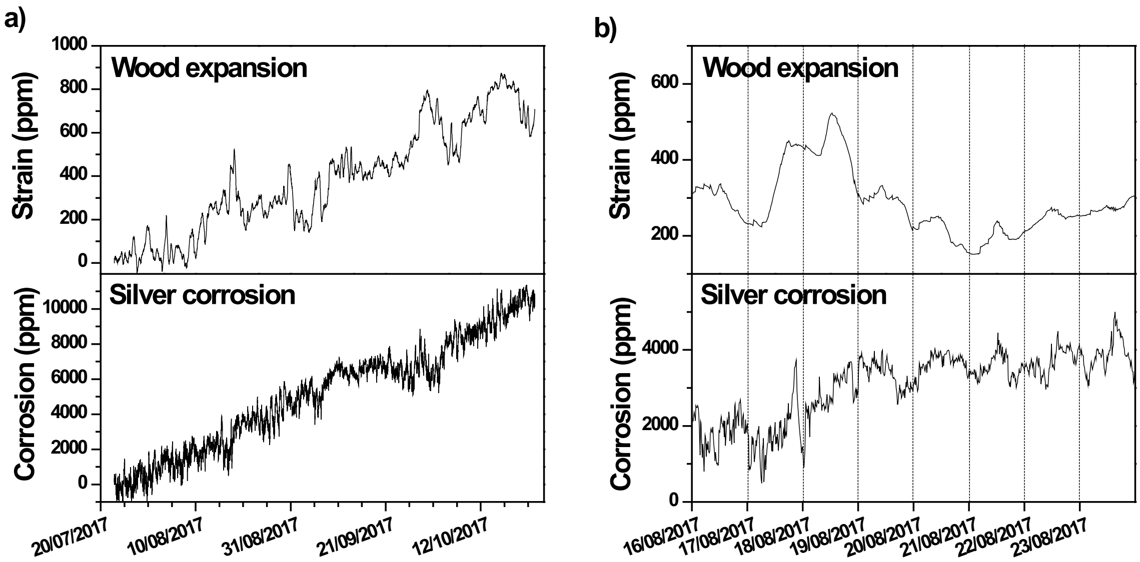

Figure 3. Continuous expansion and shrinkage information of the wood surface relative to a fixed resistance of 120 Ω and to the starting day and continuous corrosion depth information of silver relative to the reference electrode and relative to the starting day, both expressed in parts per million. (a) Plots of material behavior over time from a period of 3 months (between 23/07/2017 and 23/10/2017); (b) One week detail (between Wednesday 16/08/2017 and Wednesday 23/08/2017).

4. Discussion

This study demonstrates that current technology enables the monitoring of additional relevant environmental parameters and material behavior with a limited budget, on top of temperature and humidity measurements. The information obtained from the multi-sensor tool is relevant to determine the overall indoor air quality. The large number of parameters monitored suggests that the environmental conditions are more variable than when only temperature and relative humidity are considered. Several parameters consist of a background with peaks on top. These peaks reflect periods with elevated risk and are considered as

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undesirable situations. When identifying undesirable situations based on peak detection, caution should be exercised since their identification is affected by several factors:

- **Imperfect measurements:** Although many of the measured parameters are scalars (e.g., temperature, relative humidity, concentration of gaseous pollutants and particulate matter) other parameters are clearly vectors (e.g., illuminance, UV, air speed). Due to the use of a limited number of sensors in one position, not all directions could be monitored. Moreover, the environmental parameters are not uniform throughout a room but show gradients.
- **Imperfect sensors:** The availability and performance of continuous pollution sensors is relatively new and developing fast. It is expected that the technology will highly improve in near future. The gas sensors suffer from cross-sensitivity and the measured concentrations are rather close to the detection limits of the sensors. For certain gases such as sulfide reducing compounds, currently available sensors do not reach the low concentrations needed for heritage applications. The currently available inexpensive sensors to monitor particulate matter are generating a signal that is proportional to the number of particles per m^3. The guidelines, on the other hand, report target values in µg per m^3. Therefore an average density has to be used to convert the measurements in an appropriate quantity. This could result in large errors on the estimated PM-concentration. However, the results of these imperfect sensors could still be used to make decisions because the presence of peaks are undeniably the result of suddenly changing environmental conditions.
- **Imperfect target values:** Periods with elevated risk are easily identifiable in graphs through peak detection. However, to evaluate whether these periods should be classified as events, threshold values are needed. Such thresholds are not always well defined and are often material specific. Moreover, not all measured parameters have widely accepted threshold values (e.g., air speed). Other parameters do not affect heritage degradation in a substantial way (e.g., CO_2) but help in identifying undesirable situations.
- **Imperfect peak shapes:** Undesired situations are not always reflected as peaks in the graph. For example, a constantly too high RH-level is an event, but will not result in a peak when plotting the data. Our in-house developed software tackles this, since it detects undesirable situations based on published thresholds and not on peak detection. On the other hand, the software detects periods of undesired situations as it were sharp peaks while the actual values can be more gradually in reality.

5. Conclusion

The developed monitoring device demonstrates that a large range of relevant environmental-related parameters can be monitored simultaneously, and that also material behavior can be followed-up continuously. Many of the measured parameters show numerous peaks. These peaks are considered as undesirable situations because they are associated with periods of elevated risk. The case study demonstrates that monitoring a large number of environmental parameters allows the identification of many more undesired situations when compared to the monitoring of temperature and relative humidity only. Moreover, due to the continuous measurements the precise moments at which undesirable situations occur could be determined. This facilitates the search of the hazards causing these situations. The height of the peaks give an indication of the level of risk. Based on that height and the corresponding guidelines, the peaks could be classified as dangerous occurrences, events or incidents.

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Since hazards could reoccur in future with a possible increased level of risk, it is advised to perform mitigation actions to avoid or reduce the identified hazards to occur in future. As a result, heritage collections will be exposed to a reduced level of risk in the future. This means that identifying undesirable situations contain valuable information and should not be neglected, even when they did not cause any noticeable harm so far.

This contribution integrates risk management vocabulary in environmental monitoring. This combination becomes relevant when multiple parameters are monitored simultaneously, and when well-resolved peaks could be identified as undesirable situations.

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References
[1] Luxford N, Thickett D and Wyeth P 2010 *Applying Preventive Conservation Recommendations for Silk in Historic Houses* (Rome: ICOM-CC Joint Interim-Meeting of five Working Groups) p 12
Strlic M et al. 2015 *Herit Sci* **3(33)**
Tétreault J, Cano E, van Bommel M, Scott D, Dennis M, Barthés-Labrousse M-G, Minel L and Robbiola L 2003 *Stud Conserv* **48(4)** 237-50
[2] Pedersoli Jr J L, Antomarchi C and Michalski S 2016 *A Guide to Risk Management of Cultural Heritage* (Sharjah: ICCROM-ATHAR) p 118
Michalski S, Pedersoli Jr J L 2016 *The ABC method: a risk management approach to the preservation of cultural heritage* (Ottawa: Canadian Conservation Institute)
Brokerhof A W and Bülow A E 2016 *J Inst Conserv* **39(1)** 18-28
Waller R R 2003 *Cultural Property Risk Analysis Model. Development and Application to Preventive Conservation at the Canadian Museum of Nature* (Ottawa: Acta Universitatis Gothoburgensis) p 108
[3] Dubus M, Prosek T 2012 *e-PS* **9** 67-71
[4] Leyva Pernia D, Demeyer S, Schalm O, Anaf W and Meert C 2016 *Proc. 14th Int. Conf. on Indoor Air Quality and Climate* (Ghent: International Society of Indoor Air Quality and Climate)