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Diagnosis of abnormal patterns in multivariate microclimate monitoring: A case study of an open-air archaeological site in Pompeii (Italy)

Paloma Merello [a,b,1,2], Fernando-Juan García-Diego [a,c,*,1], Manuel Zarzo [d,1]

[a] Department of Applied Physics (UD Industrial Engineering), Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain
[b] Valencian Institute for Conservation and Restoration of Cultural Heritage (IVC+R), C/Genaro Lahuerta 25-3°, 46010 Valencia, Spain
[c] Center of Physical Technologies, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain
[d] Department of Applied Statistics, Operations Research and Quality, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain

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ABSTRACT

Chemometrics has been applied successfully since the 1990s for the multivariate statistical control of industrial processes. A new area of interest for these tools is the microclimatic monitoring of cultural heritage. Sensors record climatic parameters over time and statistical data analysis is performed to obtain valuable information for preventive conservation. A case study of an open-air archaeological site is presented here. A set of 26 temperature and relative humidity data-loggers was installed in four rooms of Ariadne's house (Pompeii). If climatic values are recorded versus time at different positions, the resulting data structure is equivalent to records of physical parameters registered at several points of a continuous chemical process. However, there is an important difference in this case: continuous processes are controlled to reach a steady state, whilst open-air sites undergo tremendous fluctuations. Although data from continuous processes are usually column-centred prior to applying principal components analysis, it turned out that another pre-treatment (row-centred data) was more convenient for the interpretation of components and to identify abnormal patterns. The detection of typical trajectories was more straightforward by dividing the whole monitored period into several sub-periods, because the marked climatic fluctuations throughout the year affect the correlation structures. The proposed statistical methodology is of interest for the microclimatic monitoring of cultural heritage, particularly in the case of open-air or semi-confined archaeological sites.

1. Introduction

One of the requirements for the preventive conservation of cultural heritage is the monitoring of factors involved in deterioration processes of artworks (Camuffo, 1998). The measurement of thermo-hygrometric parameters such as temperature and relative humidity (RH) is a priority (DM 10/2001). Microclimatic conditions are routinely controlled in museums (Camuffo et al., 2002; Pavlogeorgatos, 2003; Gysels et al., 2004; Saunders, 2008; Corgnati and Filippi, 2010; Legnér, 2011) given the importance of maintaining RH and temperatures within the recommended optimum intervals (DM 10/2001), which is easily achieved in most cases given the current technology of air conditioning systems. Several works have also studied the indoor environment in churches (Camuffo et al., 1999; Tabunschikov and Brodatch, 2004; García-Diego and Zarzo, 2010; Zarzo et al., 2011), which often contain valuable artworks. The control of microclimatic conditions inside these buildings is rarely a technical challenge, and undoubtedly the most complex problem consists of achieving an optimum conservation environment in open-air sites. In such cases, it is of interest to evaluate the effect of climatic parameters on the conservation of artworks in order to propose corrective actions.

Few works have studied microclimatic conditions in semi-confined (Pérez et al., 2013; Nava et al., 2010; Kisternaya and Kozlov, 2012) or open-air archaeological sites aimed at preventive conservation (Lillie et al., 2008; Maekawa et al., 1995). Nava et al. (2010) assessed air pollution threats to cultural heritage in a semi-confined environment by means of thermographic measurements on wall paintings, microclimatic analysis and gaseous pollutant monitoring. Another work has proposed a monitoring system for the biological control of historic timber structures aimed at preventing biodeterioration by fungi and insects (Kisternaya and Kozlov, 2012). Lillie et al. (2008) performed a monthly monitoring of water levels, pH and redox potential in waterlogged crannogs of south-west Scotland. Maekawa et al. (1995) gathered climatic data over two years to assess the effect of weather conditions on the conservation state of monuments in Tiwanaku (Bolivia).

* Corresponding author. Tel.: +34 963877521; fax: +34 963877529.
E-mail addresses: palomamerello@outlook.com (P. Merello), fjgarcid@upvnet.upv.es (F.-J. García-Diego), mazarcas@eio.upv.es (M. Zarzo).
[1] These authors contributed equally to this work.
[2] Tel.: +34 963877521; fax: +34 963877529.

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Regarding the microclimate monitoring of open-air sites, it is necessary to install sensors in several locations at the place of interest. The registered data will provide information on different ambient conditions amongst these locations. The statistical analysis can be conducted by means of descriptive methods using summary statistics (e.g. average, median and variance) or bivariate plots, amongst other basic techniques. Despite their simplicity, these methods are often applied in this context (Lillie et al., 2008; Maekawa et al., 1995; Merello et al., 2012), although multivariate statistical tools like principal components analysis (PCA) are more powerful. However, their application is not yet widely used in cultural heritage and few studies have been published (García-Diego and Zarzo, 2010; Zarzo et al., 2011; Varas et al., 2005). The present work reports, probably for the first time, the advantages of PCA in the multivariate microclimate monitoring of an open-air archaeological site.

Microclimatic monitoring systems record several parameters at different positions. The resulting data structure is equivalent to measurements of variables like temperature or pressure registered vs. time at several points of a continuous chemical process. Thus, chemometric tools developed for the multivariate statistical control of industrial processes can also be applied for this case. In the field of process chemometrics, there is abundant literature available on multivariate methods for the monitoring, diagnosis and fault detection in continuous (Raich and Çinar, 1996; Martin and Morris, 1996; Chen and McAvoy, 1998; Goulding et al., 2000) and batch chemical processes (Nomikos and McGregor, 1995; Kourti, 2001, 2005).

As a case study, the present work applies PCA to identify abnormal patterns and assess the differences amongst sensors installed in Ariadne's house (Pompeii). This *domus* (i.e., a single-family house owned by the upper classes) is situated in a privileged location at the city centre. It is a *domus* of Hellenistic inspiration composed of 31 rooms with an extension of 1700 m^2. Ariadne's house is of great archaeological value because some walls still display fresco paintings of a remarkable quality, despite the destruction caused by the eruption of Mount Vesuvius in the year 79 AD. The paintings exhibit an interesting decorative diversity and comprise different pictorial phases, from the first to the fourth Pompeian style (Fernández, 2007).

To protect the frescoes from rainwater, in the 1970s three rooms of Ariadne's house were covered with polycarbonate sheets (Pérez et al., 2013). In the 1950s another room was partly sheltered with a roof of ceramic tiles. Fresco paintings in these covered lodgings have survived up to the present day, though in a delicate condition, but most frescoes in the other rooms have entirely disappeared due to the impact of rainwater and the unfavourable weather. Optimum conditions for the conservation of indoor paintings are indicated in the Italian standard UNI 10829 (1999) and DM 10/2001 (2001). The latter recommends a range of 45–60% for RH and 6–25 °C for temperature, but no guidelines are provided for the preservation of outdoor frescoes.

Given the serious deterioration risks affecting the valuable paintings, a multidisciplinary conservation project was launched in 2008. The team studied the problems of atmospheric pollution, salt efflorescence and other pathologies associated with the materials in order to determine the causes of fresco degradation and propose conservation actions. It was found that the deterioration was mainly caused by inappropriate temperatures and RH inside the rooms (Pérez et al., 2013). Studying the different microclimatic conditions according to the room, sensor height and wall orientation is particularly important in summer due to the high temperatures, which represent a serious risk for the conservation of fresco paintings (Merello et al., 2012).

PCA is applied here to analyse temperature and RH values recorded in Ariadne's house during 372 days. Different objectives are proposed. First, it is of interest to identify abnormal trajectories that deviate from the common pattern of variability. Another target is to characterise the evolution of thermo-hygrometric parameters throughout the year.

2. Methodology

2.1. Monitoring system and sensor calibration

As part of the multidisciplinary conservation project, a microclimate monitoring system was set up to assess the environment surrounding fresco paintings in the four roofed rooms, coded as 1–4 in Fig. 1 of (Merello et al., 2012). Room 2 is delimited by four walls, but the north-east wall is missing in rooms 1 and 3. Room 4 is partly covered by an opaque roof that protects a semicircular wall oriented to the south-west. A detailed plan of Ariadne's house (*Regio* VII, *insula* 4) with pictures of each room is available in (Pompeii in pictures, 2013).

One thermo-hygrometric probe (coded as #1) was placed on the top of an outside wall to monitor outdoor ambient conditions, and 25 probes of the same type were located inside the four covered rooms. Each probe consists of one temperature data-logger (model Thermochron DS1922L) and one RH data-logger (model Hygrochron DS1923) (see (Merello et al., 2012) for technical details). Some probes were placed on the floor (#5, #6, #8, #11, #13, #14, and #16), others were installed on walls at more than 2 m from the ground level (#4, #12, #17, #18, #19, #20, #22, and #23) and the rest at an intermediate position (see Table 1 of Merello et al., 2012 for exact height). All data-loggers were calibrated

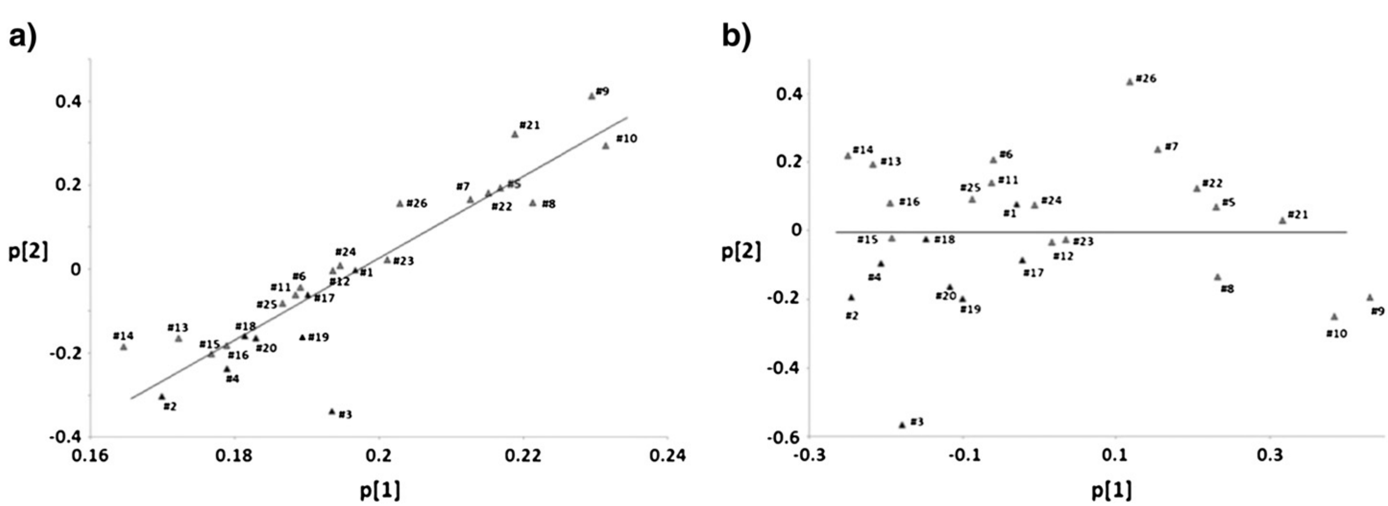

Fig. 1. Loading plot (p[2] vs. p[1]) of the PCA applied to the initial matrix of temperature (monitoring period of 372 days). a) Column-centred data, b) row-centred data. The fitted regression line is also indicated ($r^2 = 0.826$ and $r^2 \approx 0$, respectively).