Journal of Cultural Heritage xxx (2014) xxx–xxx

Available online at ScienceDirect www.sciencedirect.com

Elsevier Masson France EM|consulte www.em-consulte.com/en

Original article

An AHP-based indoor Air Pollution Risk Index Method for cultural heritage collections

Ferhat Karaca*

Fatih University, Department of Environmental Engineering, Istanbul, 34500 Buyukcekmece, Turkey

ARTICLE INFO

Article history:
Received 30 December 2013
Accepted 30 June 2014
Available online xxx

Keywords:
Risk Condition Index
Cultural heritage
Risk management
Indoor air quality
Collection management
Istanbul

ABSTRACT

The identification of risk factors and levels for cultural heritage collections in museums, archives, and libraries is an important part of their risk management plans. Air pollutants are some of the most important risk factors, and their synergic impacts on material deformations are well known; thus, they have become important criteria in collection risk management plans. Pollution levels and their potential sources should be identified, monitored, and assessed within such risk management plans. Although pollution identification and monitoring methods are well-known practices, the assessment methodologies are not yet sufficiently developed. In this study, a novel air pollution condition indexing assessment method based on an analytical hierarchy process (AHP), the so-called Air Quality Risk Condition Index (AQRCI), is suggested. It quantifies the relative potential synergic impacts (e.g., soiling and color change, salt crystallization, metal corrosion, biodegradation, swelling/shrinkage, loss of strength, cracking, and embrittlement) of measured pollution levels on collection materials in any selected location. The proposed method is based on quantitative (gaseous and particulate pollutant levels) and qualitative (pairwise comparison scores for associated risks) data. Dolmabahçe Palace was selected as a study site, and the proposed AQRCI method was used to present the relative risk levels for five different categories in several indoor locations where the Dolmabahçe Palace collections are being presented.

1. Research aims

This study aims to suggest a novel analytical hierarchy process (AHP)-based assessment method for indoor pollution levels and for associated risk factors for material deformations. This methodology allows any user to quantify and compare the potential impacts and risks of indoor air pollution levels observed in any particular location.

Instead of object-specific deformation risks, this method proposes AQRCI scores for various degradation processes in various materials: soiling and color change in all materials, paintings and frescoes; salt crystallization in porous stone and ceramic objects; corrosion in metals; biodeterioration in carbonate silicate stones and organic materials; and swelling/shrinkage, loss of strength, cracking, and embrittlement in wood and paper.

This study also presents an application of the proposed method using seasonal pollution measurements and site-specific parameters for Dolmabahçe Palace. The proposed method can easily be adapted to other places and locations.

2. Introduction

Identifying and informing of risks in a cultural heritage protection program to minimize and control the probability and impact of threats to the collection is considered an important component of risk management [1–4]. Recent studies have shown that the synergic effects of indoor air pollutants on cultural heritage materials can be devastating [1,5–10]. Thus, indoor air pollution exposure levels should be evaluated to obtain a better risk management policy for indoor spaces where collections and movable cultural heritage stocks are being presented or kept. This requires an air pollution indexing study, the Air Quality Risk Condition Index (AQRCI), which categorizes the levels of risk factors based on measurements and/or observations; the combination of all the categorical values can then be employed in a function to calculate the potential risk for any selected material. This approach is a novel and practical method of quantifying any possible synergic effects of pollutants (such as corrosion, soiling, color change, salt crystallization, and biodegradation) on the cultural heritage collection located in a particular location.

In a museum environment, it is possible to control the indoor air quality using a number of active and passive technologies and constructional designs to provide better protection against

* Correspondence. Tel.: +90 212 866 34 11; fax: +90 212 866 34 12.
E-mail address: fkaraca@fatih.edu.tr

http://dx.doi.org/10.1016/j.culher.2014.06.012
1296-2074/

Please cite this article in press as: F. Karaca, An AHP-based indoor Air Pollution Risk Index Method for cultural heritage collections, Journal of Cultural Heritage (2014), http://dx.doi.org/10.1016/j.culher.2014.06.012

pollutants. However, in the case of buildings such as Dolmabahce Palace, which has a historical value based on not only the collections kept inside but also the building itself, the original state of the building should be persevered; therefore, this limits any new construction and alteration, and it may not be possible to install any active mechanical or automatically controlled systems such as ventilation channels or HVAC systems. Thus, risk-indexing methods, as suggested in this study, have become an increasingly more important component in risk management activities and strategies for such buildings that include a combination of differently sized rooms, halls and galleries. Through the use of AQRCI values (or risk labels) in particular locations in a building, it can be possible to initiate better management plans by focusing on particular pollutants and/or materials using appropriate control methods in high-priority, risky locations.

In this study, a novel AHP-based relative pollution risk condition indexing method for different material types is suggested. This risk assessment study does not aim to express the quantitative relation between pollution exposure levels and deformation effect on the collections as dose response functions do; however, it aims to present the level of relative risk levels in selected indoor spaces where cultural heritage collections are being kept. Faced with a lack of national and international pollution risk criteria, a standard risk assessment methodology, and predefined pollution exposure risk levels for cultural heritage protection and preservation practices, this study offers a novel and useful management tool for satisfying the current demands of cultural heritage managers and experts. Dolmabahçe Palace was selected as the study area to employ the proposed method. The AQRCI was used to qualify the level of pollution risk for different material types in the selected locations having various sizes, characteristics and formations. It can be easily adapted to other places and locations.

3. Methods and materials

3.1. Study area

Dolmabahçe Palace was constructed between 1843 and 1855 as the last administrative building of the late Ottoman Empire. It is one of the most attractive palaces built during the Middle Ages in the world. The palace has an area of 45,000 m^2 and contains 285 rooms, 46 halls, six baths (hamam) and 68 toilets. The outside of the building is made of stone, while the interior walls and the floors are brick and wood, respectively. The site of Dolmabahçe is located on a reclaimed seashore on the European coast of the Bosphorus. The southern part of its imperial garden runs along 600 meters of the Bosphorus. The northern side is bordered by 10-m-high exterior walls to protect the structure from the outer environment. It is located at the heart of a megacity, Istanbul. A main city road, characterized by heavy daytime traffic, follows these outer walls. Both city traffic and the sea are the main outdoor environmental hazards to the palace. Its unique location makes this place a very interesting case for a study that aims to assess the indoor air quality impacts on cultural heritage objects. The location of the study site is given in Fig. 1.

Five different halls and interior locations were selected to measure the AQRCI for the palace due to limitations of technical resources. The selected locations were the Medhal Hall, Süfera Hall, Crystal Stairs, Muayede Hall (Ceremonial Hall), and Library. These are the most distinguished locations in the palace. They are intentionally included to demonstrate how the pollution risk index may differ between locations that are completely different in size and location and that are characterized by different exposure to pollution parameters. The Medhal Hall is a large hall that welcomes all visitors at the entrance. The Süfera Hall is another large hall where foreign ambassadors used to entertain and was the imperial reception place for the visitors of the Sultans. The Crystal Staircase serves as a connection with the upper story and carries protocol characteristics. The Muayede Hall, located between the Harem and the Mabeyn sections, is the highest (36 meters high) and most magnificent hall of Dolmabahçe Palace, with its area exceeding 2000 square meters. The library is located on the upper floor, and the old book collections of the palace, mostly belonging to the Caliph Abdulmecid, were kept in there. It is one of the most outstanding rooms and has particular importance due to its stocks. All these selected places are decorated and furnished in a manner emphasizing the historical magnificence of the empire, and they contain numerous heritage objects made of a wide range of materials and are characterized by numerous properties.

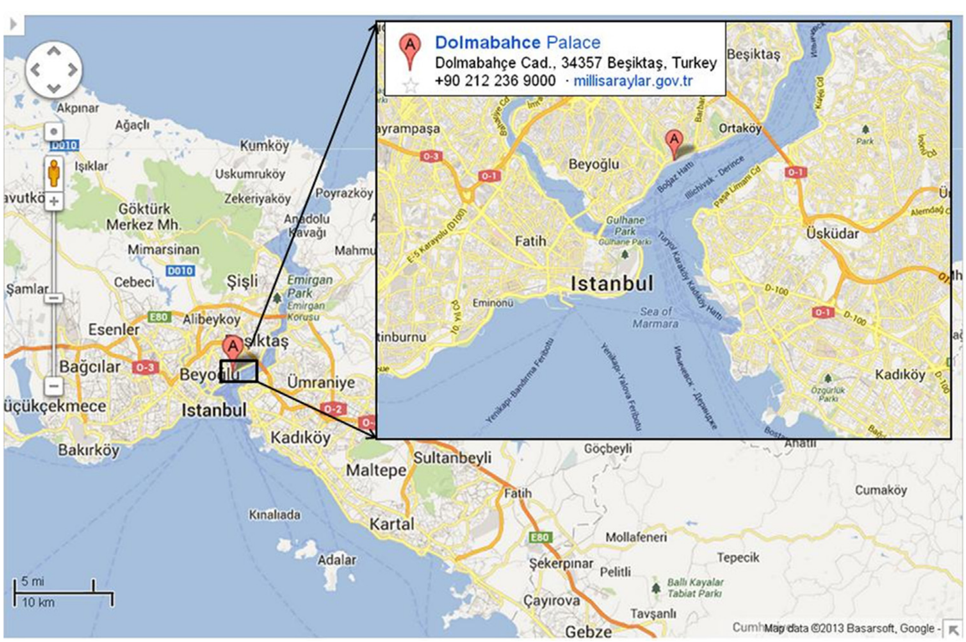

Fig. 1. Location of study site (Dolmabahce Palace).

Please cite this article in press as: F. Karaca, An AHP-based indoor Air Pollution Risk Index Method for cultural heritage collections, Journal of Cultural Heritage (2014), http://dx.doi.org/10.1016/j.culher.2014.06.012

Table 1
Sampling campaigns and details.

Sample type	Sampling location	Parameter	Analytic method
Passive sampling	Süfera Hall	SO_2	Ion chromatography (IC)
	Muayede Hall	NO_2	
	Crystal Stairs	O_3	Spectrophotometric methods
	Library		
		Formaldehyde (FA)	High-performance liquid
		Acetaldehyde (AA)	chromatography (HPLC)
Active		BC	Optical analysis
sampling/monitoring		PM counts	Light scattering

3.1.1. *Pollution measurements, QC and QA*

In this study, air pollutants, SO_2, NO_2, O_3, formaldehyde (HCHO), acetaldehyde (CH_3 CHO), black carbon (BC) and particulate matter (PM), were monitored in several indoor environments in Dolmabahçe Palace using passive gas samplers and PM monitoring systems. Radiello® 166-, 172-, and 165-type samplers were used for passive sampling. Laboratory and field blanks were also analyzed along with the collected passive samples during the winter and summer sampling campaigns. BC measurements were carried out using an MAGEE® AE-42 Aethalometer, and PM counts for six different size fractions (5.8–4.7 μm, 4.7–3.3 μm, 3.3–2.1 μm, 2.1–1.1 μm, 1.1–0.65 μm, 0.65–0.43 μm) were measured using a CLC-H603 Honri Air Clean Technology airborne PM counter.

The analytical protocols advised by Radiello® [11–13] were followed during the chemical analysis of the collected passive samples. The equipment and analytical methods used are summarized in Table 1.

In the chemical analyses, the precision of the analytic methods for all the measured species were evaluated by performed repeated analyses of fixed concentrations (diluted samples of standard solutions) on different days. The relative standard deviation (RSD) values were between 1 and 3 (in percent), indicating that the measurements were quite accurate. The detection limits (DL) of the methods were calculated to be three times the standard deviations of the blank samples. Linear calibrations were used within the calibration procedure with an accuracy of 99.9%.

3.1.2. *AHP-based Risk Condition Indexing Method (AQRCI) for indoor spaces*

This study proposes a novel risk assessment method for indoor spaces where cultural heritage objects are stored or presented, such as in halls, galleries, and old and historical buildings. The method is based on the AHP and uses quantitative (gaseous and particulate pollutant levels and air quality parameters) and qualitative (pairwise comparison scores for the risk levels) data.

AHP is a multi-criteria decision-making (MCDM) method, and it provides reasonable support in decision-making processes. It was used to provide comparative AQRCI scores for each of the investigated indoor spaces. Using the input, the AHP ranks the AQRCI scores of any selected location, relying on their risk scores, for cultural heritage objects stored or presented in these locations. Readers are referred to [14] for detailed information about AHP, which provides a decision analysis based on both quantitative and qualitative criteria and which can address multiple conflicting objectives. Each criterion has been quantified by either direct ratings (e.g., average pollution level of a pollutant in a particular season) or by pairwise comparisons (e.g., the likelihood that the selected pollutants can create soiling effects on given material types) based on the availability of relevant data and of knowledge pertaining to each of the indicators. The pairwise comparison scores, indicating the strength of correlations, range from 1 and 9. However, in this study, the maximum assigned pairwise score was a 6 (or 1/6). The hierarchy of the selected criteria and parameters as used in the AHP assessment is given in Fig. 2. Pairwise scores for the AHP assessment of the indoor-air-quality-related risk condition index were assigned for five different degradation processes and are given in Table 2. They are based on pollutant and material relations given in Table 3.

4. Results and discussion

4.1. *Selection of indoor pollution parameters*

The pollution parameters presented in Fig. 2 were carefully selected based on their significance regarding deterioration, corrosion and soiling phenomena. SO_2, NO_x and O_3 are well-known aggressive species, having certain impacts on the quality of the indoor air in museums, archives, libraries, halls, and galleries [15]. In addition, airborne PM has always been considered as an important issue in preservation strategies due to its soiling and reactive effects on building materials and objects. However, as a result of the significant increases in urban traffic volumes during recent decades, the characteristics of pollutants have changed; and fine-sized black carbon/soot particles have become a leading factor in cultural heritage surface damage [16]. We assumed that the soiling risk factor of PM on material deformations decreases as particle size increases in view of the fact that the larger particles mostly have natural origins [17–19] (e.g., pollens and geological dust) and that they can be more easily removed by physical procedures from the surfaces they have been deposited on. However, this situation might be reversed for the case of corrosion due to enrichment levels of salt particles in coarse fractions. Higher-level concentrations of smaller-sized particles can be associated with different risk values in different processes even if the total airborne PM concentrations in two places are almost identical. As a result, size-selective PM counts (in particle number) were performed. The obtained results were converted into mass concentrations by assuming that the average particle density is 1600 $kg m^{-3}$ and that all the particles are spherical [9]. These PM fractions are mainly formed from several outdoor sources and partially from indoor sources. For the case study, the main PM sources were identified as traffic, sea salt contribution, transportation, space heating (especially in winter), wind erosion, pollens, and other urban anthropogenic factors. Indoor PM sources are not that complex because there is no thermo-chemical activity in the building. Biogenic emissions and dust re-suspension during visiting and cleaning activities (by re-suspension) are the most significant indoor PM contributors.

Among all the monitored pollution species, PM fractions have particular importance. In the literature, to our knowledge, there are no studies related to cultural heritage material deformation that attempt to evaluate the potential impacts of segregated airborne particles having multiple sizes. However, chemical compositions (especially the highly reactive and soluble ones, such as sulfates, nitrates and chlorides) and their potential impacts are well studied. In this study, chemical analyses were performed on the PM samples collected by a cascade impactor located in the Medhal Hall during the project. The obtained results were not included in this study but are presented elsewhere [20]. These results confirm the fact that the

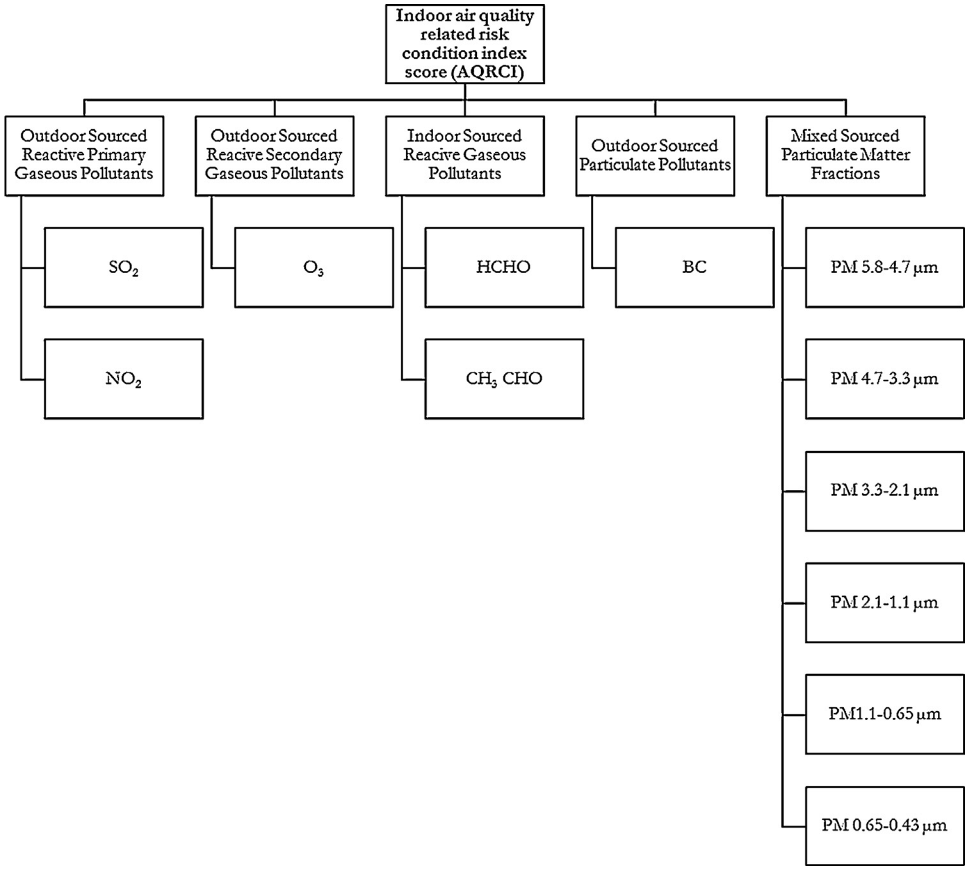

Fig. 2. AHP hierarchy of Dolmabahçe Palace indoor-air-quality-related risk condition index (AQRCI).

major reactive elements originated from crust and marine aerosol (e.g., sea and road salt components), and organic PM concentrations were higher in larger dimension ranges in the PM samples. In contrast, the inorganic content, which is typically the by-product of combustion processes and secondary formation reactive species (e.g., sulfates and nitrates), were found in greater concentrations at smaller sizes. These results are also in agreement with previous ambient-PM-related studies carried out in the vicinity [21–23]. This means that larger PM fractions play a more important role in "salt crystallization"; whereas the smaller ones are more effective in "soiling and color change" impacts on cultural heritage objects.

All these pollutants, expect ozone, are primary pollutants and are mostly generated from outdoor sources, mainly traffic emissions. Ozone is a secondary pollutant that is mostly formed outdoors by photochemical oxidation processes during daytime

Table 2
Pairwise scores used in AHP assessment.

Soiling and color change

	SO_2, NO_2	O_3	FA, AA	BC	PM
SO_2, NO_2		1	4	1	6
O_3	1		4	1	6
FA, AA	1/4	1/4		1/4	4
BC	1	1	4		4
PM	1/6	1/6	¼	1/4	

Salt crystallization

	SO_2, NO_2	O_3	FA, AA	BC	PM
SO_2, NO_2		1	1	1	1/6
O_3	1		1	1	1/6
FA, AA	1	1		1	1/6
BC	1	1	1		1/6
PM	6	6	6	6	

Corrosion

	SO_2, NO_2	O_3	FA, AA	BC	PM
SO_2, NO_2		1	1	6	4
O_3	1		1	6	4
FA, AA	1	1		6	4
BC	1/6	1/6	1/6		1/3
PM	1/4	1/4	¼	3	

Biodeterioration

	SO_2, NO_2	O_3	FA, AA	BC	PM
SO_2, NO_2		1	1/3	1	1/6
O_3	1		1/4	1	1/6
FA, AA	3	4		4	1/3
BC	1	1	4		1/6
PM	6	6	3	6	

Swelling/shrinkage, loss of strength, cracking, embrittlement

	SO_2, NO_2	O_3	FA, AA	BC	PM
SO_2, NO_2		1	2	3	4
O_3	1		2	6	4
FA, AA	1/2	1/2		4	2
BC	1/3	1/6	¼		1/4
PM	1/4	1/4	½	4	

Table 3
Relative Importance of pollution parameters involved in degradation processes on cultural heritage materials. The list is compiled based on the literature [1,5–8,10,15,16,24].

Pollutant ($\mu g\,m^{-3}$)	Soiling and color change	Salt crystallization	Corrosion	Biodeterioration	Swelling/shrinkage, loss of strength, cracking, embrittlement
SO_2	Very high	Low	Very high	Low	High
NO_2	Very high	Low	Very high	Low	Very high
O_3	Very high	Low	Very high	Low	Very high
HCHO	High	Low	Very high	High	High
CH_3 CHO	High	Low	Very high	High	High
BC	Very high	Low	Low	Low	Low
PM	Moderate	Very high	Moderate	Very high	Moderate

through exposure to sunlight; no typical indoor or outdoor ozone source was identified in this case this study.

Apart from the above-mentioned outdoor-sourced pollutants, aldehydes have specific importance because they are degradation by-products of organic materials (e.g., wood and paper-based materials) in old buildings, archives and libraries. Formaldehyde and acetaldehyde are major typical indoor-generated aldehydes, which could potentially lead to the accelerated degradation of collection materials [8]. Both were included in this study.

Pollution sampling and monitoring campaigns were carried out during summer and winter to define the indoor pollution profile in Dolmabahce Palace. All the measurements were performed in weekly periods without individually considering the visiting and no-visiting days. In each location, at least four testing spots (e.g., one in the middle and the others closer to walls and structural openings, e.g., windows and doors) were selected, and multiple samples were collected. Seasonal average values of pollution concentrations for each location were determined by calculating the mean value of the multiple measurements in a given location.

4.2. Seasonal pollution levels

Seasonal average pollution concentrations in the evaluated locations in Dolmabahce Palace are given in Table 4. The first group of pollutants, outdoor-sourced reactive gases, is typically found in higher concentrations in summer in most of the locations. This can be explained by the natural ventilation practices during the different seasons. All the windows remained closed in winter, resulting in lower infiltration level, whereas they were open in summer, providing good natural ventilation. This process allows outdoor pollutants to freely enter into the indoor environment from the windows openings, and subsequently, they can penetrate into interior sections of the building.

The infiltration of outdoor-sourced pollutants in the palace is mainly from the building sides and from sections facing outdoor environments, such as doors and windows openings, and very slightly through the building walls.

Because the Library is located at the most inner section of the building, the lowest SO_2 and NO_2 levels were observed in the Library. The highest SO_2 concentrations were observed in Süfera Hall, where the NO_2 concentrations were high. This area is located on the upper floor and is likely to be exposed to the highest levels of traffic emissions. There are two main reasons for this assumption. Air particle movements and the potential impacts of traffic emissions on Dolmabahce Palace were evaluated elsewhere using a computational fluid dynamics (CFD) model [20]. Based on that study, the exterior wall between the main road located at the northern side and Dolmabahce Palace serves as an air barrier, and it significantly reduces the direct exposure to pollutants, especially the exhaust PM emissions traveling upward from the basement levels of the northern side of the Palace. Another reason is that Süfera Hall has three balconies and large windows located on the north, south and west sides. They remain open during visiting hours during summer to provide natural ventilation, which makes this section the most ventilated but well exposed to outdoor pollution.

Indoor-sourced organic pollutants (HCHO and CH_3 CHO) were typically found in high concentrations during summer; however, higher ventilation levels were expected during that season. This is mainly a result of the higher decomposition ratio, which is supposed to be accelerated with increased temperature and humidity. It should also be noted that ventilation was only performed during visiting hours, which constitutes 1/3 of the daylight hours; consequently, indoor pollution accumulation was still significant.

Black carbon values follow a reasonable trend, being higher in winter due to higher levels of winter-time anthropogenic activities (e.g., space heating) and due to meteorological factors (e.g., lower inversion layer formations), and gradually decreases through the interior sections of the building as a result of infiltration and deposition removal processes.

Size-segregated particle measurements showed that the dominant particle size in mass contribution to the suspended atmospheric particle concentrations were coarse particles ($dp > 2.5\,\mu m$). This difference is most significant in busy (visiting, administrative activities, etc.) areas (e.g., the Medhal Halls, Süfera Hall, Crystal stairs) and is less significant in the largest areas (e.g., the Muayede Hall) and in the inactive areas (e.g., the Library). All the measurements (for both fine and coarse fractions) taken during the summer were higher than those taken during the winter. Natural ventilation practices and higher levels of visiting activities are the main dust generation processes, which contribute to the higher summer PM levels in Dolmabahce Palace. The former contributes to both the fine and coarse PM levels, while the latter most likely plays a role in the re-suspension process of the course PM formations.

4.3. Risk Condition Index (RCI) for different material types

Different AQRCI values for different objects can be obtained because materials have different sensitivities and different chemical and physical properties. Although it is very difficult to categorize items in the Dolmabahçe collection based on their materials and/or characteristics, individual AQRCI values can be used together as an effective cultural heritage management tool. In Dolmabahçe Palace, there is a vast amount of differentiation amongst valuable artifacts and in their materials, such as rugs and kilims, furniture, chandeliers, inscriptions, vases, oil paintings, photographs, carpets, and handcrafts, in almost every room. All these items are formed as compositions of different materials. Instead of object-specific deformation risks, this study focuses on degradation processes in specific materials: soiling and color change in all materials, paintings and frescoes; salt crystallization in porous stone and in ceramic objects; corrosion in metals; biodeterioration in carbonate silicate stones and in organic materials; swelling/shrinkage, loss of strength, cracking, and embrittlement in wood and in paper.

In the following sections, AHP-based AQRCI scores were calculated for five different degradation processes (Table 4). The risk indication levels of the pollutants in the degradation processes

Table 4
Seasonal average pollution concentrations in the evaluated locations in Dolmabahce Palace. All the concentrations are given in $\mu g\, m^{-3}$.

Pollutant ($\mu g\, m^{-3}$)	Medhal Hall			Süfera Hall			Muayede Hall			Crystal stairs			Library		
	Winter	Summer	Ratio	Winter	Summer	Ratio	Winter	Summer	Ratio	Winter	Summer	Ratio	Winter	Summer	Ratio
SO_2	2.80	2.00	1.40	19.1	11.0	1.73	2.2	1.75	1.26	2.50	8.60	0.29	0.30	2.47	0.12
NO_2	73.2	36.6	2.00	36.2	106	0.34	41.1	42.6	0.96	35.3	76.6	0.46	29.6	40.4	0.73
O_3	1.95	7.15	0.27	34.5	18.9	1.82	5.2	3.70	1.41	1.30	3.10	0.42	0.33	1.57	0.21
HCHO	3.56	6.98	0.51	1.56	3.16	0.49	1.31	7.11	0.18	4.57	8.48	0.54	3.59	7.54	0.48
CH_3 CHO	2.28	2.56	0.89	0.68	0.53	1.29	1.86	3.48	0.53	3.02	3.00	1.01	3.46	4.91	0.70
BC	5.80	2.60	2.23	4.80	2.50	1.92	2.50	2.20	1.14	3.60	2.70	1.33	2.40	2.00	1.20
PM 5.8–4.7	32.0	24.7	1.29	19.9	10.4	1.92	9.0	13.5	0.67	27.5	16.7	1.65	20.9	11.1	1.88
PM 4.7–3.3	29.9	21.6	1.38	19.4	9.1	2.13	7.7	11.1	0.69	25.2	14.0	1.80	19.9	9.2	2.16
PM 3.3–2.1	4.83	3.48	1.39	3.19	1.49	2.15	1.28	1.82	0.70	4.11	2.27	1.81	3.31	1.45	2.29
PM 2.1–1.1	3.97	2.84	1.40	2.78	1.32	2.12	1.20	1.57	0.77	3.49	1.88	1.86	2.84	1.22	2.34
PM 1.1–0.65	1.94	1.09	1.78	1.56	0.66	2.36	1.12	0.77	1.44	1.71	0.82	2.09	1.58	0.60	2.65
PM 0.65–0.43	0.95	0.49	1.94	0.80	0.35	2.32	0.71	0.41	1.73	0.80	0.40	2.03	0.80	0.32	2.50

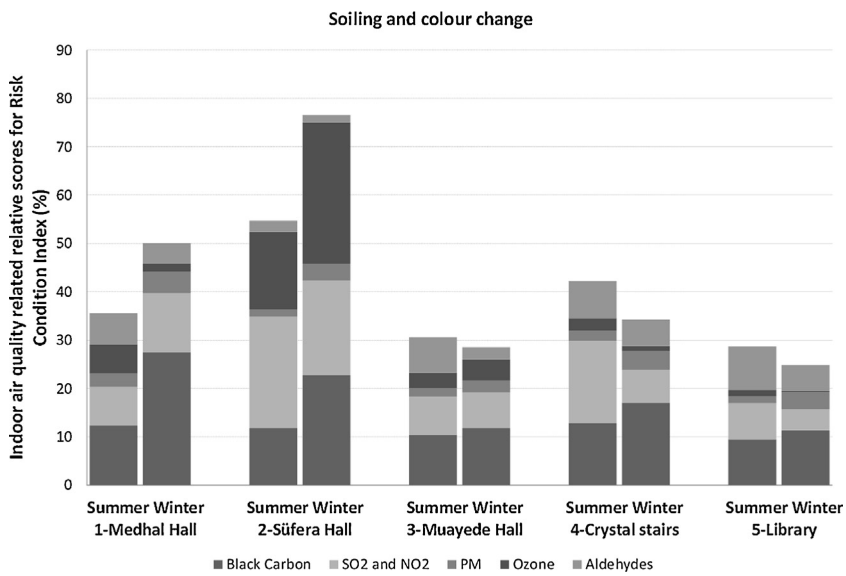

Fig. 3. AHP-based seasonal RCI scores for soiling and color change in Dolmabahçe Palace.

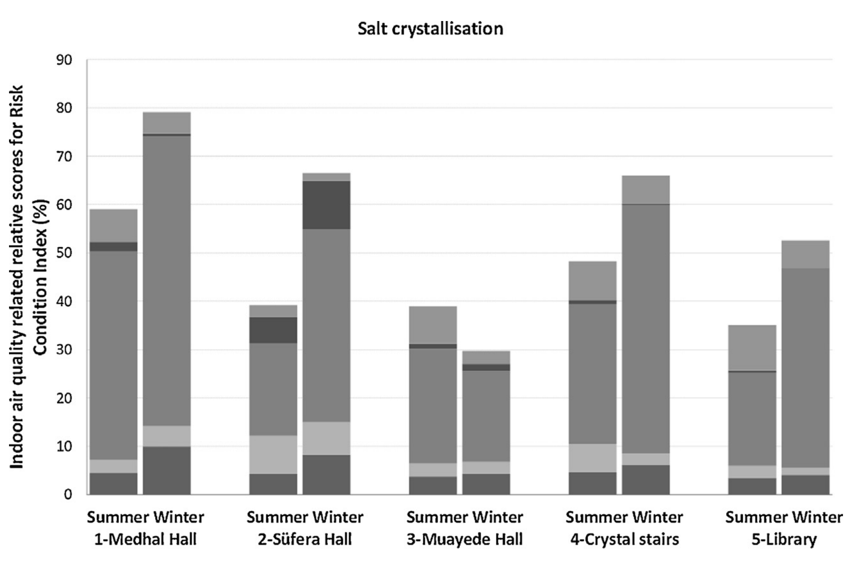

Fig. 4. AHP-based seasonal RCI scores for salt crystallization in Dolmabahçe Palace.

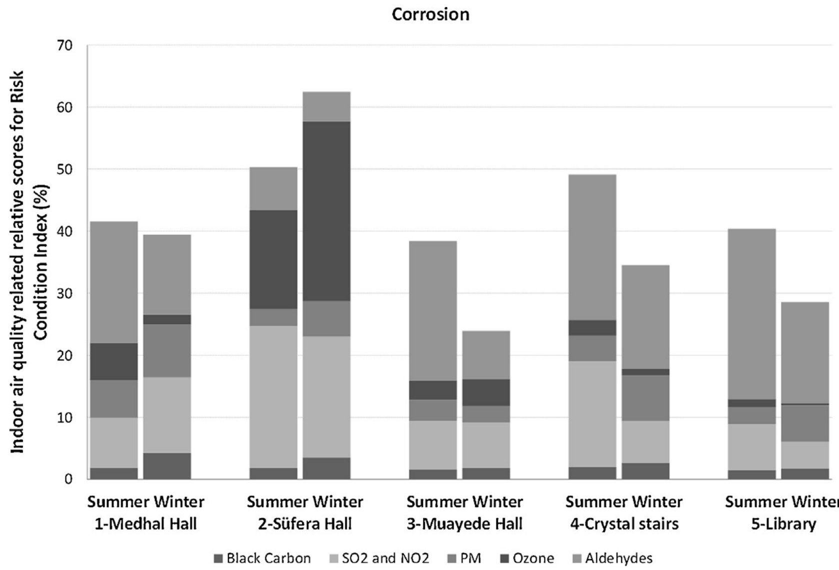

Fig. 5. AHP-based seasonal RCI scores for corrosion in Dolmabahçe Palace.

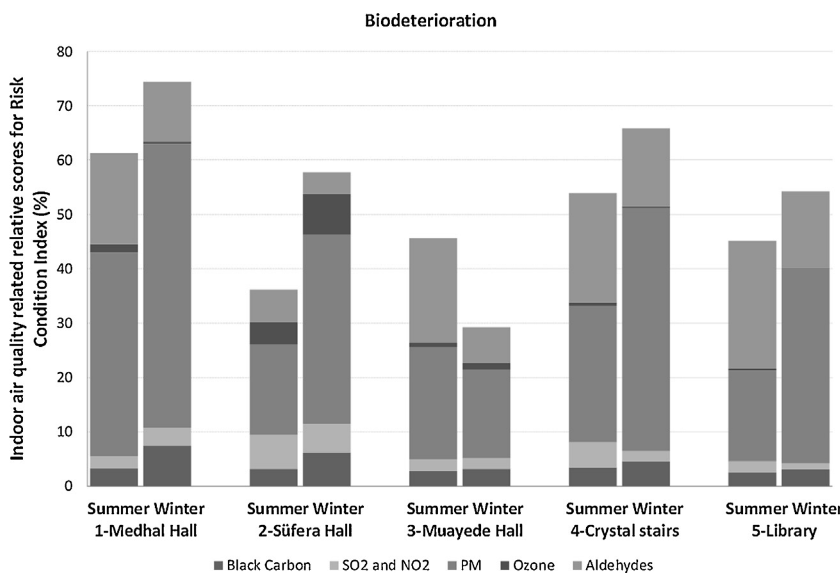

Fig. 6. AHP-based seasonal RCI scores for biodegradation in Dolmabahçe Palace.

were identified based on several dose-response functions and on impact assessment studies, explaining the material sensitivities and reaction potentials against pollutants [5–8,10].

4.3.1. Soiling and color change

The soiling and color change risks related to the measured indoor air pollutants were assessed and obtained, and the results are illustrated in Fig. 3. In this figure, the summer and winter AQRCI scores for each location were given together to provide a better seasonal comparison. It was determined that Süfera Hall was the area with the highest risk, exhibiting the highest soiling and color change impact during both seasons. The most significant factor having a potential to impact this location is the “outdoor-sourced reactive gases”. The soiling impact was higher during winter in the Medhal and Süfera Halls, and their differences were significant. The summer values were higher in the Muayede Hall, at the Crystal stairs, and in the Library, but only the seasonal difference at the Crystal stairs was significant in this group. When compared to these values, it is observed that the soiling and color change risks in Dolmabahçe Place were in the relative range between 25% (Library, winter) and 77% (Süfera Hall, winter). This indicates that the independent factors, which are not related to pollution generation (e.g., room location and physical properties), play very important roles in the air quality of Dolmabahçe Palace.

4.3.2. Salt crystallization

Salt crystallization is the second risk factor addressed and evaluated in this study. Due to the location of the study site, this parameter is of substantial importance. Sea salt particles, which dominate salt crystallization processes, are expected to be among the most significant pollution factors. To provide correct information within the constraints of our sampling and measurement campaigns and AHP-based assessment methodology, we assigned different pairwise AHP scores for PM fractions compared with the other risk factors (e.g., the highest score indicates the largest PM fraction). Details are given in the previous sections. Note that the potential risk impact of PM formations was assumed to increase as their sizes increase. Salt crystallization AQRCI scores are given

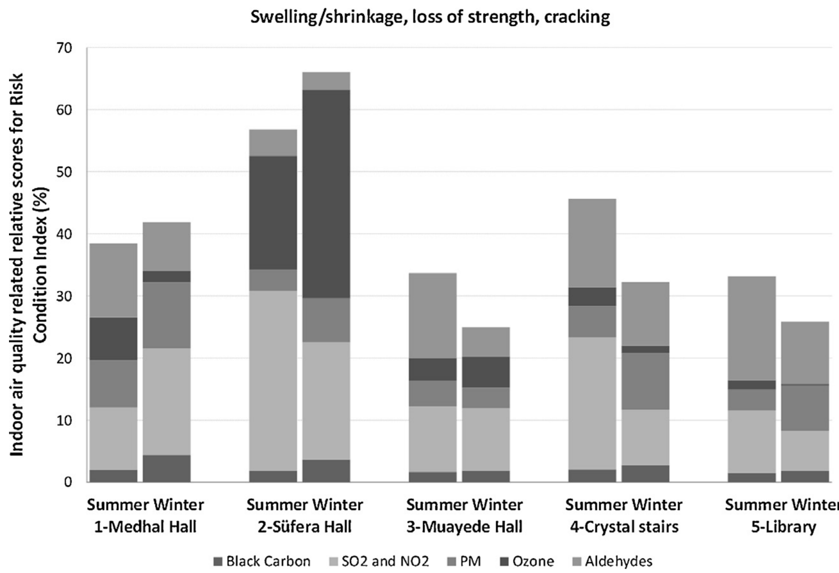

Fig. 7. AHP-based seasonal RCI scores for swelling/shrinkage, loss of strength, cracking, and embrittlement in Dolmabahçe Palace.

in Fig. 4. PM formations were the dominant factor in each group. Winter risk values were surprisingly higher than summer values in all the cases expect for in Muayede Hall. It is also determined that the Medhal Hall had the highest salt crystallization risk, while the other locations were comparable to each other.

4.3.3. Corrosion

The AQRCI results for metal corrosion are given in Fig. 5. Summer corrosion risk levels were higher in all the cases expect for in Süfera Hall. The seasonal difference in Medhal Hall was not very significant, but it was significantly different in all the other cases. Süfera Hall, again, was the most risky place in Dolmabahçe Palace due to the higher levels of outdoor-sourced reactive gases. Note that the range of corrosion risk among places and seasonal measurements did not fluctuate severely: it was in the range of 29–62%.

4.3.4. Biodeterioration

Biodegradation risk scores are given in Fig. 6. Medhal Hall is the riskiest place in terms of biodegradable materials. PM formations and aldehydes were identified as the dominating factors in biodegradation process in all the locations.

4.3.5. Swelling/shrinkage, loss of strength, cracking, and embrittlement

The last AQRCI values were calculated for swelling/shrinkage, loss of strength, cracking, and embrittlement impacts on materials and are given in Fig. 7. The scores obtained for Süfera Hall were significantly higher than those obtained at the other locations. The score trend in Fig. 7 resembles the soiling and color change trends evaluated in an earlier section.

5. Conclusion

The Dolmabahce Palace has poor indoor environmental control, mainly due to its internal layout. Several rooms border outdoor spaces and have no airtight doors or windows. It is also common practice during the summer that natural ventilation, i.e., opening windows during visiting hours, is used to provide comfort for the visitors. These features obviously determine the characteristics of the locations in the palace, which is strongly affected by the natural outdoor climate and by its dramatic seasonal variations. The soiling impact was higher during winter in Medhal and Süfera Halls, and their differences were significant. Süfera Hall was the riskiest place in Dolmabahçe Palace due to the higher levels of outdoor-sourced reactive gases. It was also determined that the Medhal Hall was exposed the highest salt crystallization risk, while the risks for other locations were comparable to each other.

Sea salt particles are a subgroup of airborne PM and have particular importance in this case study. Negative salt-induced impacts (e.g., decay, deterioration and corrosion) on cultural heritage objects are significant [24], and this parameter should be included in any air quality risk assessment study concerning the protection of cultural heritage stocks located in close proximity to a seashore. Note that no direct measurement technique for sea salt particles can be used in most applications; it requires additional chemical analyses, which can increase the complexity and cost of risk assessment studies. In future studies, sea salt components and their distribution characteristics in PM size fractions should be included in risk assessment studies carried out in Dolmabahce Palace and in similar sites located in close proximity to marine environments.

Because of the nature of the palace, the original state of the historical living conditions of the building is presented. It is also not possible to relocate/exhibit objects in a different manner. In any risk assessment stage followed by this AQRCI study, the material composition of the objects can be identified, and subsequently, the proposed AQRCI values can be used to evaluate individual risk factors for any specific object.

The sharp fluctuations among the AQRCI scores for different locations indicate that passive control techniques (e.g., better insulation, provision of dust traps, replacement of wool carpets with antistatic, dust-free materials, such as carpets) might provide better indoor quality levels. However, some active control technologies and practices (vacuuming, curtains for entrances, HVAC systems) are necessary.

Acknowledgments

The author of this study acknowledges that this project was financially supported by TUBITAK under project number 109Y272. He would like to thank the General Secretariat of TBMM (Turkish Grand National Assembly), the Department of National Palaces, and the Dolmabahce Palace management and personnel for their support and assistance. He would also like to give a special thanks to

Zeynep Öztürk and Feyza Özdemir for their assistance in sampling and in the analyses.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.culher.2014.06.012.

References

[1] H. Agbota, S.A. Lyazidi, F. Becherini, A. Bernardi, A. Bonazza, E. Al, Guidelines for air pollution evaluation, monitoring and mitigation in preventive conservation of cultural heritage, final report of a VII Framework Programme Theme 6 project. Contract No. 212458-2008, 2012, Available on: http://teach-project.isac.cnr.it/wp-content/uploads/2009/05/teach_guidelines_final.pdf
[2] A. Kioussi, M. Karoglou, K. Labropoulos, A. Bakolas, A. Moropoulou, Integrated documentation protocols enabling decision making in cultural heritage protection, Journal of Cultural Heritage 14 (2013) e141–e146.
[3] Z. Huijbregts, R.P. Kramer, M.H.J. Martens, A.W.M. van Schijndel, H.L. Schellen, A proposed method to assess the damage risk of future climate change to museum objects in historic buildings, Building and Environment 55 (2012) 43–56.
[4] S. Hillhouse, Assess and manage risk in collections care: a Collections Care How To Guide, Norfolk Museums and Archaeology Service, 2012, Available on: http://www.sharemuseumseast.org.uk/shares/resource_125.pdf
[5] M. Strlič, I. Kralj Cigić, A. Možir, G. de Bruin, J. Kolar, M. Cassar, The effect of volatile organic compounds and hypoxia on paper degradation, Polymer Degradation and Stability 96 (2011) 608–615.
[6] A.U. Leuenberger-Minger, B. Buchmann, M. Faller, P. Richner, M. Zöbeli, Dose–response functions for weathering steel, copper and zinc obtained from a four-year exposure programme in Switzerland, Corrosion Science 44 (2002) 675–687.
[7] E. Menart, G. De Bruin, M. Strlič, Dose–response functions for historic paper, Polymer Degradation and Stability 96 (2011) 2029–2039.
[8] A. Fenech, M. Strlič, I. Kralj Cigić, A. Levart, L.T. Gibson, G. de Bruin, et al., Volatile aldehydes in libraries and archives, Atmospheric Environment 44 (2010) 2067–2073.
[9] M. Pitz, J. Cyrys, E. Karg, A. Wiedensohler, H.E. Wichmann, J. Heinrich, Variability of apparent particle density of an urban aerosol, Environmental Science and Technology 37 (2003) 4336–4342.
[10] J. Watt, D. Jarrett, R. Hamilton, Dose-response functions for the soiling of heritage materials due to air pollution exposure, The Science of the Total Environment 400 (2008) 415–424.
[11] Radiello, Aldehydes, methods, Centro di Ricerche Ambientali, Padova, 2006, pp. C1.
[12] Radiello, Nitrogen and sulfur dioxides (NO_2 and SO_2), methods, Centro di Ricerche Ambientali, Padova, 2006, pp. F1.
[13] Radiello, Ozone (O_3), methods, Centro di Ricerche Ambientali, Padova, 2006, pp. G1.
[14] T.L. Saaty, L.G. Vargas, Models, methods, concepts & applications of the analytic hierarchy process, second ed., Springer Berlin Heidelberg, London, 2012.
[15] E. Metaxa, T. Agelakopoulou, I. Bassiotis, C. Karagianni, F. Roubani-Kalantzopoulou, Gas chromatographic study of degradation phenomena concerning building and cultural heritage materials, Journal of Hazardous Materials 164 (2009) 592–599.
[16] N. Ghedini, I. Ozga, A. Bonazza, M. Dilillo, H. Cachier, C. Sabbioni, Atmospheric aerosol monitoring as a strategy for the preventive conservation of urban monumental heritage: the Florence Baptistery, Atmospheric Environment 45 (2011) 5979–5987.
[17] E. Cuccia, D. Massabò, V. Ariola, M.C. Bove, P. Fermo, A. Piazzalunga, et al., Size-resolved comprehensive characterization of airborne particulate matter, Atmospheric Environment 67 (2013) 14–26.
[18] A. Srivastava, V.K. Jain, Size distribution and source identification of total suspended particulate matter and associated heavy metals in the urban atmosphere of Delhi, Chemosphere 68 (2007) 579–589.
[19] C.A. Belis, F. Karagulian, B.R. Larsen, P.K. Hopke, Critical review and meta-analysis of ambient particulate matter source apportionment using receptor models in Europe, Atmospheric Environment 69 (2013) 94–108.
[20] F. Karaca, B. Ünal, S. Gören, Ö. Ağa, A. Karaburun, Final Report of TUBITAK Project no. 109Y272, Istanbul, 2012.
[21] C. Theodosi, U. Im, P. a Bougiatioti, O. Zarmpas, N. Yenigun, Mihalopoulos, Aerosol chemical composition over Istanbul, The Science of the Total Environment 408 (2010) 2482–2491.
[22] T. Szigeti, V.G. Mihucz, M. Óvári, A. Baysal, S. Atılgan, S. Akman, et al., Chemical characterization of PM2.5 fractions of urban aerosol collected in Budapest and Istanbul, Microchemical Journal 107 (2013) 86–94.
[23] M. Koçak, C. Theodosi, P. Zarmpas, U. Im, a. Bougiatioti, O. Yenigun, et al., Particulate matter (PM10) in Istanbul: origin, source areas and potential impact on surrounding regions, Atmospheric Environment 45 (2011) 6891–6900.
[24] C. Cardell, F. Delalieux, K. Roumpopoulos, A. Moropoulou, F. Auger, R. Van Grieken, Salt-induced decay in calcareous stone monuments and buildings in a marine environment in SW France, Construction and Building Materials 17 (2003) 165–179.