A Computational Program for Estimating Atmospheric Corrosion of Monuments

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ABSTRACT

This study developed a novel computer program for predicting the deterioration of various types of materials from historic monuments caused by exposure to atmospheric pollution. The program was designed based on a set of materials' dose-response functions, which take air pollutants together with climatic parameters into account. It is a web-based application that requires three input datasets: monuments' material characteristics, local meteorological data and air pollution levels over a defined exposure time. It is also capable of estimating restoration costs. Quantification of future monument deterioration is possible by extrapolation of linear temporal relationships for air pollution and meteorological parameters. This user-friendly-interface program cooperates with Google Maps™ to find the nearest air pollution and meteorological stations to the monument site. The program may be used as a tool providing quantitative information for effective policy-making in conservation of cultural heritage monuments. To illustrate its use, the program was employed to assess the accumulated deterioration of 75 Buddhist monuments comprised of various materials located in a historical area of Bangkok, Thailand. It was estimated that the total accumulated material loss from all monuments over seven years exposure in this environment to be approximately 410 cm^3 with an overall restoration cost of about 210,000 USD.

1. INTRODUCTION

Air pollution and its effects are well recognized as important environmental issues worldwide. Increasing road traffic and industrial emissions cause elevated levels of air pollutants and create multi-pollutant exposure situations. The effects are not only on human health but also on exposed materials. Deterioration of materials due to atmospheric pollution is a complex phenomenon. The process of atmospheric corrosion involves interactions between various atmospheric pollutants (gaseous and particulate) and meteorological conditions with pollutant deposition mechanisms also playing a role (Syed, 2005). For example when specific gaseous air pollutants (i.e., SO_2 and NO_2) dissolve in precipitation, they form sulfur and nitrogen containing protic acids that potentially corrode building materials. Occurrences of acid deposition are found in many countries in Asia (Duan, 2016). Particulate matter and O_3 can also damage building materials via certain mechanisms. In the case of invaluable and irreplaceable cultural heritage buildings, deterioration of component materials due to atmospheric corrosion is of serious concern.

The effects of the corrosion on building material may take a relatively long period of time to manifest. Previous comprehensive studies have employed empirical dose-response functions for deterioration of monument materials when exposed to atmospheric pollution (Melcher and Schreiner, 2004). These functions describe the deterioration of the individual materials such as cast bronze and limestone with individual material loss or surface recession as dependent variables, and exposure period, air pollutant concentrations and meteorological conditions as independent variables. This allows assessment or prediction of the deterioration of a material under current or new environmental and climatic conditions respectively (Lefèvre and Ionesco, 2010). Recent studies have employed such functions to assess the effects of air pollution on atmospheric degradation of cultural heritage monuments and buildings as part of initial protection planning (Agostini et al., 2005; Tidblad et al., 2012; Kambezidis and Kalliampakos, 2012; Karaca, 2013). The application of such dose-response functions has mainly been in European countries however. Care must be exercised to establish whether such functions are also applicable in other regions and climates. In addition, development and use of computer programs incorporating these functions as a tool to estimate deterioration of monument material are rare.

This aim of this study was to develop a web-based computer program based on a set of dose-response functions in order to quantify the deterioration of monument materials. The program was designed to automatically collect air pollution and meteorological data from the nearest monitoring stations to the location of the investigated monument enabling estimation of its deterioration in terms of loss of material volume. This would provide an easy, efficient and useful way to quantify the damage to monument surfaces from atmospheric corrosion and assess restoration costs. To illustrate use, the program was employed to assess the deterioration of Buddhist monuments located in a historical area of Bangkok, Thailand. Information obtained from the program can be used for initiation of monument conservation and air quality management measures that take monument degradation into consideration.

2. METHODOLOGY

2.1 Program development

The developed program is hereinafter denoted as the Air Pollution Impact on Monument Materials (APIMON) program and was created within the conceptual framework presented in Figure 1. It was developed by means of a web-based application, a so-called Enterprise Mashup (EM), enabling the integration of data from different sources to create new visual content, most commonly on the internet (Yu et al., 2008; Tuchinda et al., 2011; Soylu et al., 2012). The APIMON program's structure is displayed in Figure 2. Dose-response functions for corrosion of materials (Table 1) were obtained from the European Union's MULTI-ASSESS project for multi-pollutant impact and assessment of threshold levels for cultural heritage (Melcher and Schreiner, 2004), as well as other relevant studies, i.e., Lan et al. (2005) and Viitanen et al. (2010). These functions were transformed into the EM's codes. Parameters relevant to monuments were specified as objects. Atmospheric pollution variables in the dose-response functions are defined as subjects in the program. Air pollution and meteorological parameters are provided as databases (described as the sensor database in Figure 2), which can be developed either using datasets obtained from air quality and meteorological monitoring stations in a study area or by online cooperation with measuring instrument sensors in these stations. A function for estimating restoration cost due to atmospheric degradation is also provided. The program's output then is amount of material loss from monuments over defined exposure periods and corresponding restoration cost.

To enable the program output for material loss to be in terms of accumulated volume of material loss (m^3), the values of material loss (ML) and recession (R) from the original source dose-response functions were modified. In case of ML, accumulated ML (g/m^2) from the original function was multiplied by material area (m^2) and divided by material density (g/m^3) while for R, recession of material thickness was multiplied by material area.

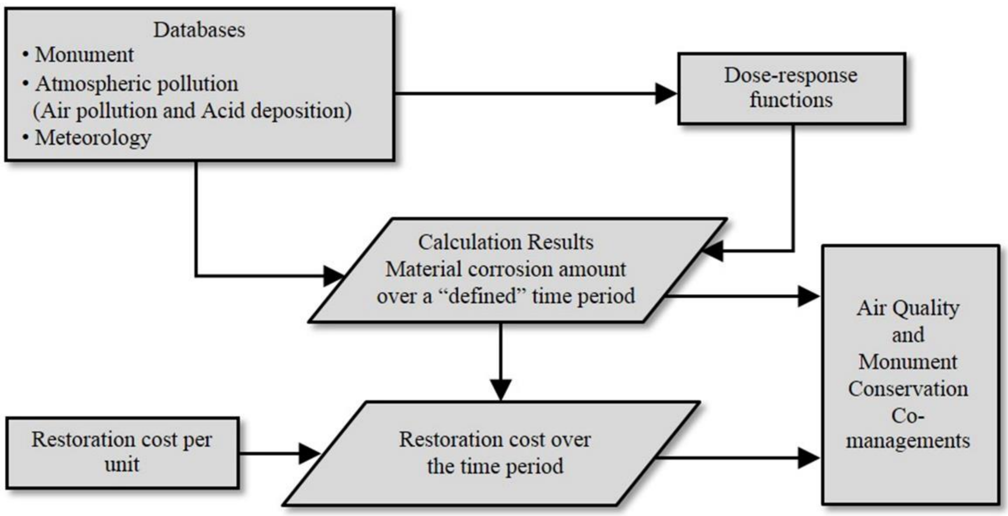

Figure 1. Conceptual framework for program development.

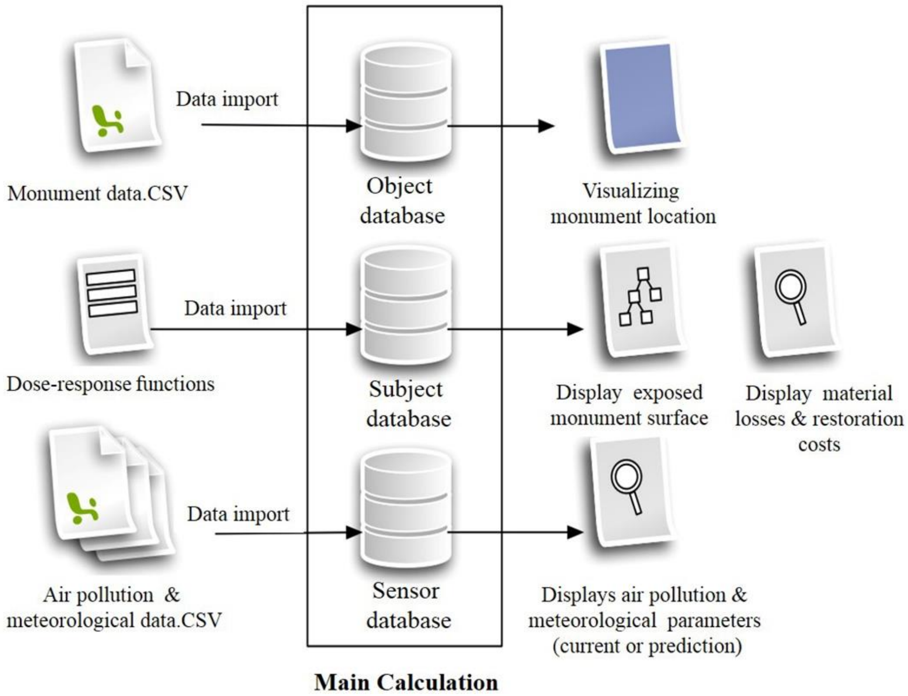

Figure 2. Structure of the program APIMON (CSV stands for comma-separated values).

Table 1. Dose-response and associated temperature functions for unsheltered materials used in program development.

Material	Functions
Carbon Steel[a]	$ML = 29.1 + \{21.7 + 1.39[SO_2]^{0.6}Rh_{60}e^{f(T)} + 1.29Rain[H^+] + 0.593PM_{10}\}\ t^{0.6}$ $f(T) = 0.15(T-10)$ when $T<10$ ºC, $-0.054(T-10)$ otherwise
Zinc[a]	$ML = 1.82 + \{1.71 + 0.471[SO_2]^{0.22}e^{0.018Rh+f(T)} + 0.041Rain[H^+] + 1.37[HNO_3]\}\ t$ $f(T) = 0.062(T-10)$ when $T<10$ ºC, $-0.021(T-10)$ otherwise
Copper[a]	$ML = 3.12 + \{1.09 + 0.00201[SO_2]^{0.4}[O_3]Rh_{60}e^{f(T)} + 0.0878\ Rain[H^+]\}\ t$ $f(T) = 0.083(T-10)$ when $T<10$ ºC, $-0.032(T-10)$ otherwise
Cast Bronze[a]	$ML = 1.33 + \{0.00876[SO_2]Rh_{60}e^{f(T)} + 0.0409Rain[H^+] + 0.0380PM_{10}\}\ t$ $f(T) = 0.060(T-11)$ when $T<11$ ºC, $-0.067(T-11)$ otherwise
Portland limestone[a]	$R = 3.1 + \{0.85 + 0.0059[SO_2]Rh_{60} + 0.054Rain[H^+] + 0.078[HNO_3]Rh_{60} + 0.0258PM_{10}\}\ t$
Marble[b]	$R = \{0.00233\ (Rh)\ (0.38\ [SO_2])\}\ t + 0.00309Rain$
Wood[c]	$ML^* = -42.9(12t) - 2.3(T) - 0.035(Rh) + 0.14\ (T)(12t) + 0.024(T)(Rh) + 0.45(Rh)(12t)$

Remarks: ML is material loss (g/m^2), R material recession (µm), $[SO_2]$, $[NO_2]$, $[O_3]$, and $[PM_{10}]$ concentrations of these air pollutants in µg/m^3, t duration of exposure in years, T the temperature in ºC, Rh relative humidity (%) (Rh_{60}=60 when Rh>60 %, Rh_{60}=0 otherwise), Rain the cumulative amount of precipitation (mm) over the exposure period (t) (years) and (H^+) the concentration of H^+ in precipitation (mg/L). The annual HNO_3 concentrations (µg/m^3) were calculated from $(HNO_3)=516\ e^{-3400/(T+273)}\times([NO_2][O_3]Rh)^{0.5}$. *denotes that the equation only applies when ambient temperature is greater than or equal to 0 ºC and Rh>95%. [a]Melcher and Schreiner (2004), [b]Lan et al. (2005), and [c]Viitanen et al. (2010).

2.2 Program application

Once the program was developed, its application was illustrated for monuments in Ko Ratanakosin, a historical area in Bangkok, Thailand covering an area of 1.8 km^2. While air quality has improved in Bangkok over recent years, it is still problematic, particularly for pollutants such as O_3 and PM_{10} (PCD, 2015). A group of Buddhist monument objects were selected from those identified and announced in the Royal Thai Government Gazettes. In total, there were 75 individual monuments belonging to 12 different Buddhist temples. Information on these monuments, (i.e., monument names and types), were collected from the Office of Archeology, Fine Art Department of Thailand and an onsite survey conducted to record geographical coordinates, material types and their surface areas. These parameters (Table 2) formed the object database.

For the sensor database comprising air pollution and meteorological parameters, they were recorded at diurnal resolution from four-year datasets (from 2005 to 2008). The air pollution dataset (consisting of air pollutant concentrations and hydrogen ion concentrations in precipitation (Table 2) was based on data from permanent monitoring stations located in Bangkok and surrounding provinces. The meteorological dataset was created using the data from the two nearest Thai Meteorological Department stations, namely those in the Bangna district and at Suvarnabhumi International Airport. Geographical coordinates of the stations were also recorded. (Note that for the hydrogen ion concentration in precipitation, an alternative data source is the Acid Deposition Monitoring Network in East Asia (EANET) (http://www.eanet.asia/) which operates a number of monitoring sites in 12 East Asian countries).

Table 2. Datasets and relevant parameters required for the program application.

Dataset	Parameters
Monument (Object database)	Monument names and types, geographical coordinates, material types and their surface areas (m^2)
Air pollution (Sensor database)	Monitoring stations' coordinates, daily air pollutant concentrations ($\mu g/m^3$), i.e., sulfur dioxide, nitrogen dioxide, ozone and particulate matter (PM_{10}), and daily hydrogen ion concentrations in precipitation (mg/L)
Meteorology (Sensor database)	Monitoring stations' coordinates, daily meteorological parameters, i.e., temperature (ºC), relative humidity (%) and precipitation amount (mm)

3. RESULTS AND DISCUSSION

3.1 Program development

Overall APIMON program operational features are illustrated in Figure 3. The program consists of 2 main components: 1) information entries, and 2) program outputs. As mentioned earlier, information entries require the user to provide three separate datasets (Table 2). The first contains the relevant monument-specific information, and the remaining two comprising air pollution and meteorological parameters, are necessary for the various material-specific dose-response functions (Table 1). If information relating to the monument is not available from responsible organizations, on-site observation may be necessary. The three datasets are arranged as comma-separated value (CSV) files before input into the program to generate the databases ready for subsequent calculations. The program also provides an option where the users can modify the dose-response functions to suit their local application. In addition, the APIMON program is configured to cooperate with Google Maps™ to determine the nearest air pollution and meteorological stations to the site(s) of interest automatically in order to increase accuracy of calculations of monument deterioration. The user is requested to specify preferred exposure period at the program's main page, either from past to present or from present to future. The program then calculates the monuments' material losses according to this exposure period. If the user requests a prediction of future monument deterioration the program generates the corresponding datasets by means of linear extrapolation of temporal relationships for air pollution and meteorological parameters. In addition, the program provides an option to calculate restoration cost both for individual and groups of monuments (total cost) in an area of interest. For this, the user is requested to input the cost per material volume, (e.g., USD/m^3) for each separate type of a monument's material. For the current application, this information came from the work of a Thai architectural conservation expert (Thammavatevitee, 2016).

The program outputs (Figure 3) provide three sets of information; 1) visualization of monuments' locations in a study area; 2) the exposed monument material surfaces together with accumulated loss volume (m^3) of each individual type over specified exposure periods and relevant restoration costs for each monument; and 3) tabular and graphical displays of air pollution and meteorological parameters (current or predicted).

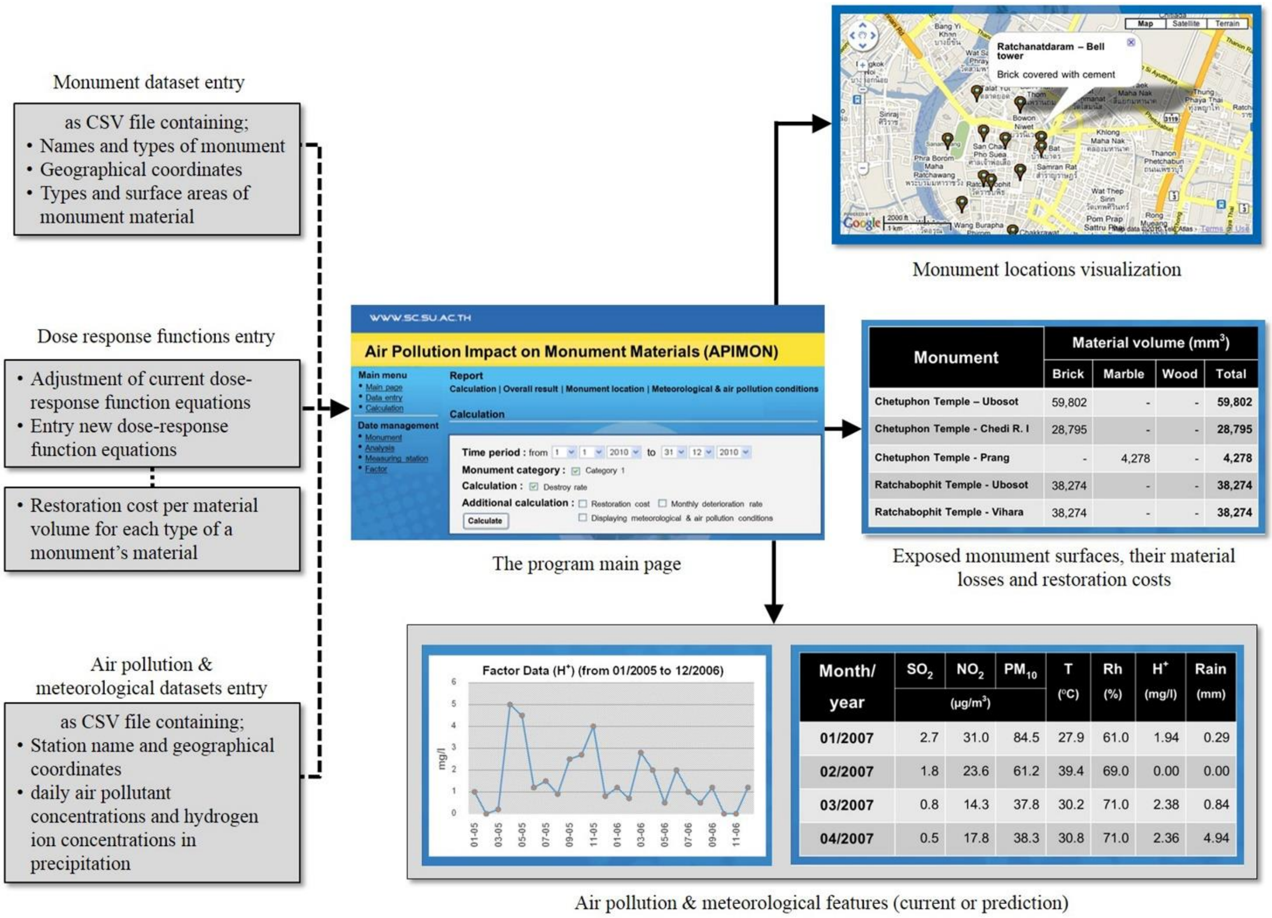

Figure 3. Diagram showing the operational features of the APIMON program. Dashed and solid arrows indicate the program inputs and outputs, respectively. (Currently, the program has been developed as a Thai version for local application purposes. The features were modified from the original one for clearer view).

3.2 Program application

Characteristics of the Buddhist monuments in the Ko Ratanakosin area of Bangkok included in the deterioration assessment are summarized in Figure 4. It can be seen that although there were a variety of different types of monuments, the majority were Vihara (Assembly Halls), Chedi (Reliquary Towers) and Ubosot (Ordination Halls) (in total 43 out of 75). The surface area of the monuments subdivided on the basis of these monument types can be seen in Figure 5, where the Ubosot group had the highest (estimated as 23,793.5 m^2), while the single Stupa had the lowest (137.6 m^2). In regard to the total surface areas of the various materials comprising these monuments, the majority was brick covered by cement, followed by cement, cement covered with ceramic and uncovered brick, respectively (Figure 6).

Following collation, this requisite information for the monuments of interest was imported into the model. Since the selected exposure time period was set to be seven years (from 2005 to 2011), on executing the program, it firstly simulates the following three years (2009 to 2011) of air pollution and meteorological data using the current four-year datasets (from 2005 to 2008) previously entered into the program. A monument restoration specialist provided the restoration costs for each material type by volume. These costs depend on a number of factors such as the monument's material type and age, composition of monument, (e.g., windows, doors, floors, roofs), monument's structure and shape, restoration techniques and labor costs (Thammavatevitee, 2016). The estimation of restoration cost can be considered in different ways. Grøntoft (2017) proposes a method similar to that employed here, but additionally takes into account time intervals between past conservation-restoration interventions. Rabl (1999) identifies the components of restoration cost to be not only cleaning and repair cost, but also the cost of preventative measures and a cost due to loss of amenity, e.g., aesthetic loss as the monument becomes dirty.

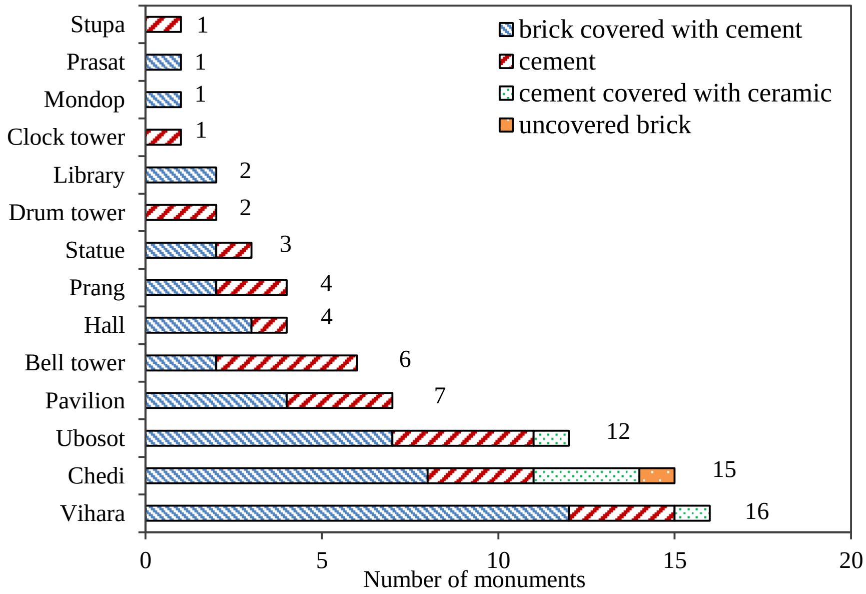

Figure 4. The 75 Buddhist monuments categorized by type for inclusion in the APIMON program to demonstrate its application. (The Hall category comprises Meditation Halls, Sermon Halls and Tripitaka (Scripture) Halls).

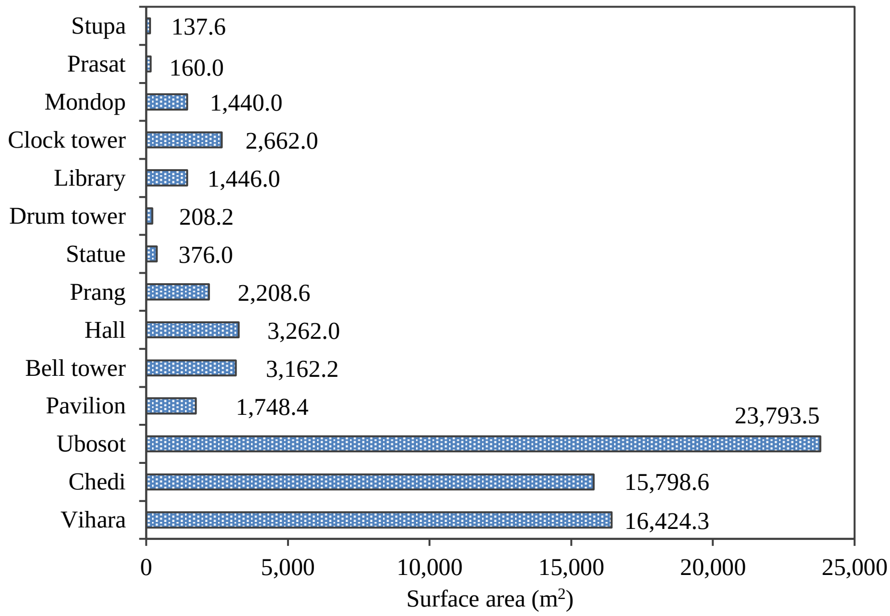

Figure 5. Aggregate surface areas of the different types of Buddhist monuments for the APIMON program case study.

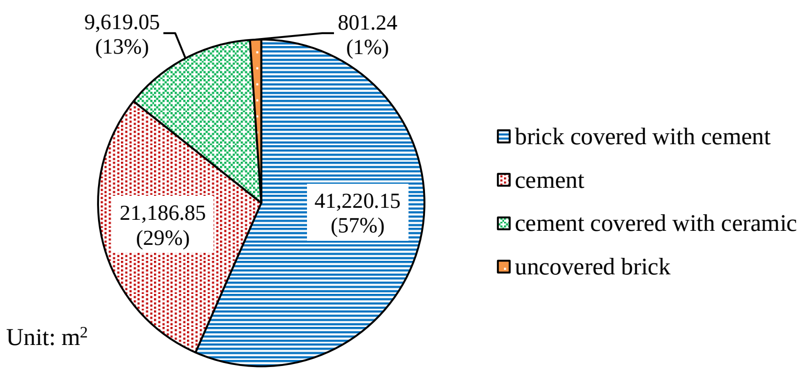

Figure 6. Aggregate proportions of the various monuments component materials in the case study.

Once all required datasets were populated, the monuments' material losses (by volume) and relevant restoration costs were then computed as illustrated in Figure 7 and Figure 8, respectively. The total accumulated material loss from all monuments over seven years exposure to the ambient atmosphere in Bangkok was estimated to be approximately 410 cm^3 with an overall restoration cost of about 210,000 USD.

Since the material losses were as a function of exposed surface areas in addition to depending on air pollution and metrological factors, a higher restoration cost was determined for those monument types with relatively large surface areas, i.e., Ubosot, Chedi and Vihara (Figure 7). They accounted for 32.7%, 21.7% and 22.6% of the overall surface areas of monuments investigated, respectively.

Typical Buddhist monuments were built with a variety of materials and decorative techniques. Buddhist temple complexes, for example, were covered with superimposed tiers of roof ornaments with different gable-end shapes, smooth plaster surfaces on masonry walls and floor finishing in sandstone, brick, ceramic or wood (Chitranukroh and Buranakarn, 2006). This can complicate corrosion estimations. The variety of response-function equations available are relatively limited and do not match precisely to the monument materials found in the study area. While brickwork is regarded as being relatively unaffected by HNO_3 for example, mortar is not and degradation of mortar may affect the structural integrity of brickwork (Yates, 2003). All observed materials were therefore treated as Portland limestone.

During the selected exposure time period, Bangkok has been facing constantly increasing annual O_3 levels, while NO_2 concentrations have remained relatively constant and SO_2 and PM_{10} levels decreased, but remain problematic, particularly in the case of particles. O_3 plays a key role in HNO_3 formation that in turn likely plays a major role in corrosion of the monuments' materials in this study.

A monument's structure and shape play an important role in atmospheric degradation of component materials. The high-pitched roof covered with ceramic plates characteristic of Ubosot and Vihara enable these structures to minimize accumulation of particulate atmospheric pollutants in the top part of the structures. Different shelter alignments can protect material losses caused by wind (Roberge et al., 2002). The large eaves of these two monuments types provide sheltered conditions mitigating material recession of the upper part of their walls. However, these sheltered conditions can also result in an accumulation of soiling effects on materials in concrete (Tzanis et al., 2011). Chedis on the other hand are typically conical in shape, with vertical to horizontal dimension ratios larger than those of Ubosot and Vihara. Such an aerodynamic structure may diminish material corrosion by wind and rainfall.

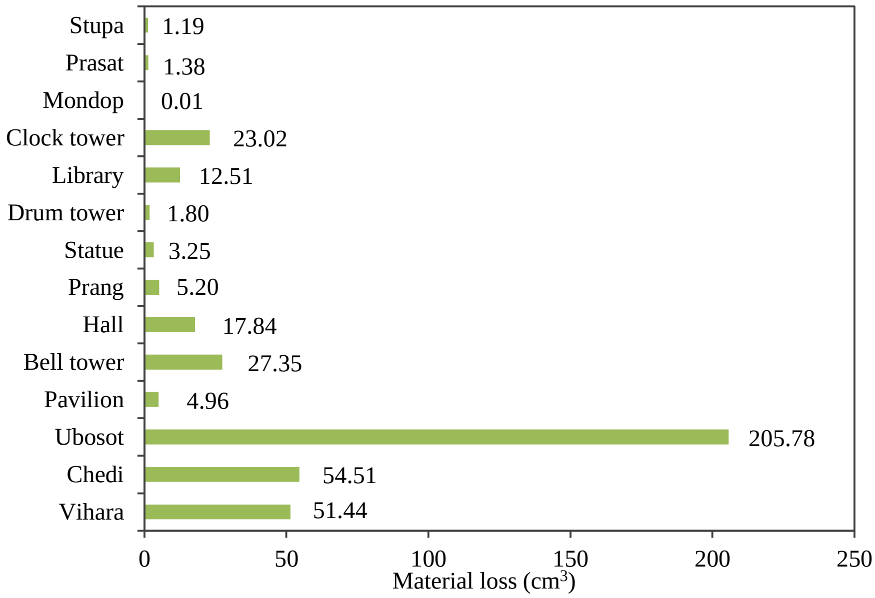

Figure 7. Material losses by volume of the different types of Buddhist monuments derived from the APIMON program for the case study.

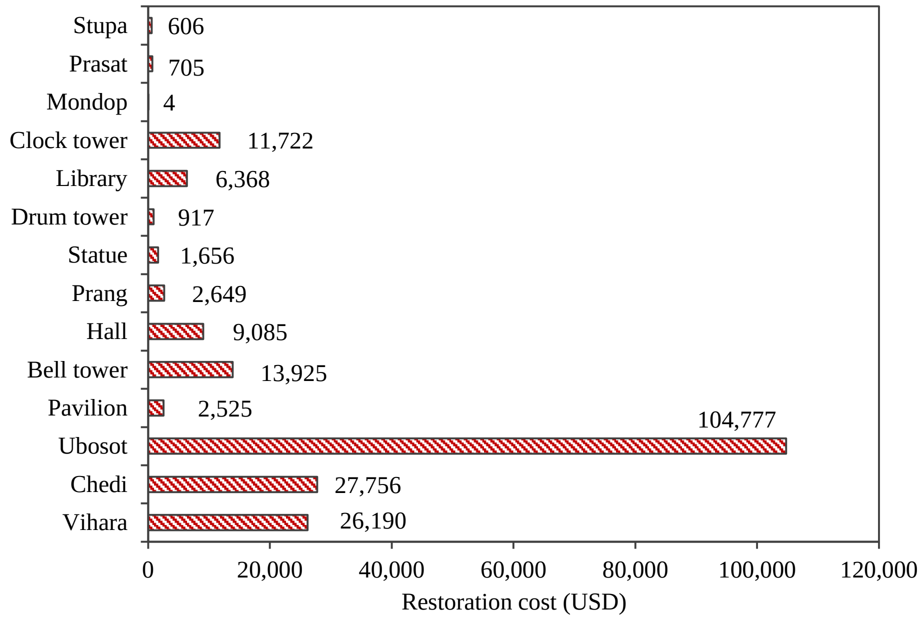

Figure 8. Restoration costs for the different types of Buddhist monuments based on their estimated material losses in the case study.

3.3 Program output uncertainty

It should be noted that program output uncertainty might result from a number of factors. The use of empirical dose-response equations may result in predictions with reduced levels of accuracy. An example is the directionality of damage associated with the prevailing exposure conditions. In regard to the material that the monument is comprised of, different characteristics, (e.g., porosity), in the same category of material, e.g., limestone, may lead to greater or lesser damage (Agostini et al., 2005). Additionally, different air pollution levels and atmospheric conditions play a key role in the specific extent of material corrosion in different regions. For example in the case of limestone, the dose-response of European-based expressions underestimates the actual loss under Asian conditions. This may be due to the fact that the relatively high pollution levels combined with the elevated temperature levels and high precipitation amount observed in this region result in higher corrosion rates than previously observed in Europe (Tidblad et al., 2007). Such specific conditions or factors are not accounted for in the equations employed, but there is little relevant data to construct more area-specific relationships. In addition, the accuracy of the program's results relies on air pollution and climatic parameters that are derived from simple linear relationships in the program that may not always be appropriate. Furthermore, restoration costs are highly dependent on material types together with their particular characteristics and the existing condition of individual monuments. Nonetheless, the APIMON program may be used as a tool providing quantitative information for effective policy-making and to support decision-making for conservation of cultural heritage monuments. It is an easy, efficient and useful way to quantify the damage to monument surfaces from atmospheric corrosion and assess restoration costs. Research on corrosion of materials is ongoing and while not all is applicable to monuments, it is important to establish an updating procedure and apply this, as appropriate. Further studies on validation of the empirical dose-response equations in particular in the case of tropical countries (such as Thailand) should be carried out. In this way, the accuracy of APIMON program results will improve.

4. CONCLUSIONS

The web-based program APIMON employs dose-response function equations to compute the deterioration of a monument's material caused by air pollution and climate exposure. The program employs datasets of monument characteristics, air pollutant concentrations and meteorological conditions to estimate monuments' material losses and relevant restoration costs with either existing or future scenarios supported. As such the program can act as a tool for effective policy-making in conservation of cultural heritage monuments. It was tested by quantifying material losses of a group of various types of Buddhist monuments located in Bangkok, Thailand. The corresponding cost provided for the restoration was also estimated. The program accuracy depends on factors such as directionality of damage relevant to the prevailing exposure conditions, varying material characteristics as well as the applicability of dose-response functions in different atmospheric conditions. These are challenges for future work to enhance the program's accuracy.

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