Application of an Air Pollution Modelling Tool to Cultural Heritage Buildings

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1 Introduction

Air pollution from the outdoor environment whether it is from industrial, transport or domestic sources has long been recognised as a significant agent of deterioration of cultural heritage collections housed in museum, gallery, archive and library buildings. [1]. Past responses to the need to understand the behaviour of reactive air pollution in museum buildings[1] have largely been based on measurement techniques. In the last couple of decades, with the widespread availability of personal computers, mathematical modelling has also begun to be used to understand air pollution behaviour and effects on collections [2]. Many of the models have been adapted from the public health field where they have been used to predict exposures to pollutants of humans inside buildings. This paper describes the application of a Java applet based on the mass balance equation of Weschler et al. [3] for non-specialist use by conservators, architects and engineers, to predict damaging pollutant exposure of collections in the indoor environment. The Weschler equation relates the indoor/outdoor pollutant ratio (C_i/C_o) directly to building parameters: the air exchange rate (λ), indoor volume (V) and indoor surface area of materials (A), and their affinity for reaction with air pollutants which is expressed in the term deposition velocity (v_d):

$$\frac{C_i}{C_o} = \frac{\lambda}{\lambda + \bar{v}_d A / V}$$

This equation assumes that the principal mechanism for reactive pollutant removal in the indoor environment (assuming no filtration) is heterogeneous reaction, i.e. reaction between a pollutant gas and internal building surfaces. Homogeneous reactions (gas-gas interactions) are considered to be insignificant. Another underlying assumption is that the only source of pollutant gas is the external environment and that there are no indoor sources. The validity of these assumptions is discussed below. Gases that cause damage to the material heritage will, by definition, be those that have significant deposition onto indoor surfaces, be they objects or parts of the building fabric. The most important gases that are sourced outdoors have long been considered to be sulphur dioxide, nitrogen dioxide and ozone. Their main sources are, respectively fossil fuel combustion (sulphur dioxide and nitrogen dioxide), motor vehicle emissions (nitrogen dioxide) and photochemical reactions of those emissions (ozone). In domestic and workplace environments there may well be significant indoor sources of these pollutants, for example, nitrogen dioxide from gas heating and cooking appliances, and ozone from electrical appliances such laser printers and photocopiers. Such appliances are normally specifically excluded from collections spaces, so our assumption of no indoor sources is valid for these spaces. Homogeneous reactions can also be discounted for sulphur dioxide but are

[1] Reference to museum buildings throughout this paper includes all cultural heritage building types

known to play a part in the formation and decomposition of nitrogen dioxide and ozone [4]. The validity of this assumption will be discussed later in the paper.

The simple Weschler mass balance equation is useful for understanding the relationship between air pollution and collections. Objects and materials do not have the ability to metabolise pollution, but instead slowly react over time, accumulating damage with the overall pollutant dose (i.e. concentration over time) that they receive. The Weschler equation predicts the long-term average pollutant concentration, rather than the short-term dynamic concentration, minute by minute. A measure or prediction of long-term average pollutant exposure will be more relevant to the collection environment than a dynamic model for predicting object deterioration due to air pollution. Dynamic predictions of effects such as peak traffic hours, diurnal variations are more relevant for human health, where increases in concentration above a threshold can overwhelm people's ability to metabolise or adapt to pollution exposure.

2 Interpreting the Weschler Equation Parameters for the IMPACT Model

Interior volume and surface area. The building interior volume and areas of different materials are relatively easy to obtain, being calculable from building plans and an inventory of the main surface types and the area exposed to pollutants. Not every surface needs to be considered; it is sufficient to estimate up to the six most significant surface types.

Air exchange rate. The building air exchange rate can be measured using standard tracer gas decay or pressurisation testing techniques. These methods are rather specialised and expensive, and therefore likely to have been carried out on only the most prestigious heritage buildings. Therefore an estimate method is provided for users who do no have measured ventilation rates.

Pollutant surface deposition velocity. Though somewhat confusingly expressed as a velocity with units of cm per second or m per second, deposition velocity can be better understood as the flux of pollutant gas to a surface per unit time, expressed as m^3 gas per m^2 surface per second. Normalisation of these units gives velocity units, hence the confusing term deposition velocity. However deposition velocity usefully expresses how well a particular pollutant gas will react and deposit on a particular surface material, be that a historic object or building interior finish. Deposition velocity is usually measured in controlled laboratory experiments. In the IMPACT model these data were organised for the users so that the selection of a surface material would automatically select the appropriate value of deposition velocity for the pollutant gas in which they are interested. To achieve this, a large number of deposition velocity measurements were carried out on the types of material found in museum buildings, and existing literature data was critically evaluated. This work is described by Grøntoft and Raychaudhuri [5].

Gas-surface reactions can be reversible and re-emission can occur. The deposition velocity measurement method used expresses the equilibrium between deposition and re-emission, thus a gas which is not very reactive at surfaces will have a low deposition velocity since when it comes into contact with a surface there is a lower probability of reaction and decomposition, and it may simply be reemitted after a short time. This process of reaction and reemission is temperature and relative humidity dependent – the presence of adsorbed water on a surface increases its reactivity to pollutant gases, particularly for acidic reactions involving sulphur dioxide and nitrogen dioxide, and less so for oxidative reactions, such as those involving ozone. Therefore temperature and relative humidity are needed in the calculation. Fortunately relative humidity and temperature are parameters that museums and other cultural heritage organisations expend considerable effort on controlling and measuring, and these data will usually be available. Surface reactions involving sulphur dioxide are thought to result in non-reversible assimilation of sulphur dioxide as involatile sulphate, e.g. the accumulation of high concentrations of sulphate in materials such as leather [6]. Ozone is also thought to decompose fully at surfaces, but the reaction is less water-dependent than for sulphur dioxide, being oxidative rather than acidic in its chemistry. For nitrogen dioxide the situation is more complicated. It tends to have lower deposition velocities than the other two gases, indicating a lesser affinity for surface reaction. Where it does react on indoor surfaces it is believed to decompose to nitric (HNO_3) and nitrous (HONO) acids. Nitric acid is a strong acid and will cause damage to surfaces, whereas the weaker nitrous acid is volatile and over a period of several hours after deposition it is re-emitted to the air [7,8]. HONO is less reactive and therefore not a significant threat to materials, and is eventually removed by ventilation within the space. It is important to recognise the significance of surface chemistry as deposition is simply not the end of the story.

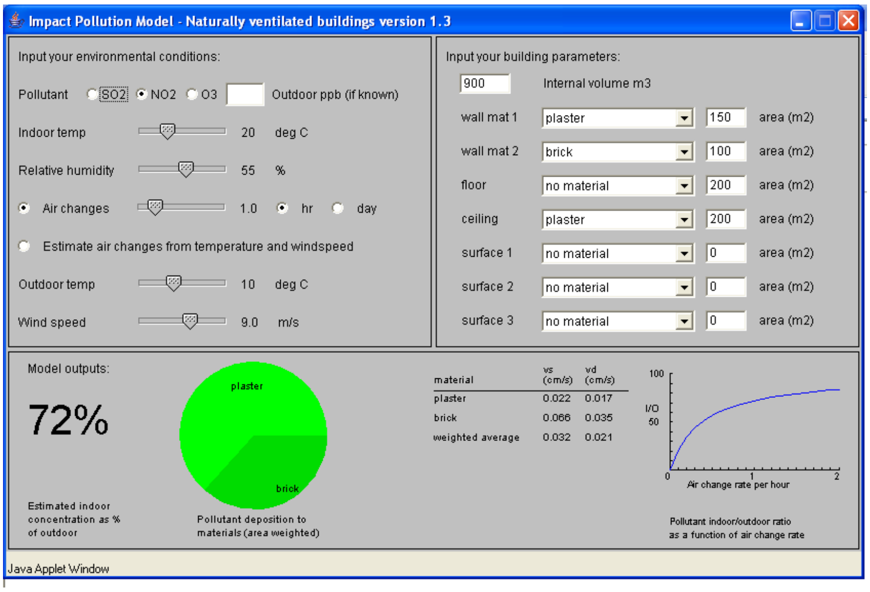


Figure 1: The IMPACT model computer interface. The model is written as a Java applet that can be accessed freely using any internet browser programme at: http://www.ucl.ac.uk/sustainableheritage/impact/.

Figure 1 shows the interface of the IMPACT model implementation of the Weschler equation. The applet interface is divided into three sections: environmental inputs, top left; building inputs, top right; and outputs, below. It is not the purpose of this paper to describe the input process – a set of help pages are provided to do this. However, the model outputs will be described. These consist of: (i) the building I/O pollutant ratio for the gas selected; if the outdoor pollutant concentration is known, then this can be inputted and the model calculates the corresponding indoor concentration; (ii) A pie chart showing the relative amounts of deposition occurring to different indoor surfaces. It assumes all inputted surfaces are equally likely to come into contact with the polluted air. It does not take into account strategic location of materials, such as window and door materials that are closest to paths of infiltration. The pie chart gives a useful visual indication of the most important surfaces for pollutant removal. In some cases the most active surface may have one of the smallest areas, but it may play a greater role than might be anticipated due to its high deposition velocity. This output is also useful for appraising what happens to collections materials indoors – what will be the pollutant deposition to materials we wish to protect? Deposition to objects is particularly important when they form a large part of the surface area of a room, for instance paintings hung in a gallery, or tapestries on walls and historic carpets on floors; (iii) The model also outputs the deposition velocity values for the selected surface materials and (iv) a graph of I/O ratio vs. air exchange rate to show how building pollution levels will vary with differing air change rate.

3 Case Study Applications of the Model

The modelling of two case-study buildings will be described, demonstrating the application of the IMPACT natural ventilation model to the understanding of the interaction of buildings with outdoor air pollutants and the implications for the collections housed within them.

3.1 Sainsbury Centre for Visual Arts, University of East Anglia, Norwich, UK

The Sainsbury Centre for Visual Arts (SCVA) is an early building of the international architect Sir Norman Foster. When first opened it was unique among museum buildings in that collections, teaching spaces, offices, café and restaurant were all housed in the same open plan space. Note that the description, images and data presented relate to the SCVA prior to its major refurbishment in 2004-06. The SCVA has a rectangular design and is of lightweight construction with double skinned metal long sidewalls and huge glass end walls and a metal and glass ceiling. The inner surfaces of the sidewalls consist of a slatted metal skin, behind which is a layer of a chipboard-type insulation material. The floor of the gallery and restaurant area is carpeted whilst the lobby and café areas have synthetic hard flooring similar to linoleum.

Figures 2 and 3: The Sainsbury Centre for Visual Art, Norwich, UK. Figure 2, left: the metal and glass exterior; figure 3, right: the open plan gallery interior.

Table 1: Data on the SCVA used in the modelling. Dimensions are taken from the architect's drawing and the ventilation rate was measured as described above. The model default values of temperature and relative humidity were used.

Internal surfaces	Area m^2	Other parameters	
Metallic wall finish	2620	Room volume	42570 m^3
Metallic ceiling finish	4585	Air change rate	1.5ach
Glass	528	Temperature	20°C
Carpeted floor	4257	Relative Humidity	55%
Inner wall insulation	2064		

The SCVA has a simple mechanical ventilation and heating system with air intake using fans installed in the side walls. There is no facility for humidification or cooling. The ventilation rate of the SCVA was measured using the sulphur hexafluoride tracer gas decay technique. It was found to be 1.5 air changes per hour (ach), a comparatively high rate for a museum building, for instance a museum gallery of traditional 19^{th} century design was found to have a ventilation rate of 0.7ach. As a single zone building the SCVA was relatively straightforward to model using the IMPACT tool. The data in table 1 were used as the model inputs.

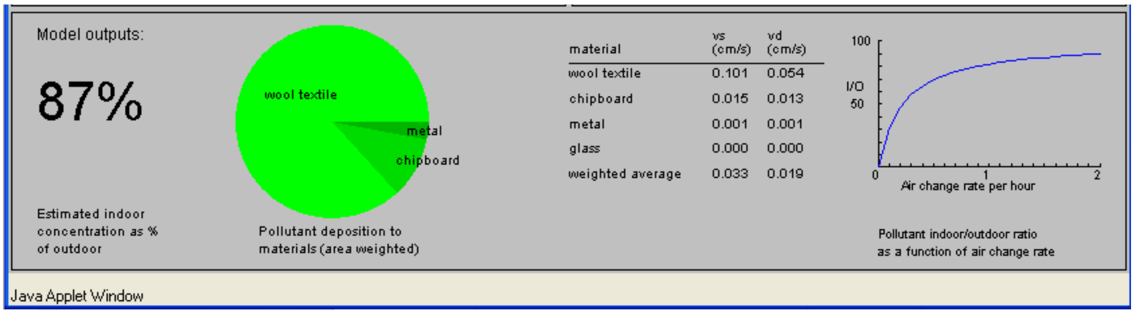


Figure 4: IMPACT model outputs for nitrogen dioxide at the SCVA using the inputs in table 1.

The IMPACT model estimated the indoor/outdoor ratios (I/O) for the different gases to be: sulphur dioxide, 0.89; nitrogen dioxide, 0.87 (expressed as 87% in figure 4) and ozone 0.88. These ratios indicate a close relation between external air pollution and the building internal environment. The model outputs of deposition velocity and the area weighted deposition pie chart (see figure 4) show that of all the interior materials, only the wool carpet plays a significant role in absorbing or reacting with the outdoor pollutants, accounting for approximately 80% of the total deposition in the case of nitrogen dioxide and ozone and around 66%. The other surfaces are relatively insignificant as pollution sinks, glass not registering at all. The high air change rate of 1.5 ach also contributes to the high pollution level by drawing in fresh pollution into the building with the intake of fresh air.

The combination of these factors explains the high I/O ratios for the SCVA, exposing the objects on display outside display cases, to the virtually the same amounts of pollution as are present outdoors. Fortunately the SCVA is located in a semi-rural site on the outskirts of Norwich, in a relatively unpolluted location. Furthermore, most of the collection is exhibited in display cases, principally to act to stabilise relative humidity and temperature conditions, but also providing protection against outdoor pollutants. For objects on open display at the SCVA, the building design and construction do little to mitigate outdoor pollution; it is chiefly because the building is in an unpolluted location that there is little pollution threat to the collection. Were this type of building to be constructed in a polluted urban location much greater problems for the collection could be expected. The IMPACT model can also be used to explore changes to the building that could improve control of external pollutants, such as: (i) reduce the building ventilation rate; (ii) change the surface materials to increase their pollution absorbing properties; (iii) increase the surface area; or (iv) introduce mechanical ventilation with filtration. These measures are graded in the order of increasing intrusion, with (iv) involving major modifications to the building and unlikely to be acceptable from a design aesthetic.

The SCVA has a comparatively high ventilation rate, given the level of occupancy of the building, so it may be feasible to undertake measure (i) reduce the ventilation rate. For instance, a UK authority [9] recommends a fresh air ventilation rate of 10 litres per second per person. The SCVA with a volume of 42570m^3 and an air change rate of 1.5 ach has a sufficient fresh air ventilation rate for occupancy of over 1700 people, much higher than the likely peak occupancy of the building, which receives in the order of 100,000 visitors per year. So there is scope to reduce the ventilation rate. From the graph of I/O ratio vs. air change rate in figure 4 it is apparent that substantial reduction in ventilation rate would be needed to make a significant difference to the I/O ratio. For instance, reducing the ventilation rate from 1.5 to 0.3 ach would reduce the nitrogen dioxide I/O ratio from about 0.9 to around 0.5. Practically this would entail improving the sealing of the building, especially the entrance doors, with the introduction of more tightly sealed lobbies or revolving doors. Such measures may still be insufficient in a building where people are coming and going all the time. This measure will also require consideration of the amount of cooling needed during summer. The SCVA is known to overheat on hot summer days [10], and reducing the amount of ventilation could make the problem worse. Pollution control issues cannot be considered in isolation from other building factors. The IMPACT model should be used as one of several tools or approaches needed to achieve a sustainable solution to museum environments.

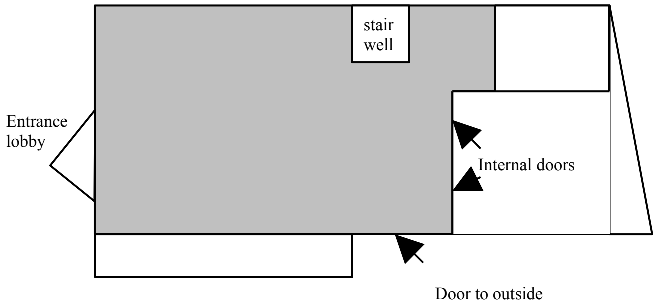
An alternative approach to pollution control that might be carried out with less impact on other aspects of building management, would be option (ii) change the surface materials to increase their pollution absorbing properties. Paints and other surface coatings with enhanced pollution absorbing properties are currently under development [11] for both indoor and outdoor applications. If we assume that such a paint finish may have a similar affinity for absorbing nitrogen dioxide as carbon cloth, currently the only enhanced absorber in the IMPACT materials database, then its effect can be modelled using IMPACT. The simulation assumes that the paint is applied to all the metal surfaces in the SCVA by modelling them as carbon cloth and that other parameters are unchanged. The modelled I/O outdoor ratios for various control strategies are summarised in table 2. The results show that introducing highly absorbing surfaces causes a greater reduction in pollution concentration than reducing the ventilation rate, but even with both these measures combined, the pollutant I/O ratios are still of the order of 0.6, a value that is often achieved in more traditionally designed and constructed museum buildings without the need for special measures. This reflects the open plan design of the SCVA, which makes it inherently difficult to control pollution by passive means. To achieve reductions of below I/O=0.6 may well entail the installation of a full air conditioning and filtration system. As stated above the SCVA is in a low pollution environment and hence the indoor levels of pollutants are not as serious a concern, as they would be if it was constructed in a more polluted urban area.

Table 2: Comparison of pollution control methods on pollutant I/O ratios calculated by the IMPACT model.

Model scenario	Sulphur dioxide	Nitrogen dioxide	Ozone
(a) SCVA without interventions	0.89	0.87	0.88
(b) Reduce ventilation rate to 0.3ach	0.76	0.78	0.78
(c) Introduce enhanced pollution absorbing paint	0.72	0.70	0.72
(b) and (c) combined	0.62	0.62	0.62

3.2 Archive store in a converted factory building, London, UK

The second building studied is an archive store, housed in a former factory building in an urban location that has been adapted for use primarily as a repository. It is a 1930s concrete structure with substantial floor slabs, and originally it had a large glazed area to provide natural daylight to the main factory hall. The glazing has been largely covered over in order to improve the security and to help achieve the thermal performance required from an archive building. The original open plan factory hall has been divided up into several rooms by partitioning, so that it is now one large rectangular repository with several smaller storerooms.



Figures 5 and 6: Interior view of the archive store and plan of the building (figure 5, left). Plan of the archive store ground floor (figure 6, right) with the modelled room shaded.

The IMPACT model was applied to the main archive storeroom, treating it as though it were a single zone building. This was a reasonable assumption because doors to adjacent store rooms and entrances to the building are kept tightly closed most of the time. The storeroom will be largely exchanging air with the external environment, but there will also be some exchange with the adjacent internal rooms and through the stairwell, though this is also closed off by doors. The archive has made considerable efforts to seal up the building against the entry of dust and pollutants, but chiefly to stabilise the indoor climate. The surface materials inside the repository are quite different from those at the SCVA, being more reactive to air pollution. This includes the collections materials of paper, board and leather, which form a substantial proportion of the indoor surface area of the storeroom.

Table 3: Data on the archive store used in the modelling. Dimensions are taken from the architect's drawing and the ventilation rate was measured as described above. The exposed area of paper was estimated on the basis of the archive records of the run of used shelves in the repository. It was assumed that only book spines and the tops and ends of pages were exposed to the air. The model default values of temperature and relative humidity were used.

Surface	Area m^2	Other parameters	
Concrete wall	582	Room volume	7972m^3
Chipboard window covers	214	Air change rate	0.3 ach
Synthetic flooring	1355	Temperature	20°C
Concrete ceiling	1355	Relative humidity	55%
Exposed paper and book boards	6934		

The archive building relies on natural air infiltration to provide sufficient ventilation for the collection and the small number of people who use the repository from time to time. The ventilation rate was measured on a working day and a weekend with the result in both cases of 0.3 ach, indicating that the occupancy level on a working day did not lead to detectable changes in ventilation due to the opening of doors. In absolute terms, this measurement is also a low value reflecting the fact that the building has been well sealed. Using the data in table 3, the IMPACT model calculated the following of I/O ratios for the storeroom: sulphur dioxide 0.33, nitrogen dioxide 0.46 and ozone 0.34. These are much lower values than those calculated for the SCVA, and are a function of the low air change rate of this building and also the large amount of available surfaces with good pollutant adsorbing properties. Whilst at first sight these low I/O values may seem quite beneficial for the collection of archive material, a closer inspection revealed that much of the pollutant removal has been occurring by deposition onto the collection itself, as is evident from the IMPACT model output shown in figure 7.

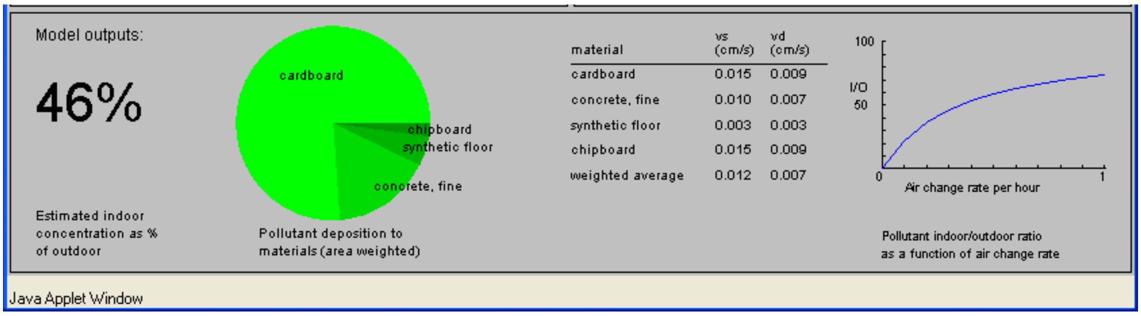


Figure 7: IMPACT model outputs for nitrogen dioxide at the archive store using the inputs in table 3. The absorbing properties of collections materials in the store (paper, end boards and boxes were simulated as 'cardboard' in the model).

The collection is the largest area component in the room, as was shown by the model output, but it also has the highest deposition velocity of all the materials present, greater even than the pollutant-reactive material, concrete that forms the building structure. Hence approximately 75% of the deposition of nitrogen dioxide and ozone and slightly less for sulphur dioxide is taking place on the paper collection itself. At first glance in might appear beneficial that the archive store has low I/O pollutant ratios, but as the IMPACT output in Figure 7 shows this is at the expense of pollution deposition and hence degradation to exposed collections materials.

3.3 Discussion

These two case studies demonstrate a number of important points when considering the effects of air pollution in buildings. At the SCVA the high I/O ratio indicated that, there is little pollution deposition taking place inside the building, but that introducing vulnerable objects or materials on open display would expose them to pollution concentrations comparable with outdoors. Conversely, at the archive store, the pollutant concentration is quite low indoors because the collection is acting as the main sink for the external pollutants that get into the building, quickly removing them from the air. Thus, a low internal air pollution concentration in this situation, where most of the deposition surfaces are objects that we wish to protect and not 'sacrificial' surfaces such as structural elements, building surfaces or decorative finishes, can be an indication of the damaging uptake of air pollutants, not the opposite. The location of the archive store in a busy urban area which is more polluted than the environs of the SCVA, could lead to significant collections damage over time.

4 Comparison of modelled and measured data

Pollution measurements have been made at both case study buildings using both passive and active sampling methods. In particular long-term passive measurements are on the most appropriate basis for comparison with the steady-state predictions of the IMPACT model. Table 4 compares measured and modelled data for the two case study buildings. The measured ratios are generally lower than the modelled ones, with reasonable agreement for nitrogen dioxide and sulphur dioxide less so for ozone. This discrepancy could occur for a number of reasons:

(i) the amount of active surface area in the building had been underestimated. The model included only the geometric surfaces and shelved archive paper surfaces. Other fixtures and fittings, for example display cases or shelves have not been estimated.

(ii) In the case of the archive store some of the air infiltration comes from other parts of the building, such as the adjacent storerooms. These have a lower pollutant concentration than outdoors, causing the model to overestimate the concentration in the modelled zone. In this type of situation, the single-zone nature of the model increases the level of approximation.

(iii) Related to this, it is possible that enhanced pollutant deposition occurs onto surfaces neared to the points at which air infiltrates the building, rather than deposition being equally distributed on all surfaces which is an assumption that the model makes. This process could enhance pollutant removal, leading to lower measured than predicted I/O ratios. This explanation has also been suggested by Glytsos et al. [12].

(iv) Homogeneous chemistry could play a role in reducing ozone concentration. Evidence of this has been found recently in monitoring of European museums [13].

Table 4: Comparison of measured and modelled I/O ratios for the SCVA. Sulphur dioxide was not detected inside the SCVA and only at very low levels outside, so I/O ratios could not be calculated.

Pollutant	Measured	Method	Modelled
SCVA:			
Nitrogen dioxide	0.74–0.91	Diffusion tube	0.87
Ozone	0.3	Diffusion tube	0.88
	0.7	Instrumental measurement [14]	
Archive Store:			
Nitrogen dioxide	0.24	Diffusion tube	0.46
Ozone	0.1	Diffusion tube	0.24
Sulphur dioxide	0.4	Diffusion tube	0.33

5 Conclusions

The comparison of measured and modelled results shows reasonable agreement between the IMPACT model predictions and measured data for nitrogen dioxide and sulphur dioxide, with a considerable underestimation of ozone concentrations. It would be possible to improve the prediction of ozone concentration by more complex modelling techniques, and many such models already exist. However, the philosophy of the IMPACT tool was that it should be a simple and straightforward method of estimating pollutant concentration inside buildings that could be used to show how different building designs and characteristics can influence pollution levels indoors. Provided its limitations are recognised then it can usefully achieve this aim.

The case studies presented here have demonstrated how materials, layout, ventilation and other services affect the pollutant concentration found indoors. The model predicts indoor concentrations, but also allows the conservator or conservation scientist to gain insights into deposition of air pollutants onto surfaces, which include the surfaces of objects. For building designers and engineers, the IMPACT model has shown how building structures can provide a means of passive pollutant control through low ventilation rate and the use of sacrificial surface pollutant-absorbing materials. The advent of new products such as pollution-absorbing paint can make this feasible for controlling pollutants inside collections spaces. This has been demonstrated to work best in building and rooms with low air change rates, and so may be more suitable for closed stores rather than open galleries.

Air pollution is a trans-national problem and there is a need across Europe for these issues to be better understood in relation to the care of cultural heritage. The IMPACT model is contributing to this process and has found a role as an educational tool for conservators and conservation scientists in particular. It is being used as part of a case study exercise for students on conservation courses in the UK and Malta and has also been used as part of a COST G8 Training School [15]. The model has also been taken up by organisations such as English Heritage to assist in their work on collections care.

6 European Project Details

IMPACT, Contract No. EVK4-CT-2000-00031, Innovative Modelling of Museum Pollution and Conservation Thresholds, Nigel Blades, UCL Centre for Sustainable Heritage.

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