Investigation into impacts of large numbers of visitors on the collection environment at Our Lord in the Attic

Shin Maekawa, Bart Ankersmit, Edgar Neuhaus, Henk Schellen, Vincent Beltran, and Foekje Boersma

Abstract

Our Lord in the Attic is a historic house museum located in the historic center of Amsterdam, The Netherlands. It is a typical 17th century Dutch canal house, with a hidden Church in the attic. The Church was used regularly until 1887 when the house became a museum. The annual total number of visitors has grown from 36,000 in 1990 to 75,000 in 2005; this trend is exponentially increasing. The museum had between 100 – 650 visitors each day in 2005; they typically stayed in the building for about an hour. There were two visitation peaks: one in the mid-morning and another in mid-afternoon. On two separate days each year the museum records large numbers (well over 1,000) of visitors. Masses, weddings, and music concerts, attended by 50 – 150 persons, are regularly held in the Church. The museum has consequently expressed major concern over the impact of the growing number of visitors on the various collection environments.

A historic indoor climate of 10% - 95% relative humidity was estimated, from when the central heating system, which may have caused the majority of damages to the collection, was installed in the 1950's to the installation of humidifiers in the 1990's. However, between January 2005 and January 2006, in spite of a few central heating system malfunctions and large visitor numbers that particular year, the recent climate in the museum building did not reach harmful levels for the collections.

Direct impacts of visitors were documented as increases in temperature, relative humidity, and CO_2 concentration when the museum opened each morning as well as during special events in the church. However, relative humidity peaks remained less than 75%, and the value decayed quickly after the visitors had left the rooms or near the end of the museum's visiting hours. As confirmed through air exchange rate measurements in the church, a high infiltration rate of outside air was the reason for reduced peaks and fast decay of the relative humidity and CO_2 concentration.

Daily maxima of CO_2 concentration exceeding 1500 ppm were recorded whenever the daily total of visitors exceeded 500. Daily averages over the 08:00 – 17:00 period exceeded 1000 ppm whenever more than 600 visitors were recorded. However, the high infiltration rate completely diluted the CO_2 concentration to an ambient level by the following morning.

From the consideration of the CO_2 and moisture accumulations, 600 visitors per day, well-distributed over the museum's operational hours, can be safely accommodated in winter. The number can be increased to twice this during the summer by opening the entrance door and a window in the attic for increased natural ventilation. However, other important issues, such as safe levels of floor loading and vibration, as well as overall visitor comfort and experience, will have to be taken into consideration and may well result in allowing fewer visitors than what is recommended based on these calculations.

Introduction

Our Lord in the Attic ('Ons' Lieve Heer op Solder') is a historic house museum located in the red light District of Amsterdam, The Netherlands. It is a typical 17th century tall Dutch canal house with brick walls and large windows. The building has an approximate footprint of 260 m^2 with five floors and an estimated volume of 2500 m^3. After Jan Hartman, a German Catholic and successful merchant, purchased the building in 1661, he created a hidden Catholic church in the attic, since the open practice of Catholic Mass was officially forbidden at that time in the Dutch Republic. The church was used until 1887 when the house became a museum. Since the 1950s, the church has been used periodically for religious ceremonies and special events.

The museum (see Figure 1) consists of several historic rooms: Canal Room, Sael, Kitchens (not indicated in

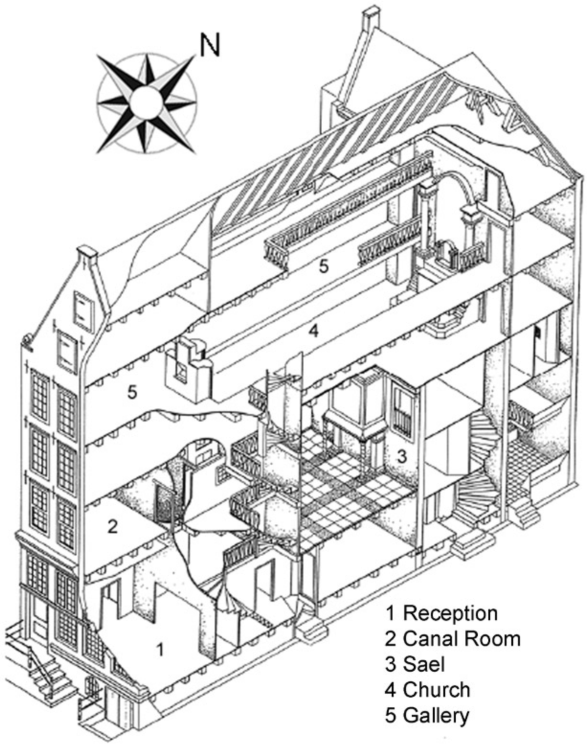

Figure 1: A schematic view of the museum Our Lord in the Attic

the figure), and Church. The church is located in the middle of the building and extends from the 3rd to the 5th floor and through partially removed floors on the 4th and 5th floors. The southwest wall is mostly shared with the next building; the northeast wall faces an alley. The church has a floor area of 150 m^2 and a height of 9 m (volume of 1350 m^3). The brick walls are plastered, and the floor and galleries are constructed from wood. The painted wooden ceiling has a 0.55 m diameter opening leading to the attic above. There are several accesses to the Church, and the galleries are connected by steep and narrow stairways.

The museum's collection consists of approximately 7,000 objects of various materials dating from the 16th century to the present day. In fact, the building itself is seen as an important part of the collection. As is common in a historic house museum, most objects, such as furniture, paintings and wooden sculptures, are on open display. Some metal objects are exhibited in showcases for security. The objects currently on display in the museum came to the building at different times. The first religious objects were brought to the building shortly after it became a church. When the church operated as a museum, objects from other hidden churches in the area which were being closed were added to the collection.

In the 1950s, the museum installed a central heating system to provide comfort for both visitors and staff members. In the early 1990s, portable humidifiers and dehumidifiers were placed at various locations in an attempt to control seasonal variations of relative humidity for an improved collection environment. There is no air-conditioning system, and visitors have often complained of the uncomfortable climate during hot and humid days in summer. Recently, freestanding oscillating fans were placed throughout the museum to provide some relief during the summer.

The number of museum visitors has been steadily growing. The annual total number of visitors grew from 36,000 in 1990 to 75,000 in 2005, and this trend is exponentially increasing. The museum has consequently expressed major concern over the impact of the growing number of visitors on the collection environments for both objects and the building's historic interior. Therefore, the present study was conducted, combining an environmental assessment with a condition survey, to identify the impact of visitors on the collection, building, interiors and the environment in order to develop an environmental management strategy that balances presentation, access and preservation.

First, the historic indoor climates in the museum were estimated, based on available historic outdoor climate data of the area, thermal characteristics of similar Dutch historic buildings, and recorded historic heating methods in the building. Then, the current indoor climate in the building was examined. And last, the impact of special events involving large groups in the building was analyzed. The effect of visitors on the indoor climate was analyzed and an attempt was made to estimate the maximum number of visitors that would limit environment change to acceptable levels.

Historic climate

The historic indoor climate was estimated using 20th century outdoor climate data of nearby cities (KNMI website) and available indoor climate data of other historic buildings in The Netherlands. The outside air was assumed to infiltrate into the building and be heated by the building, resulting in a lower indoor relative humidity.

Light buildings, such as a typical canal house, remain warmer than the outside throughout the year. However, in winter, these buildings were often heated to provide additional thermal comfort for occupants. Heating methods applied in Our Lord in the Attic over the years were recorded as follows:

1661 - 1953: Local heating by fireplaces and wood or coal stoves in individual rooms but no heating in the Church.

1953 - Present: A centrally located boiler provides heated water to radiators throughout the building, except the Canal Room and Reception, which have gas fired stoves. The thermostat is currently set at 20˚C in winter.

In 1990, twelve portable cold-evaporative type humidifiers (capable of 0.9 litres per hour) and two refrigerant-based dehumidifiers (capable of 0.25 litres per hour) were introduced into the building to improve the relative humidity for collection preservation. These devices have been set to maintain 50% RH.

Local heating (till 1953)

The environmental monitoring conducted in other unheated buildings in The Netherlands showed that indoor temperatures never dropped below 17.5 °C during summer and 8 °C in winter. In wintertime, local heaters such as fireplaces and stoves were used to provide thermal comfort. However, the church did not have a heater until 1953. During mass, people would use small portable stoves with glowing peat.

The unheated church would have had the temperature of typical unheated buildings, with only some heat drifting from other parts of the house. However, the overall contribution of the local heating in the Canal Room and the Sael to the temperature in the Church is assumed to have been relatively small. The following assumptions are made:

Objects displayed during this period were exposed to indoor temperatures ranging from 8˚C to about 25˚C. The relative humidity in the church was slightly different from the heated rooms and would have varied annually between 15% and 90%, while in the heated Seal and Canal Room the relative humidity would have varied annually between 10% and 90%. However, these ranges include short excursions. When the short-term variations were excluded, the relative humidity ranges reduced to 30-70% for the unheated space and 25-70% for locally heated spaces.

Table 1: Estimated temperatures in Canal Room and Sael (heated) and Church (unheated) till 1953

	$T_{outside}$	T_{Church}	$T_{Canal Room}$ and T_{Sael}
Winter	<-5°C		Heated to 8 °C
	-5°C < and < 0°C		Heated by 10 °C
	0°C < and < 5°C		Heated by 7.5 °C
	5°C < and <10°C		Heated by 5 °C
	>10°C		Same as $T_{outside}$
	< 8°C	Heated 8 °C	
	8°C < or < 10°C	Heated by 0.5 °C	
	>10°C	Same as $T_{outside}$	
Summer	< 17.5°C	Heated to 17.5 °C	Heated to 17.5 °C
	> 17.5°C	Same as $T_{outside}$	Same as $T_{outside}$

Central heating (1953-1990)

After the central heating system was installed in 1953, winter indoor temperatures became warmer and stable. Unfortunately, we were unable to find set temperatures of the heating system during that period; therefore it was assumed that indoor temperatures were kept at 17˚C during the day and 13° C at night. In summer, indoor temperatures remained similar to those observed in 2005 and 2006, never below 17.5˚C. These temperatures produced wide relative humidity ranges, between 10% and 95% in winter and 30% to 95% in summer.

Central heating with humidifiers and dehumidifiers (1990-present)

After humidification and dehumidification were introduced to the building, control of relative humidity became possible. Since January 2005, climate data have been collected throughout the building. Temperature and relative humidity have been continuously recorded in various rooms and outside. The concentration of carbon dioxide was also recorded in the church for a limited period in 2006. In addition, the air exchange rate of the church was measured in both winter and summer. The museum staff also recorded daily totals of visitors and total amounts of water both supplied to humidifiers and collected from dehumidifiers.

Monitoring results (2005-2006)

Although all windows of the museum are always closed for the security reason, they allow direct sunlight onto the collection. The windows near the altar and the Lady Chapel have roller blinds, which are opened by museum staff when appropriate. It is expected that both floor and ceiling allow some air leakage through floor planks.

Table 2 lists annual extremes, means and daily variations of temperature and relative humidity in the Church. During summer, the relative humidity in the Church remained mainly between 50% and 65% with most daily fluctuations approximately 5%. However, day-to-day fluctuations were approximately 7% with peaks up to 18%. Relative humidity started to

Table 2: Annual and daily extremes and daily variations of temperature and relative humidity in the Church (January 2005 – January 2006)

Variable	Temperature (°C)	Relative Humidity (%)
Mean	20.7	52
Maximum	28.1 (24 June 15:00-21:00)	72 (28 July 15:00)
Minimum	12.9 (01 March 08:00-08:30)	34 (28 Feb. 09:00-10:00)
Daily Variation		
Mean	1.5	5
Maximum	5.3	16
Minimum	0.3	1

drop in early November to 40-50% by the end of the month, remaining at that level throughout the winter in spite of the fact that humidifiers were set to maintain 50% RH.

Winter fluctuations of the temperature were small (typically 1˚C as can be seen from Figure 2) due to a thermostatically controlled heating system. It should be noted, however, that in winter, large outliers were seen only at the low extreme. These were attributed to the malfunction of the heating system. The generally tight relative humidity range during winter was the result of the operation of humidifiers in the building. However, the controlled

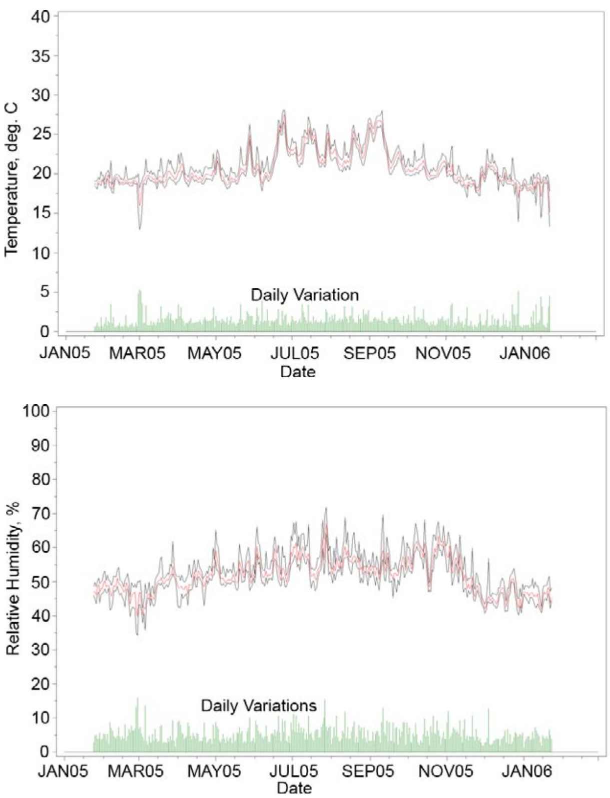

Figure 2: Plots of daily maximum, minimum, average, and variation of temperature and relative humidity in the church between January 2005 and January 2006

winter condition can be easily lost if the heating system malfunctions.

Although significantly high relative humidity was not recorded in the building on days with large visitor numbers and events, condensation was observed on window panes in the Church and the main staircase, which resulted in rotting of window members lattice. However, inspections with a high resolution IR camera showed that condensation was limited to the windows and not on building walls. An inspection of beam heads which are submerged into external walls of the building found five with a rotting problem. however, it was determined that this was caused by water infiltration from the outside through a deteriorated external stucco finish.

Air exchange rate

In an attempt to understand the natural ventilation for diluting visitor-generated heat, moisture, and carbon dioxide, the air exchange rate in the church was measured. This was done in three conditions over two days by first injecting SF6 tracer gas and then measuring rates of its dilution. The first measurement was performed on a cold spring day with all windows and the entrance door closed. An air exchange rate of 2.3 h^{-1} was determined. The second and third measurements were performed on a warm autumn day. The second measurement, again with all windows and doors remained closed, produced the rate of 4.5 h^{-1}. During the final measurement, one window located high in the church and the entrance door at the reception were left open, producing the highest rate of 5.9 h^{-1}. Wind conditions during the measurements were similar on both days.

The rate nearly doubled in summer, and tripled by the combined effects of fresh air supply through the entrance opening and exhaust through the window high up in the church. These results proved that high ventilation rates in the church were the reason for the relatively fast dissipation of visitors' impact on the environment, as well as for partial loss of winter humidification.

Visitor numbers and CO_2 concentration

Daily visitor totals averaged 233 per day, ranging between less than 100 to more than 650 per day in 2005. Visitor numbers were generally distributed evenly throughout the year. However, the museum experienced higher visitor numbers between April and June in 2006 than over the same sampling period in 2005. Two daily peaks, one in the morning, between 10:00 and 11:00, and another between 14:00 and 15:00 in the afternoon, were also identified.

In Figure 3, the CO_2 concentration in the Church air was plotted for the period between March 13 and June 2, 2006, with the daily total of visitors. The majority of daily maximum values were less than 1500 ppm, and daily averages were less than 1000 ppm, which is considered a safe level for long-term exposure (ASHRAE, 2002). Daily maximum values were normally recorded during the afternoon and exceeded 1000 ppm. Larger daily totals of visitor numbers corresponded to both high daily maxima of CO_2 as well as higher averages over the 08:00 – 17:00 period. Daily maxima exceeding 1500 ppm were recorded whenever the daily visitor total exceeded 500. Daily averages exceeded 1000 ppm whenever more than 600 visitors were recorded. The infiltration of a large volume of outside air completely diluted the CO_2 concentration to the ambient level by the following morning, as there was no sign of daily CO_2 accumulation.

The average occupation in the church was less than 10 visitors, with a high extreme of 40 visitors at one time. The Church has 86 seats and is used for masses, concerts and other special events. On occasion there have been over 100 people in the Church, although the museum staff tries to observe the restricted number of 86 set by the local fire department. During some of these events, especially in summer, visitors have been complaining of uncomfortable conditions, hot and humid with no fresh air, in the Church.

Example of a large number of visitors

Exceptionally large numbers of visitors have been recorded on the annually scheduled Open Monument Days. In 2005, 1,064 visitors were recorded over a four-hour period, between 13:00

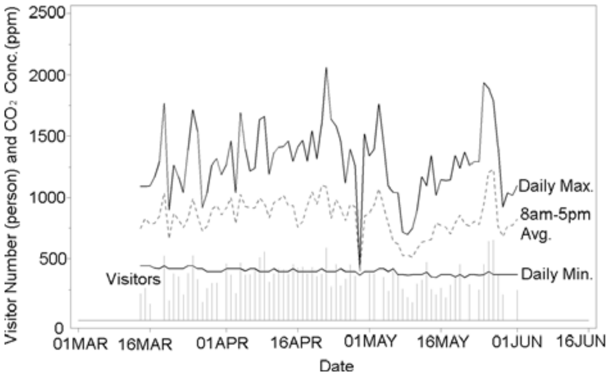

Figure 3: Daily visitation and maximum, minimum, and average CO2 concentration in the Church of Our Lord in the Attic Museum between March 13 and June 1, 2006

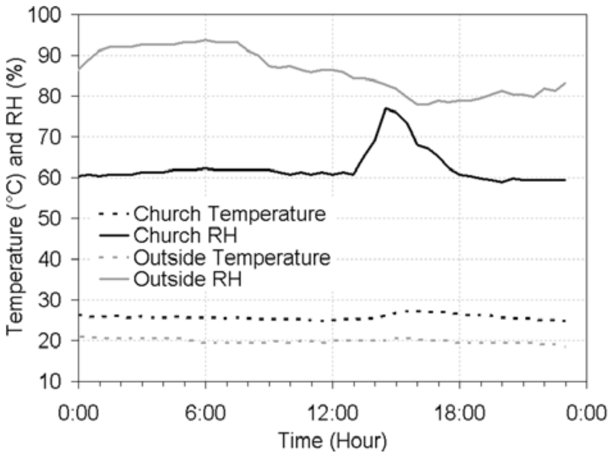

Figure 4: 24-hour variations of temperature and relative humidity in the church and outside on September 9, 2005 (Open-Monument Day).

and 17:00. 24-hour variations of the temperature and relative humidity in the Church and the outside on that day were plotted in Figure 4. Temperature increases were observed starting at 13:00 in all parts of the building, except in the reception, with the largest increase (approximately 2.5°C) in the church and the smallest (0.5°C) in the Sael. The eception's temperature drop during this period was probably due to the front door being opened continuously and cooler outside air entering the room. Temperatures in the building returned to normal before midnight.

Both the relative humidity and the humidity ratio increased significantly over the four-hour period in all rooms, including the Reception. However, relative humidity values throughout the building returned to normal by 21:00. The humidity ratios in both the Canal Room and the Sael peaked around 14:30, decreased for half an hour, then started to increase again, producing the second peak at 16:30 before again decreasing towards the end of visiting hours (17:00). However, throughout the day only one peak of the humidity ratio in the Church was recorded. This indicated that visitors stayed in both the Canal Room and the Sael for relatively short periods immediately after they had entered the museum. Therefore, humidity ratios in these rooms were directly affected by the rate of museum admission. However, visitors remained longer in the church, probably up to 30 minutes. The highest occupancy in the church must have been reached at 14:30, then, it gradually reduced toward closing time. The humidity ratio of the building returned to normal by midnight.

Spring wedding in the church

As usual, Our Lord in the Attic opened its door to the public at 9:00 on May 21st, 2005, but it temporarily

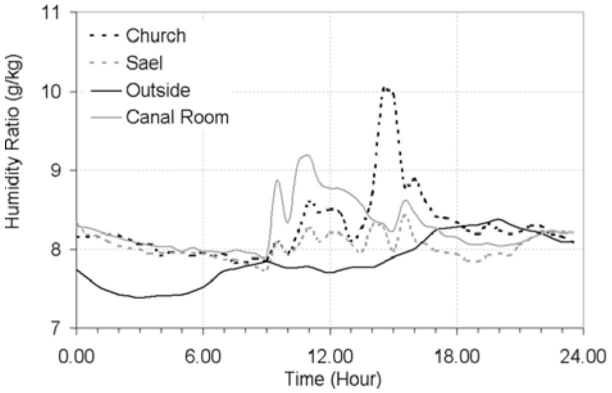

Figure 5: 24-hour variations of the humidity ratio in Our Lord in the Attic and in the outside air on May 21, 2005. A wedding with 100 attendees was held in the Church between 13:00 and 15:30.

closed at 13:00 to accommodate a wedding in the church, which began around 14:30 and ended at 15:30. According to records kept by the museum staff, a total of 110 persons gathered for the event. The public was then allowed back in the building shortly after 15:30, after all the wedding attendees had left the building. The museum closed at 17:00 as usual.

24-hour variations of humidity ratios in Our Lord in the Attic and the outside air on that day were plotted in Figure 5. Between midnight and 09:00, the humidity ratio was constant at 8 g/kg throughout the building. A morning peak of visitors was reached between 10:00 and 11:00, exiting by 13:00. When the wedding attendees started to enter the church soon after 13:00, the church's humidity ratio had returned to 8 g/kg, the same as the outside. The humidity ratio in the church exponentially increased as wedding participants started to gather; however, the rate soon reduced to linear, and then plateaued at 10 g/kg by 15:30, indicating that the attendees had started to leave. The high rate of humidity ratio increase was due to the continuous increase of attendees in the Church over a short period. Once the ceremony had started (all attendees seated and reduced physical activities), the rate reduced due to infiltration of dry outside air.

While the church air had a significant increase in humidity ratio, both the Canal Room and the Sael were only slightly affected. Museum visitors gradually exited the museum around 17:00 and the elevated humidity ratios of all spaces dissipated towards that of the outside. All spaces equilibrated at 8.2 g/kg by 22:00.

During the wedding, the temperature and relative humidity increased from 20.9°C to 22.6°C and 54% to 60%, respectively. Relative humidity returned to 54%, a normal value without visitors, within two hours after the event. These peak values were within the limit considered to be "safe" for both objects and the building interior. And, neither the objects nor the building interior in the Church had time to respond to the change.

Estimated safe occupancy rate in rooms based on CO_2 concentration

If 100 persons are in the Our Lord in the Attic Museum at any given time, fresh air has to be provided at a rate of 7.5 *l* s^{-1} per person to maintain a CO_2 concentration of less than 1000 ppm (ASHRAE, 2002). This rate would also control any moisture build-up. This would give the required ventilation rate of 2700 m^3 h^{-1} for the building. We estimated that the building has air exchange rates of 1-1.5 h^{-1} in the winter and 2 - 3 h^{-1} in the summer when the entrance door and an attic window are left open. The infiltration rates roughly yield the necessary fresh air for the winter condition. If each visitor remained in the building for less than one hour, 600 visitors can be admitted to the museum over seven hours of operation. These results further indicate that in winter, a well-distributed admission of 600 visitors during the museum's daily operating hours is the maximum at which the building would be able to provide a suitably comfortable visitor environment. However, during the summer, nearly twice the number can be admitted while a safe CO_2 concentration limit is maintained in the building.

Conclusions and recommendations

Estimated historic climates in Our Lord in the Attic revealed potentially damaging relative humidity variations (ASHRAE, 2005), especially during 1953-1990 when the central heating system was operated without control of relative humidity. The data recorded between January 2005 and January 2006 did not indicate any critical conditions in which either the collections or building interiors would be subjected to high rates of deterioration. However, our monitoring documented condensation on window panes during high occupancy events in autumn, winter, and spring, possibly causing wood rot problems for window frames and sills. These events have not caused either condensation on walls or the rotting of beam heads. The museum may consider turning off humidifiers and possibly activating dehumidifiers during such events to avoid or reduce condensation. Furthermore, lowering the relative humidity set point from the current 50% to

40% may reduce the possibility of condensation on high visitor days in heating seasons.

Both the building and the church were found to have high infiltration rates that limited heat and moisture accumulation and quickly dissipated visitors' impact on the indoor environment. This was also the reason for humidifiers not being able to maintain the set 50% relative humidity in winter. The results indicated the building's ability to handle more visitors with just open-door and window ventilation. However, this may result in an increased deposition rate of particulate matter.

From the carbon dioxide and moisture build-up consideration, the analysis indicated that the maximum number of well-distributed visitors can be nearly 600 per day in winter. It can be increased to twice the current maximum daily visitor number during the summer, especially when opening the entrance door and a window in the attic for increased natural ventilation. However, other important issues, such as safe levels of floor loading and vibration, as well as overall visitor comfort and experience, will have to be taken into consideration and may well result in allowing fewer visitors than is recommended based on these calculations.

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Authors

Shin Maekawa,Vincent Beltran, Foekje Boersma.
The Getty Conservation Institute,
1200 Getty Center Dr. Suite 700, Los Angeles, CA 90049-1684 U. S. A.
smaekawa@getty.edu

Bart Ankersmit,
The Netherlands Institute of Cultural Heritage,
Gabriël Metsustraat 8, Amsterdam, The Netherlands

Edgar Neuhaus, Henk Schellen.
Eindhoven University of Technology,
Den Dolech 2, 5612 AZ Eindhoven, The Netherlands

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