MONITORING FAÇADE SOILING AS A MAINTENANCE STRATEGY FOR THE SENSITIVE BUILT HERITAGE

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ABSTRACT

The colour patterns generally found on the façades of architecturally sensitive buildings have an adverse impact on their aesthetics, to the detriment of their identity and potential economic value. A quantitative and qualitative study was conducted of the perception of aesthetic decay in the limestone on a heritage building. The study assessed building aesthetics between two façade cleaning operations, conducted in 1984-1986 and 2006-2008. Based on the calculation of the final or total soiling index, by means of in situ lightness measurement and three architectural design variables, the colour distribution of the façades was quantified in 2006 and a model was developed to monitor façade soiling over time. The proposed model, a tool for planning preventive façade maintenance on architecturally sensitive buildings, advocates for sustainable cleaning operations. Its premise that periodic cleaning should only be conducted in areas where the limestone is affected by aesthetic decay redounds to minimised intervention and lower building management costs.

Running Head: **Preventive conservation: monitoring façade soiling**

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1. INTRODUCTION

In highly polluted urban areas, the concentration of particulate matter is the primary cause of the façade soiling that induces heritage building decay (Bonazza et al., 2007; Grossi and Brimblecombe, 2008; Rampazzi et al., 2011; Barca et al., 2014). The adverse visual impact resulting from colour patterns on these façades may be detrimental to a building's architectural value.

Pale-hued construction materials are particularly vulnerable to progressive soiling and the concomitant aesthetic decay (Grossi and Brimblecombe, 2008; Grossi et al., 2003). One of the many factors that condition façade soiling is architectural design-dependent deposition and retention of particulate matter on material surfaces (Pio et al., 1998). Very intense aesthetic decay, in turn, may denote material damage, mainly surface sulfation and formation of so-called black layers (Bonazza et al., 2007; Sabbioni et al., 2001; Ruffolo et al., 2015).

The environmental assessment of the urban surrounds where heritage buildings are located is one preventive measure for façade conservation (Fort et al., 2004; Ghedini et al., 2011; Sablier and Garrigues, 2014). The perception of façade soiling has been evaluated with non-destructive techniques: applying greyscale in photographic images to decipher the rates of re-soiling associated with cleaning/soiling cycles (Searle et al., 2000), monitoring the progressive decline in lightness (L*) values over time (Grossi et al., 2003), quantifying soiling with integrated digital photography and image processing (Thornbush and Viles, 2004; Thornbush, 2010; Janvier-Badosa et al., 2013), or assigning lightness (L*) perception based on a soiling index (Thornbush, 2014). Visual impact resulting from façade aesthetic decay entails establishing aesthetic tolerance thresholds in terms of human sensibility to colour patterns (Grossi and Brimblecombe, 2008; Grossi et al., 2003; Grossi and Brimblecombe, 2004), estimating when (Marie, 2013) or exactly where on façades cleaning operations are needed (Swann, 2013).

In light of the high costs involved and the essentially invasive nature of cleaning, in the absence of material damage such operations are not justified simply to improve a building's visual impact. Balancing air pollution against cleaning operations to recover or maintain the architectural value of historic structures is a complex task with significant economic implications (Ball et al., 2000; Young et al., 2003). Assessing façade aesthetic decay and establishing preventive conservation measures are useful preliminaries in the pursuit of a balance between the costs and benefits of cleaning.

In this study, lightness measurements and three factors of architectural design were used to quantify the colour patterns on the façades of an emblematic, pale limestone building in the city of Madrid, Spain. On the grounds of that quantification, the effect of the design variables on colour patterns was established. The findings were also used in conjunction with non-destructive techniques to develop a model for monitoring progressive façade soiling. This versatile model can be applied to other architecturally sensitive buildings, i.e., with pale hued materials sited in areas where the air has high particulate matter content. From the perspectives of weathering and environmental science, the model constitutes a strategic planning tool for the preventive maintenance of such buildings and the performance of sustainable cleaning operations.

2. MATERIALS AND METHODS

2.1. Former Maudes Workers' Hospital, Madrid, Spain: façade colour patterns (pre-2006 cleaning)

The building chosen for the study, the former Maudes Workers' Hospital, was erected in Madrid, Spain, by Antonio Palacios Ramilo (1874-1945) between 1909 and 1916. Its façades consist in pale-hued limestone quarried in the area (Perez-Monserrat et al., 2017). Two major interventions were performed, in 1984-1986 and 2006-2008, and the limestone was cleaned mechanically on all the façades in both (Perez-Monserrat et al., 2011).

The building consists in four wings, an entrance pavilion, a church and two annexes. The compound occupies a full city block behind a perimetric wall. The main façades of the church and the entrance run parallel and the façades on the bays diagonal to the adjacent city streets (Figure 1a). Façade overhangs off the primary plane protect large areas of the limestone. The building has a highly systematic design, divided vertically into several levels (Figure 1b).

FIGURE 1

The building is located in an area with heavily polluted air and intense vehicle traffic all day long. The main church façade faces a very busy, eight-lane street, Raimundo Fernández Villaverde (RAI). A flyover built on this street very close to the building in 1969 was torn down and replaced with an underpass in 2003-2005. Air quality improved considerably in the 20 years between the two cleaning operations, largely thanks to the elimination of coal boilers in the nineteen eighties. Perez-Monserrat et al. (2016)

identified domestic heating systems, diesel-fuelled vehicles and urban aerosols as the main sources of sulfur emissions and particulate matter in the immediate vicinity. They also noted that the climate in the area grew warmer and dryer between 1979 and 2009.

In 2006, twenty years after the 1984-1986 intervention and before the latest cleaning operation, the building's architectural value was jeopardised by the aesthetic decay on its façades (Figure 2a), which had also induced material damage of the limestone in many areas (Perez-Monserrat et al., 2016). The colour patterns on the façades exhibited pale- and dark-hued areas. Overall, the façades were characterised by scaled surface soiling. The transition from any one of the four degrees of soiling defined (A, B, C, D) to the next was consistently gradual. Each degree was assigned a tolerance or aesthetic perception category, shown in Figure 2b.

FIGURE 2

After the second operation (2006-2008), the limestone surface was treated for water repellence. Prior to such intervention, two water repellents were assessed (Fort et al. 2005), one composed of methylethoxy-polysiloxanes (H1) and another based on silanes and siloxanes (H2). These products lower surface moisture and therefore particle retention (Doehne and Price, 2011), retarding the decline in lightness (L*). Special attention was paid to the chromatic change of the surfaces tested, by means of the comparison between treated and untreated limestone's specimens (Fort et al., 2005). The overall color change index ($\Delta E^* = \Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{½}$), understood as total color difference of one surface with respect to reference one, was calculated. This index considers the parameters of the CIELAB space (CIE 1978). The limestone surfaces treated with H1 underwent a color change corresponding to $\Delta E^* = 1.1 \pm 0.1$ and in those treated with H2 an $\Delta E^* = 0.0 \pm 0.0$ was determined. Neither of both products did not cause perceptible chromatic modification on surfaces -with respect to the limestone untreated-, Berns (2000) pointed out in $\Delta E^* = 3$ units the limit of perceptibility of the human eye. Taking into account such results and those achieved from the complete evaluation of the two water repellents tested, silane and siloxane based treatment was selected to protect limestone façades in the 2006-2008 intervention, once the surfaces were cleaned.

2.2. Development of the soiling model

Façade design conditions colour patterns, for particle settlement depends on the orientation, height, exposure and shape of construction elements (Pospísil et al., 2006). The degree of stone exposure (protected or unprotected from the rain and wind) conditions the amount of moisture retained on its surface and consequently the accumulation of the pollutants deposited there (Rampazzi et al., 2011; Grossi et al., 2005). These particles tend to accumulate in protected areas and to be washed away in areas exposed to rainwater (Butlin et al., 2006).

As surface soiling is related to the area covered by dark particulate matter, it can be measured as a change in optical reflectance (Hayne, 1985; Creighton et al., 1990). CIELAB (1978) is the system generally used to analyse soiling-induced chromatic change in façades. The CIELAB space considers the parameters of the luminosity (L*), which shows values between 0 (pure black) and 100 (pure white), as well as the chromatic coordinates a* and b*, which represent the degree of saturation towards green (-a*) and red (+a*), blue (-b*) and yellow (+b*). Since pale-hued materials exposed to environmental pollution undergo a significant decline in lightness (L*) with time, that parameter is taken as an indicator of aesthetic decay (Grossi et al., 2003).

The soiling model proposed was developed on the grounds of the quantification of the colour patterns observed on the former Workers' Hospital in 2006. These patterns were generated primarily in the 20 years lapsing between two façade cleaning operations, i.e., from 1986 to 2006. Three design variables were applied in that quantification: i) façade alignment (direct or indirect, i.e., parallel or diagonal to the streets that border the city block occupied by the building); ii) exposure of the areas measured (exposed or protected, regarding protected areas as surfaces immediately below overhangs); and iii) height (one of the vertical levels or sub-levels displayed in Figure 1b).

The six façades selected as representative of the entire building are shown in Figure 3: two (main church façade and entrance) directly and four (four façades on two diagonal wings) indirectly aligned. The number assigned to each façade was preceded by the letter D or I to respectively specify direct or indirect alignment. In addition, the streets they face were indicated by subscripts: R (RAI), M (Maudes) and A (Alenza). For readier handling of the very long, directly aligned façades, they were divided into three sections: a centre and two sides.

Lightness (L*) is defined as the amount of light stimulus received by the viewer of a surface, with values ranging from 0 (black) to 100 (white). A Konica Minolta CM-2002 spectrophotometer running on Colour

Data CM-1 software was used. Such device uses a pulsed xenon arc light bulb, which illuminates a round aperture 0.8 cm in diameter. The light reflection is focused on a silicon photodiode and measures the wavelength range between 400 and 700 nm (in 10-nm steps). The light source applied was the standard CIE D_{65} and measurements were performed at a 10° vision angle. The measuring grids prepared for each façade (Figure 3) covered all vertical levels (heights) and in most, both exposed and protected areas. In all, 42 levels were measured: 22 on directly and 20 on indirectly aligned façades. In 14 of the 22 levels on directly aligned façades and in 12 of the 20 on indirectly aligned façades, measurements were taken in both exposed and protected areas. One in situ measurement was taken on the limestone at each point on the grid, for a total of 989 measurements. Photographs of the limestone surface were made at each measuring point.

Soiling indices were calculated for each measuring point as proposed by Grossi et al. (2003). On the one hand, the final or total soiling index (ΔL^*) was defined as the soiling taking place in a given period, 20 years in this case:

$$\Delta L^*_n = L^*_n - L^*_0 \qquad [1]$$

$$\Delta L^*_n\ (\%) = ((L^*_n - L^*_0)/L^*_0))\cdot 100 \qquad [2]$$

where L^*_n is the lightness measured at each point in 2006 and L^*_0 the reference value described below.

On the other, the area covered (AC) or area effectively covered (ACE%) by dark particles was calculated as:

$$L^*_n/L^*_0 = (1 - AC) + (L^*_p/ L^*_0) \cdot AC \qquad [3]$$

Assuming L_n^* as the lightness measured in 2006, L^*_0 as the reference value and L^*_p as the lightness of the particles deposited on the surface (assumed by Grossi et al. 2003 to be 30) yielded the formula:

$$AC = ((L^*_n/L^*_0) - 1)) / - 0.60 \qquad [4]$$

The other parameter applied in this study, the area effectively covered by particles (ACE%), is inversely proportional to colour lightness:

$$ACE\ (\%) = 100 \cdot AC \qquad [5]$$

The reference value, L^*_0=74.3±2.4, was the mean of 10 measurements taken on the surface of limestones that until the 1984-1986 cleaning formed part of the perimetric wall. After it was cleaned, one of the panels was demolished and its limestone ashlars were stored. As their surface exhibited essentially the same appearance as the rest of the limestone immediately after the aforementioned cleaning, it was adopted as the reference.

The mean lightness values ($\bar{X}L^*$) shown on graphs are given for each level, broken down by exposed (blue) and protected (red) surfaces. Similarly, the photographs are grouped by levels, also divided into exposed and protected surfaces to draw direct relationships between each group of photos and the mean lightness values. Images equivalent to each mean L* value were obtained by overlaying all the photos in a given group with Adobe Photoshop CS4 software. These images were then compared to the four degrees of façade soiling (A, B, C, D; Figure 2b) and assigned to one of the aesthetic tolerance categories.

FIGURE 3

3. RESULTS AND DISCUSSION

3.1. Quantification of façade colour patterns (pre-2006 cleaning)

The lightness (L*) values measured on the façades studied at the points defined by the grids are given in Table 1. The highest lightness values, $L^*_{n(max)}$, observed at the points on the grid where the limestone exhibited a pale colour, were >74 points on all the façades. The lowest lightness values (32 points), $L^*_{n(min)}$, were found on the directly aligned façades. Similarly, the data in Table 1 show that the mean final soiling index values ($\bar{X}\Delta L^*_n$) declined more steeply in the period studied on the directly ($\bar{X}\Delta L^*_n \approx$-19) than on the indirectly aligned façades ($\bar{X}\Delta L^*_n \approx$-12). As this index is inversely proportional to the area effectively covered, the mean ACE% values recorded were higher on the directly than on the indirectly aligned façades: $\bar{X}ACE^*_n \approx 42$ compared to $\bar{X}ACE^*_n \approx 27$. These findings stood as further proof that the colour patterns on the directly aligned façades had more dark areas and hence greater soiling than those on the indirectly aligned façades.

TABLE 1

3.2. Effect of design factors on colour patterns (pre-2006 cleaning)

Figure 4 shows the mean decline in lightness (final soiling index, ΔL*) on the limestone surface in the period studied by vertical level (x-axis) and exposure type (blue=exposed and red=protected). Photographs of two of the façades studied are reproduced in the figure: the substantially soiled, directly aligned sides on the main church façade ($1D_{R1}$-$1D_{R3}$); and the scantly soiled, indirectly aligned façade on wing 6, facing Alenza Street ($6I_A$).

Lightness declined at all levels in both exposed and protected areas, but more significantly on directly aligned façades. As a rule, declines were steeper at lower levels, a pattern particularly visible in the exposed areas. On the directly aligned façade, the decline in L* values was similar in the exposed and protected areas, level by level, whereas particularly significant intra-level differences were observed on the indirectly aligned façade.

Further to the façade colour patterns quantified, soiling was favoured in directly aligned, lower, protected areas. Aesthetic decay was most significant in these areas, an indication that the limestone there was also more vulnerable to material damage. Façade alignment was found to be the design factor with the heaviest impact on colour distribution, for directly aligned façades soiled substantially more intensely than the others. Alignment had a greater impact in exposed areas, although above a certain height it ceased to be a determinant in soiling. It also affected colour pattern uniformity. In directly aligned façades, therefore, soiling was almost as intense in exposed as in protected areas, whereas differential soiling was observed in indirect alignments.

FIGURE 4

3.3. Soiling model

3.3.1. Façade aesthetic decay with the passage of time

The straight line in Figure 5a represents the pre-2006 cleaning mean L* and ACE% values for the limestone in some areas of the façades. Inasmuch as the ACE% values calculated from equations 4 and 5 covered the 20 year interval between the two façade cleaning operations, the full range of values was divided into 20 equal segments, with the (post-cleaning) 1986 ACE% ($L_0^* = 74$) as segment 0 and the (pre-cleaning) 2006 as segment 19.

Given the inverse linear relationship between parameters L* and ACE, based on the relationship $\bar{X}L^*/\bar{X}ACE\%$ vs time, the model postulated that since limestone soiling progresses linearly, these two parameters could be represented on a straight line. ACE% rises with time. Hence, the greater the decline in limestone surface lightness the farther to the right are the values: i.e., the values clustering on the left represent areas where soiling particles barely settled or were washed away by the wind and rain, while values on the right denote areas where particles accumulated and the limestone was more intensely soiled. The limestone in the latter areas was more vulnerable to material damage.

After the 1986 cleaning, initially all the construction elements were equally susceptible to re-soiling. The model premised that façade alignment and element height and exposure would determine whether an area would soil and when the lightness value (L*) would cease to decline. In other words, the limestone lightness values would begin to decline at all levels after the 1986 intervention and cease to do so when the value intercepted the slanted line on the graphs. After reaching that point, the limestone would look the same as in 2006 (when L* was measured), either because it soiled no further or because such further soiling could not be perceived (Figure 5a).

The appearance of the limestone surfaces where L* was measured were entered into the model as well (Figure 5b), in the form of the overlaid photographs (grouped by level and degree of exposure) and their respective aesthetic tolerance categories (A, B, C or D, see Figure 2b). Therefore, each degree of aesthetic tolerance covered a range of L* and ACE% values as well as a period of time. L* values of 64 or lower and ACE% values of 25 % or higher (pink arrows in Figure 5b) were set as the thresholds for the human perception of surface aesthetic decay that would call for limestone cleaning based on aesthetic criteria.

Further to the L* vales and overlaid images for the façades and sections thereof analysed, in 2006, in all the protected areas except the ones on the upper level (3), limestone soiling was perceived as aesthetic decay (tolerance category C) or significant aesthetic decay (tolerance category D). In the exposed areas, the limestone exhibited all four tolerance categories on the directly aligned façades, whereas on the indirectly aligned façades aesthetic tolerance categories A and B prevailed.

The model developed postulates that façade alignment and the height and degree of exposure of the construction elements determine whether surfaces will soil and when further soiling will cease to be perceived. It was able to establish approximately when, in the 20 years between the two façade cleanings, the exposed and protected areas on each level acquired the appearance observed in 2006.

FIGURE 5

3.3.2. Preventive façade conservation

The aesthetics of the limestone surface can be related to a need or otherwise for cleaning operations based on aesthetic or damage criteria or both. On those grounds, stone surfaces perceived to be pale (A) or perceptibly soiled (B) would not require cleaning, whereas stone soiling classified under categories C (aesthetic decay) or D (significant aesthetic decay) would respectively denote a need for cleaning and an absolute need for cleaning on aesthetic grounds (Table 2). Tolerance category D stone surfaces may very possibly also be severely damaged, calling for cleaning on those grounds as well.

The model showed, for instance, that while all the protected areas in the centre sections of directly aligned façades had an ACE% > 43 % (significant aesthetic decay, tolerance category D) in 2006, as early as 7 years after the 1986 cleaning they exhibited category C aesthetic decay, indicating a need for cleaning on aesthetic grounds (Figure 5b).

TABLE 2

The model establishes the period of time (post-cleaning) in which the perception of limestone aesthetic decay would denote a need for further cleaning, as well the levels in both exposed and protected areas that should be cleaned. Therefore, as soon as the L* values for any of the levels that in 2006 exhibited aesthetic tolerance C or D declined to <64, both they and all the other levels lying in those categories in 2006 would be cleaned. That would not only prevent the limestone from acquiring an appearance perceived as aesthetic decay but also help retard the processes that damage its surface. In fact, sulfation-induced black crust was detected especially in areas where the limestone had darkened intensely (Perez-Monserrat et al., 2016) to tolerance category D.

In the 2006-2008 intervention, the entire limestone surface was cleaned on all façades. According to the model, however, based on aesthetic criteria, not all the areas would have needed cleaning (Table 3). On the directly aligned façades, 16 of the 20 exposed areas measured (80 %) were found to lie in tolerance category C or D, whereas in protected areas the limestone in all 15 areas measured exhibited such degrees of soiling. In other words, while the limestone needed to be cleaned in all the protected areas, action was called for in only 80 % of the exposed areas. On the indirectly aligned façades, the limestone in 3 of the 16 exposed areas measured was found to lie in tolerance category C or D, whereas in protected areas this was true of 12 of the 16 areas measured. Consequently, only 19 % of the exposed areas required cleaning on aesthetic grounds, compared to 75 % in protected areas. Table 3 also lists the model prediction, in number of years, of when cleaning would again be required in the levels that in 2006 were classified in tolerance categories C or D. Most levels would require cleaning in 7 to 10 years. For both the exposed and protected areas on the façades aligned directly and indirectly with RAI Street, cleaning would be recommended at least every 7 to 8 years. Cleaning intervals of no more than 10 years would be advised for the exposed and protected areas on façades aligned indirectly with Alenza Street.

TABLE 3

3.3.3. Façade aesthetics in 2017

In 2017, 10 years after completion of the latest façade cleaning, the appearance of the former Workers' Hospital was aesthetically satisfactory (compare Figures 6a and 6b). Nonetheless, the perimetric wall facing the main street (RAI) was badly soiled (Figure 6b) and the limestone on the dado (0) of the main church façade exhibited a fair amount of soiling (compare Figures 6c and 6d). In certain areas, a dark biofilm had developed on the limestone surface (Figure 6d), contributing significantly to a perception of aesthetic decay (Perez-Monserrat et al., 2013).

Lightness was measured on construction elements in areas where, according to the model, the stone surface should exhibit aesthetic decay. Further to the model, the exposed and protected areas on levels where the mean L* values were under 64 in 2006, i.e., where the limestone surface was classified in tolerance categories C or D (Figure 5b), would need to be measured, for the 7 to 10 year cleaning interval recommended for the façades had obviously lapsed by 2017.

Inasmuch as the façades were not scaffolded in 2017, the measurements were taken from the ground, windows or roofs, and many of the areas measured in 2006 were inaccessible. The levels that in 2006 exhibited a mean L* value of <64, i.e., in tolerance categories C or D, were chosen for measurement. In the areas where the measurements were taken, the surfaces were also photographed and the photos for a given level were grouped in a general image representative of that level.

FIGURE 6

In most of the exposed areas measured, the limestone surface exhibited no aesthetic decay, for the mean L* values were >64 on nearly all levels (Figure 7). Certain inter-façade differences were detected in L* value patterns in the directly aligned façades: the limestone surface was pale in all the levels measured on the entrance façade (facing Maudes Street, with only one lane of traffic), whereas the limestone was soiled on those same levels on the church façade (facing RAI Street, with eight lanes of traffic), with aesthetic decay present on the lower levels (0 and 1). L* value clustering was particularly dense on the indirectly aligned façades, where the limestone was pale on all the levels measured.

Ten years after the latest façade cleaning, only the dado (0) and the lower level (1) on the main church façade fulfilled the model's prediction on the need for cleaning (Figure 7). The limestone surface on those levels was perceived to be aesthetically decayed in 2017 (Figure 6b) due to its proximity to a street with very heavy vehicle traffic and concomitantly intense emissions. That the limestone did not exhibit aesthetic decay ($L^* < 64$) in all the areas predicted by the model was a very promising finding, for it translated to a lengthening of the time in which cleaning operations would be required for aesthetic reasons. It also meant that façade soiling was less intense after 2008 than it must have been in the first 10 years after the 1986 cleaning.

FIGURE 7

One of the questions posed by the model was illustrated by an indirectly aligned façade: initially, after the 2008 cleaning, the limestone on all levels was equally vulnerable to soiling. Ten years after the most recent cleaning, the lightness values for the limestone façades analysed had barely declined. With time, some of these values will drop and others will not, depending on the position of the construction element.

It should be borne in mind that the linear soiling model proposed was based on the two lightness measurements available (reference value, L^*_0, for 1986 and L*, measured in 2006) but the surface soiling is a cumulative process. Moreover, the deposition-mediated decline in surface material lightness values is steepest in the early years of exposure. As particles accumulate, the surfaces are perceived to be aesthetically decayed, although a point is reached when soiling is not perceived to worsen, even though particles continue to settle on the surface.

4. CONCLUSIONS

The former Workers' Hospital façades were less soiled in 2017 than predicted by the model for a number of reasons, attributable primarily to the measures adopted to improve air quality in the building's immediate surrounds and the actions taken to conserve its façades. On the one hand, the improvement in air quality and decline in the relative humidity in the immediate surrounds, in keeping with the pattern observed by Perez-Monserrat et al. (2016) for the period 1986-2006, and retarded particle accumulation in the period 2008-2017. On the other, the replacement of the flyover with an underpass on the main street (RAI) reduced air pollution. Although traffic continues to be very heavy in the proximity, the construction of the tunnel must have changed the distribution and deposition of traffic-induced pollutants, particularly on the façades facing that street. Moreover, the water repellent applied to all the façades after the 2008 cleaning would also have a beneficial effect, particularly in the early years.

The model proposed aims to minimise interventions. It suggests periodic, localised cleaning, specifying the areas that should be cleaned on the grounds of soiling intensity. The action proposed by the model is economically beneficial, for local interventions are less costly. The timing for cleaning operations predicted by the model was fulfilled for the surfaces on the lower levels of the façades, which happen to be the most readily accessible.

Over time, the façades on the former Workers' Hospital may be expected to exhibit colour patterns similar to those described in this paper, for design variables remain unaltered. Nonetheless, the intensity of limestone soiling and the soiling rate are changing in keeping with weathering and environmental science parameters. In a nutshell, the model premises sustainable façade cleaning as an optimal approach to preventive conservation and appropriate management of architecturally sensitive buildings.

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FIGURE CAPTIONS

Figure 1. a) Overview of the former Workers' Hospital prior to the 1984-1986 cleaning (courtesy of the Specialized Documents Centre, Madrid Regional Department of Environmental Affairs, Housing and Land Management), showing the four streets (one with eight heavily travelled lanes) bounding the city block occupied [AADT (average annual daily traffic: number of vehicles driven across a section of street in 24 hours on an average business day) was, in 2006: Alenza Street, 2630; Maudes Street, 2010; RAI Street; 77 510; Source: City of Madrid Security and Traffic Division]; b) Vertical levels on the diagonal wing façades (SE façade on NE wing, facing Alenza Street). The dado on the southeast and southwest wings, the entrance and the main façade on the church occupies a full storey or level. The upper level of the main church façade comprises (3a) a cornice, (3b) a balustrade and (3c) a tower.

Figure 2. a) Façades facing the main street (RAI) prior to the latest cleaning, in 2006; b) progressive soiling on the limestone surface in 2006 and tolerance categories assigned to each degree

Figure 3. Façades on the former Workers' Hospital chosen to quantify the colour patterns observed in 2006, prior to the most recent cleaning (red lines on the building floor plan) and to develop the soiling model; (1) church façade divided, like (2) the entrance, into a centre and two side sections, showing grid used. The number assigned to each façade is preceded by the letter D or I to respectively specify direct or indirect alignment. In addition, the streets they face are indicated by subscripts: R (RAI), M (Maudes) and A (Alenza). For readier handling of the very long, directly aligned façades, they were divided into three sections: a centre and two sides.

Figure 4. Final soiling index (ΔL^*) on intensely ($1D_{R1}$-$1D_{R3}$) and slightly ($6I_A$) soiled façades in 2006 (vertical levels shown on the x-axis).

Figure 5. Soiling model for aesthetic decay on façades over time (pre-2006 cleaning): mean values of L* and ACE% on directly aligned centres on the main church façade ($1D_{R2}$) and the entrance ($2D_{M2}$), and indirectly aligned façades facing Alenza Street ($6I_A$ and $5I_A$), by height (vertical levels, from 0 to 3c) and surface exposure (exposed, blue; protected, red).

a) $\bar{X}L^*/\bar{X}ACE\%$ versus time. On lower level (1), for instance, the ACE% value on the stone surface of the exposed areas on indirectly aligned façade $5I_A$ rose for around 10 years. Thereafter, due to their position on an indirectly aligned façade and a lower, exposed level, the value of ACE% remained flat through 2006 at around 36 % (equivalent to an L* value of ~60: green arrows).

b) $\bar{X}L^*/\bar{X}ACE\%$ versus limestone aesthetic decay.

Figure 6. Photographs of the façades facing the main street (RAI) in 2008 (a and c) and 2017 (b and d), showing generally satisfactory aesthetics 10 years after the latest cleaning (2006-2008), barring the substantial soiling on the perimetric wall (b) and the darkened limestone and biofilm development on the dado (0) of the main church façade (d).

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TABLE CAPTIONS

Table 1. Quantification of colour patterns on façades based on in situ L* measurements.

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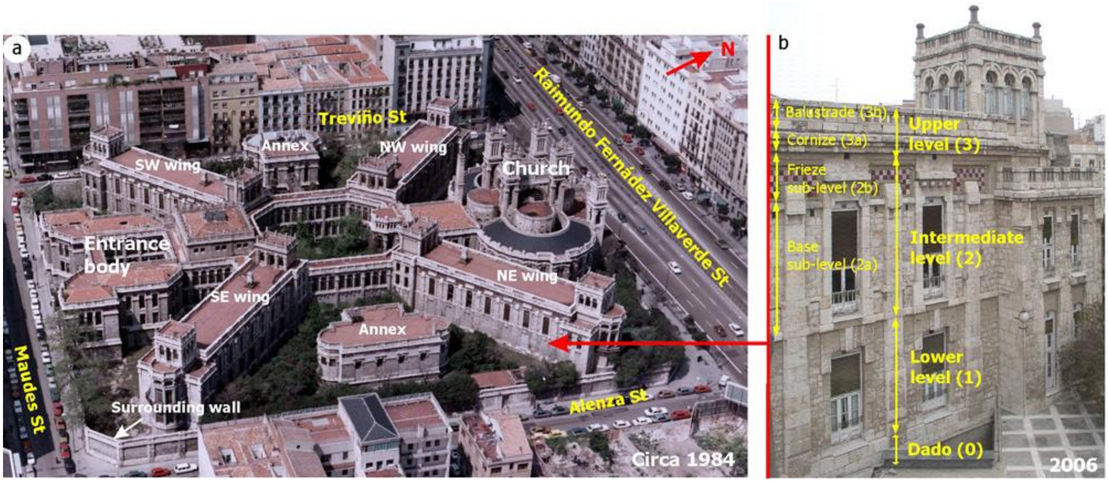
Table 3. Areas to be cleaned on aesthetic grounds and recommended cleaning intervals.

FIGURES

Figure 1



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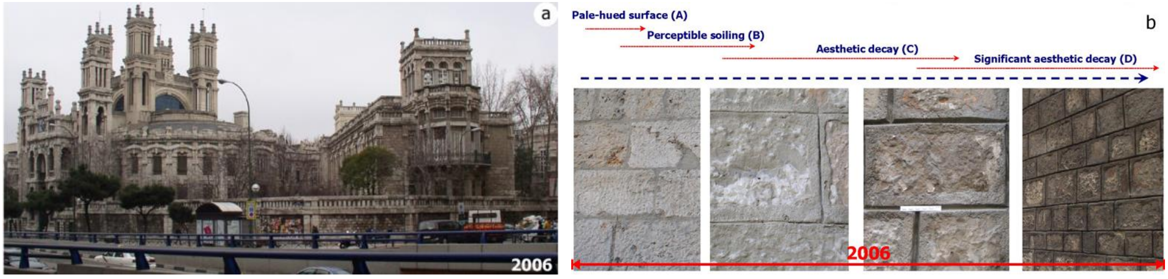

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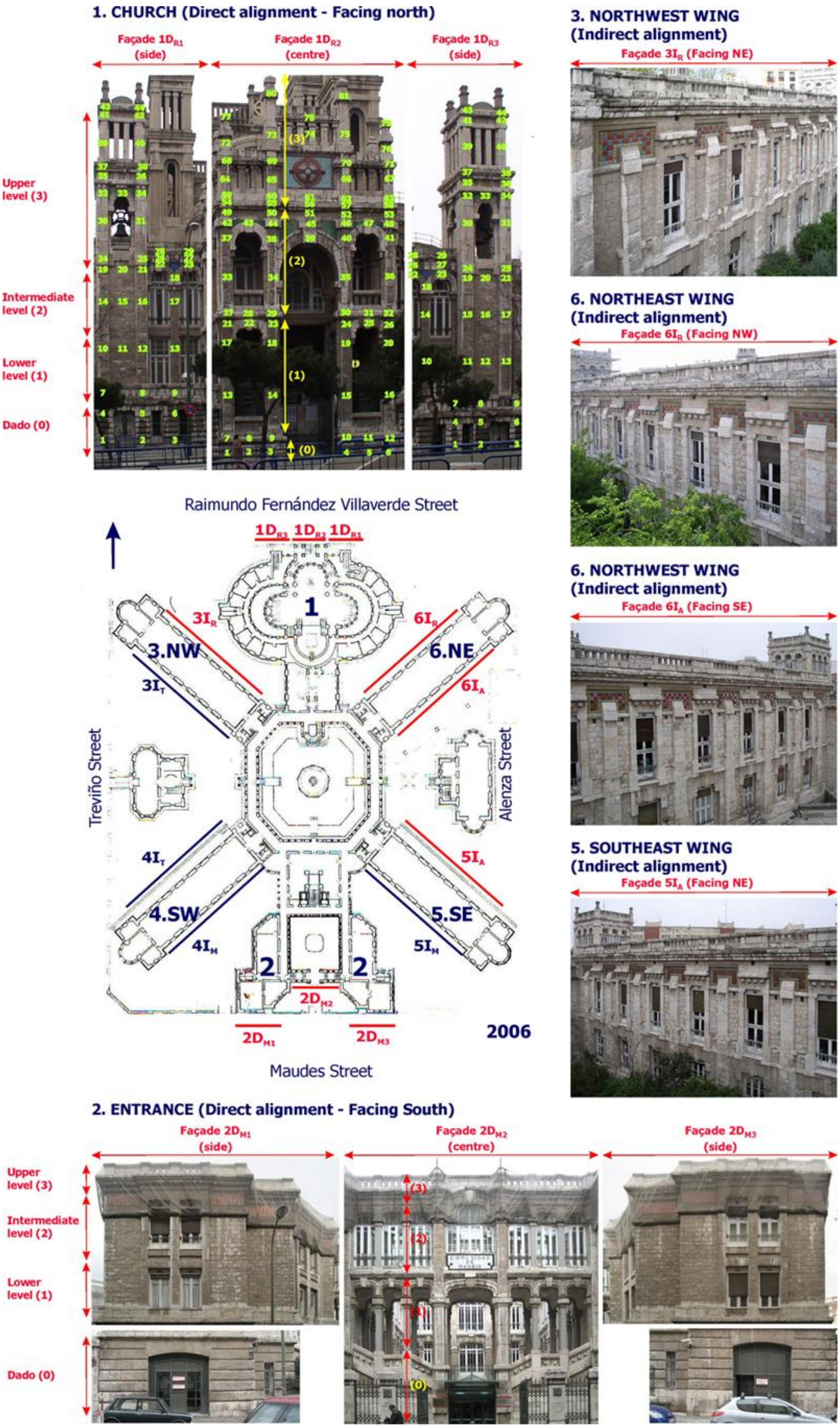

1. CHURCH (Direct alignment - Facing north)
Façade 1D$_{R1}$ (side)
Façade 1D$_{R2}$ (centre)
Façade 1D$_{R3}$ (side)
Upper level (3)
Intermediate level (2)
Lower level (1)
Dado (0)
3. NORTHWEST WING (Indirect alignment)
Façade 3I$_R$ (Facing NE)
6. NORTHEAST WING (Indirect alignment)
Façade 6I$_R$ (Facing NW)
6. NORTHWEST WING (Indirect alignment)
Façade 6I$_A$ (Facing SE)
5. SOUTHEAST WING (Indirect alignment)
Façade 5I$_A$ (Facing NE)
Raimundo Fernández Villaverde Street
1D$_{R3}$ 1D$_{R2}$ 1D$_{R1}$
1
3I$_R$
6I$_R$
3.NW
6.NE
3I$_T$
6I$_A$
Treviño Street
Alenza Street
4I$_T$
5I$_A$
4.SW
5.SE
4I$_M$
5I$_M$
2
2
2D$_{M2}$
2D$_{M1}$
2D$_{M3}$
2006
Maudes Street
2. ENTRANCE (Direct alignment - Facing South)
Façade 2D$_{M1}$ (side)
Façade 2D$_{M2}$ (centre)
Façade 2D$_{M3}$ (side)
Upper level (3)
Intermediate level (2)
Lower level (1)
Dado (0)

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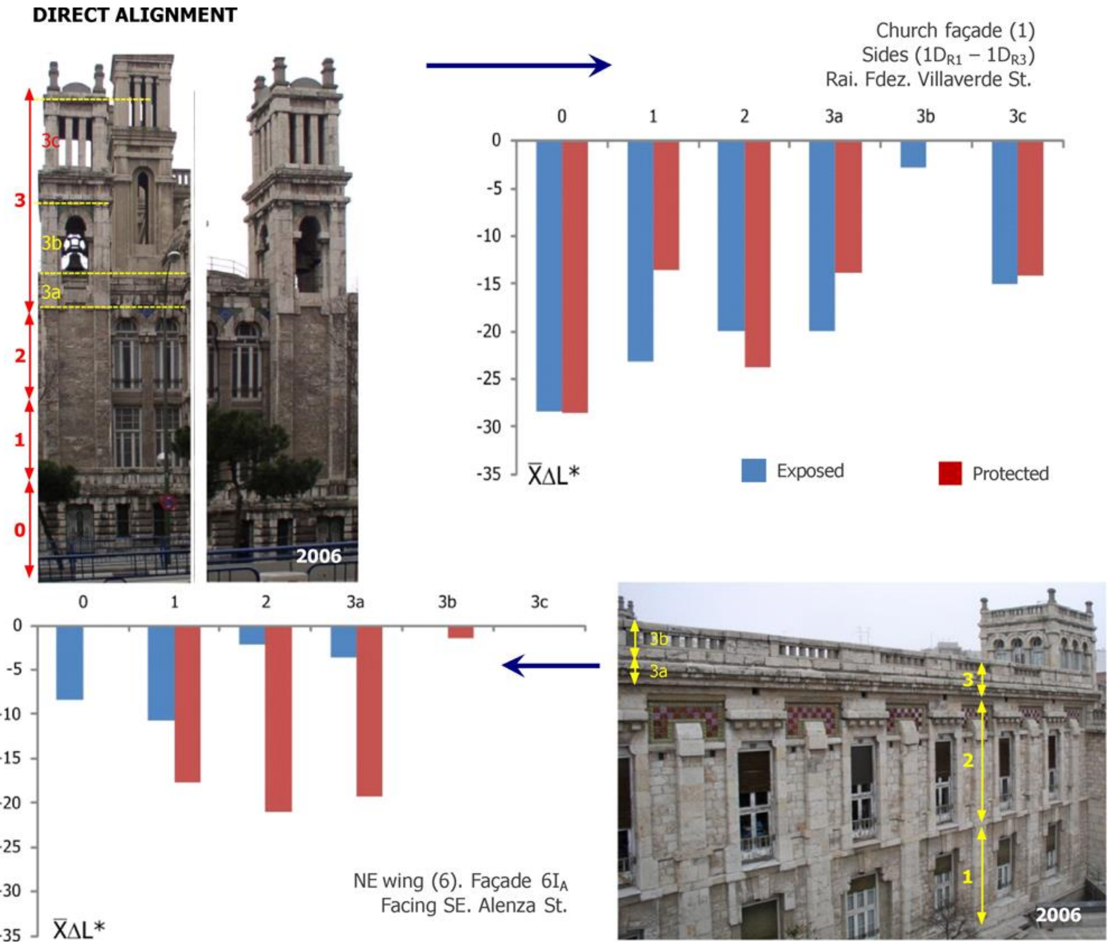

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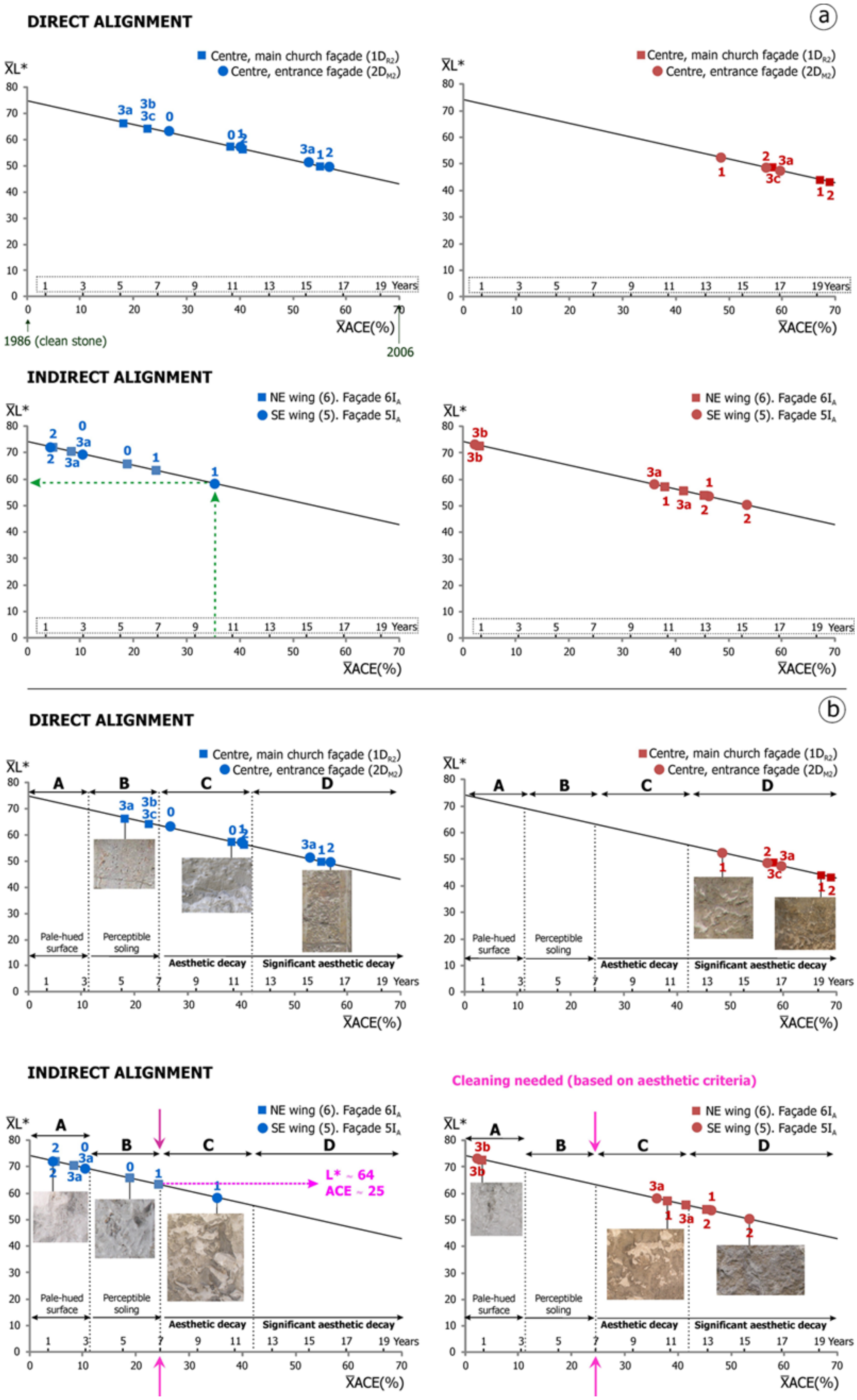

a
DIRECT ALIGNMENT
Centre, main church façade (1DR2)
Centre, entrance façade (2DM2)
X̅L*
X̅ACE(%)
Years
1986 (clean stone)
2006
INDIRECT ALIGNMENT
NE wing (6). Façade 6IA
SE wing (5). Façade 5IA
b
DIRECT ALIGNMENT
A
B
C
D
Pale-hued surface
Perceptible soling
Aesthetic decay
Significant aesthetic decay
INDIRECT ALIGNMENT
L* ~ 64
ACE ~ 25
Cleaning needed (based on aesthetic criteria)

Figure 5. Soiling model for aesthetic decay on façades over time (pre-2006 cleaning): mean values of L* and ACE% on directly aligned centres on the main church façade ($1D_{R2}$) and the entrance ($2D_{M2}$), and indirectly aligned façades facing Alenza Street ($6I_A$ and $5I_A$), by height (vertical levels, from 0 to 3c) and surface exposure (exposed, blue; protected, red).

c) $\bar{X}$L*/$\bar{X}$ACE% versus time. On lower level (1), for instance, the ACE% value on the stone surface of the exposed areas on indirectly aligned façade $5I_A$ rose for around 10 years. Thereafter, due to their position on an indirectly aligned façade and a lower, exposed level, the value of ACE% remained flat through 2006 at around 36 % (equivalent to an L* value of ~60: green arrows).

d) $\bar{X}$L*/$\bar{X}$ACE% versus limestone aesthetic decay.

Figure 6

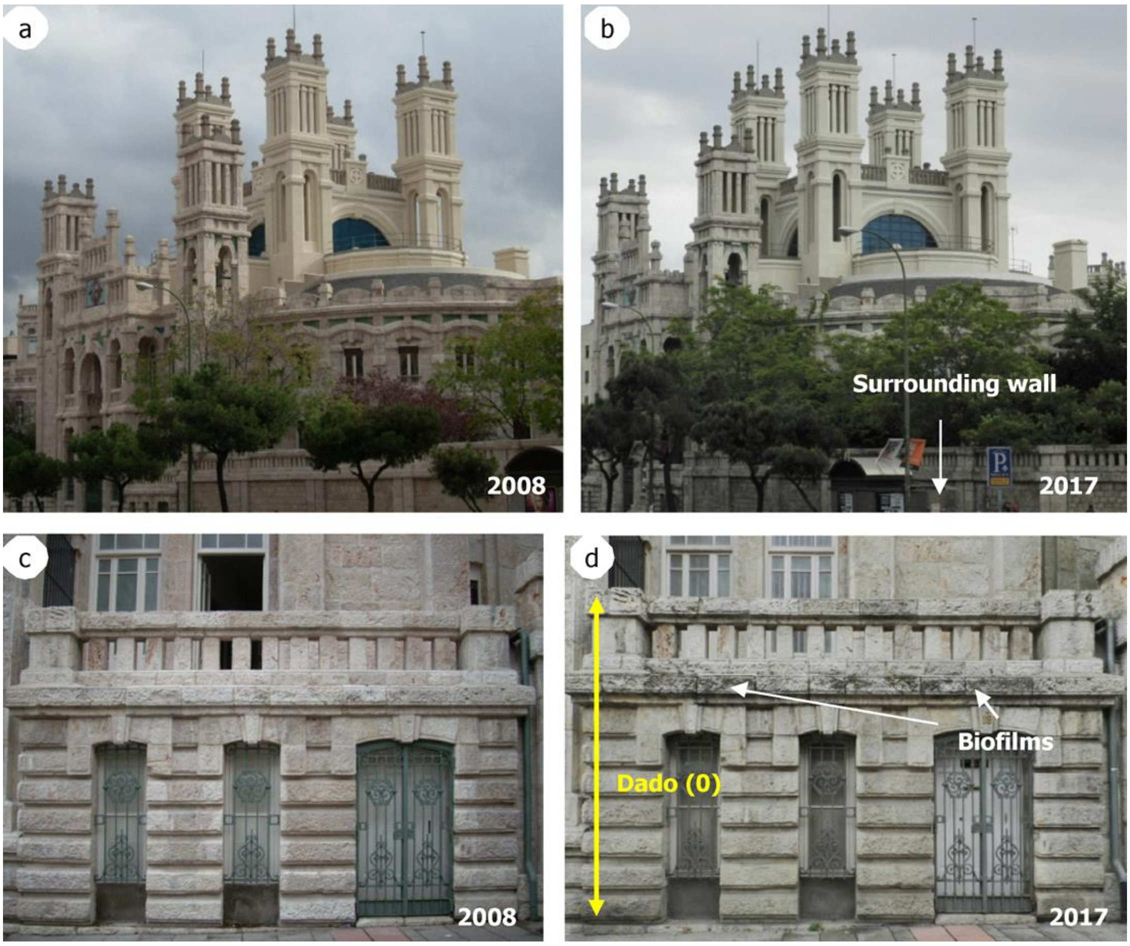

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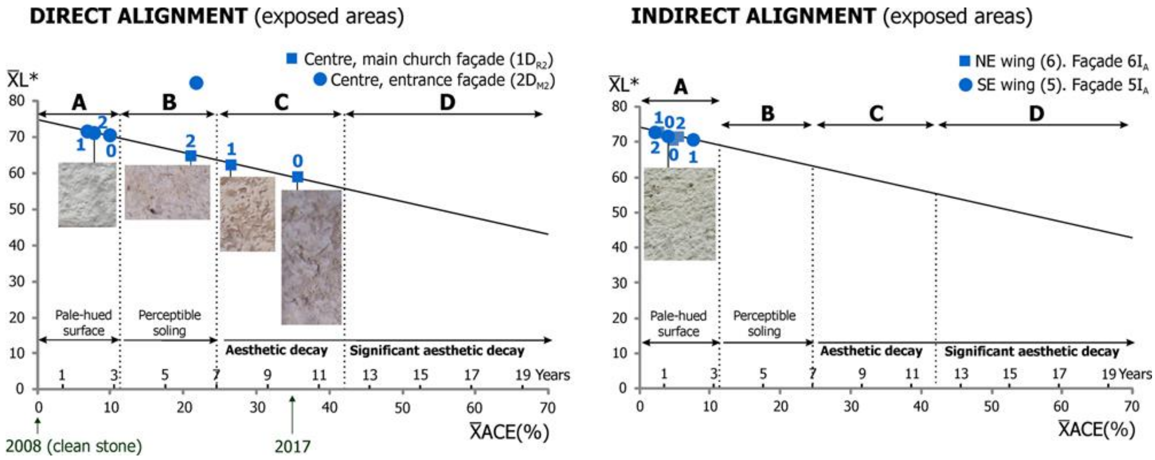
Figure 7



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TABLES

Table 1. Quantification of colour patterns on façades based on in situ L* measurements.

FAÇADE ALIGNMENT			$L^*_{n(max)}$	$L^*_{n(min)}$	$\bar{X}L^*_n$	$\bar{X}\Delta L^*_n$	$\bar{X}ACE_n$(%)
Directly aligned	Main church façade (1) North	Centre ($1D_{R2}$)	79.2	40.4	56.2	-18.2	40,7
		Side ($1D_{R1}$)	77.3	40.8	56.6	-17.6	39,4
		Side ($1D_{R3}$)	75.3	32.3	54.6	-19.6	43,9
		$\bar{X}$ church façade	77.3	37.8	55.9	-18.4	41,4
	Entrance façade (2) South	Centre ($2D_{M2}$)	79.2	32.3	54.3	-20.0	44,9
		Side ($2D_{M1}$)	74.4	40.0	55.9	-18.5	41,4
		Side ($2D_{M3}$)	74.6	32.0	54.7	-19.6	44,0
		$\bar{X}$ entrance	75.9	34.8	55.0	-19.4	43,4
	$\bar{X}$ directly al. façades		**76.6**	**36.3**	**55.4**	**-18.9**	**42.4**
Indirectly aligned	Wing 3 (NW) / Northwest façade ($3I_R$)		79.5	41.1	60.8	-13.5	30.3
	Wing 6 (NE) / Northeast façade ($6I_R$)		79.7	36.2	62.7	-11.6	26.1
	$\bar{X}$ RAI St façades		79.6	38.7	61.8	-12.6	28.2
	Wing 6 (NE) / Southeast façade ($6I_A$)		81.3	40.1	63.7	-10.6	23.8
	Wing 5 (SE) / Southeast façade ($5I_A$)		81.5	41.7	62.0	-12.4	27.8
	$\bar{X}$ Alenza St façades		81.4	40.9	62.8	-11.5	25.8
	$\bar{X}$ indirectly al. façades		**80.5**	**39.8**	**62.3**	**-12.0**	**27.0**

Table 2. Aesthetic parameters and time in each tolerance category.

Tolerance category	**L***	**ACE%**	**Perception of limestone surface**	**Cleaning (aesthetic criteria)**	**Time (y)**
A	74-68	0-12	Pale-hued surface	No action required	0-3
B	68-64	12-25	Perceptible soiling	No action required	3-7
C	64-55	25-43	Aesthetic decay	Action necessary	7-12
D	< 55	>43	Significant aesthetic decay	Action absolutely necessary	>12

Table 3. Areas to be cleaned on aesthetic grounds and recommended cleaning intervals.

Façade/section studied		Ratio of areas* in tolerance categories C or D in 2006			
		Exposed	Interval	Protected	Interval
Directly aligned	Centre	7/10	±7 years	6/6	±7 years
	Sides	9/10	±7 years	9/9	±8 years
Indirectly aligned	Facing RAI St.	2/8	±7 years	6/8	±8.5 years
	Facing Alenza St.	1/8	±10 años	6/8	±10 años

* Number of areas that were classified in tolerance categories C or D (necessary or absolutely necessary cleaning, on aesthetic grounds) in 2006 relative to the total number of areas analysed. All areas were cleaned in 2006-2008.