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Original article

Application of climate-based daylight simulation to assess lighting conditions of space and artworks in historical buildings: the case study of cetacean gallery of the Monumental Charterhouse of Calci

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ABSTRACT

Exhibits are often displayed in spaces originally not designed to be museums. Thus, is common for those spaces to fail adequate lighting display conditions, both in terms of the artworks' conservation and visitors' comfort. In order to objectively assess if an exhibition meets the required standards it is necessary to establish a proper evaluation method. This work proposes a novel procedure relying on climate-based data and dynamic daylight metrics. The procedure, that considers both artworks' and visitors' needs, can provide museum curators with scientific, repeatable data. These data can help them screen out potential interventions until the most adequate is found. The main advantages of the new approach are that, if properly validated, the simulations can substitute annual measurement campaigns (thus leading to time and costs savings), and the results are very reliable (thanks to the use of climatic data specific for the site in exam) and that the effectiveness of potential interventions can be predicted simulating as many sceneries as needed. The novel procedure can be applied to assess the exhibits' display conditions in historic building whenever daylight is the main light source. The validity of the procedure is demonstrated through its application on a case study: the Cetacean Gallery of the Monumental Charterhouse of Calci, near Pisa. The outcome of the assessment demonstrated that the Gallery is over-lit and the exhibits are being damaged, for this reason four potential interventions have been analysed and compared. The accuracy of the simulations was validated through a comparison with on-site measurements.

Introduction: a research background

Museum lighting has been investigated from many points of view, including visitors' visual experience and comfort [1,2], collections' exposure to daylight [3–5], artificial lighting sources appropriateness [6–8], energy savings and retrofitting [9–11]. The key concern of all these studies is to balance conservation requirements and exhibition needs [12,13], that becomes harder in case of exhibits housed in spaces originally designed for different purposes, especially in historical buildings (e.g. churches monasteries, villas, palaces and castles) which have been frequently converted into museums [9]. Using such spaces to host a museum is a challenge for the designers: exhibits need to be displayed under a proper microclimate. Lighting conditions and thermo-hygrometry of the exhibition rooms must be carefully designed to meet the exhibits' needs [14–17]. In addition, designers must come up with a solution for the energy savings issue, as historical buildings are often energy-consuming [18–20]. Moreover, modern museums often feature additional functions as cafeterias, shops, conference rooms and play areas [21–23]. Lastly, it often happens that interventions on historical buildings are limited by the Italian Heritage Protection Department. Given these premises, it is quite common that historic buildings, although endowed with great charm, do not have adequate characteristics to accommodate artworks. In this casuistry, one of the main factors that must be carefully studied is daylight. The characteristics of daylight can greatly influence the exhibits' display conditions since daylight was often the only light source when these buildings were being constructed. It happens frequently that exhibits are exposed to a high amount of daylight because there are large windows. Daylight, can lead to both positive and detrimental effects on exhibits and also on visitors. The positive effects are economical, i.e. linked to the reduction of the artificial

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lighting usage [24,25] and they are also visual, since daylight has special characteristics in terms of Correlated Colour Temperature, Colour Rendering Index and emission spectrum, the variations of these parameters have been found very impactful on the appreciation of artworks [26]. The negative effects include harmful impacts on artwork conservation and concerns about how daylight spectrum and its daily fluctuations can damage sensitive collections. Although there are researches considering both artworks' conservation and visitors' comfort [27], they focus on already-existing museums and on a single case study solution [28–30]. Almost no research investigates the impact of daylight on both artworks and visitors, and links it to the conversion of historical buildings into museums. Thus, a repeatable procedure for assessing daylighting adequacy in this casuistry is needed.

Research aim

This paper proposes a procedure to assess the adequacy of exhibits' exposure to daylight inside historical buildings. It develops an approach combining dynamic daylight metrics [31] and exhibits' light exposure concerns. Lighting designers face a threefold problem: they have to consider exhibits' conservation needs, visitors' comfort needs while respecting the historical host-building's architectural character. As these needs are often in contrast, the novel procedure can help designers as an operative mean of work. The novel procedure allows to perform annual evaluation without the need of prolonged measurements campaign, thus allowing time and money savings.

Definition of the proposed novel procedure

The novel procedure is articulated in three phases, subdivided into ten steps (Fig. 1). Steps 1–3 correspond to the first phase "cognitive", steps 4 and 5 correspond to the second phase "setting the model", steps 6–9 correspond to the third phase "analysis". Finally, conclusions about the adequacy of the exhibition can be drawn in step 10. In the following subsections each step is given a brief explanation.

Historical analysis of the host-building

When historic buildings are converted into a museum, it is important to define their architectural and historical value. In many cases they are listed buildings, meaning that certain kinds of interventions will not be allowed. Step 1 helps to understand the host-building character and its evolution through the centuries. For what regards light, this step involves discovering changes in the original colours and materials, locating openings and closings of original windows or skylights, and identifying the carried-out interventions (e.g. installation of lighting systems, UV filters on the windows). Information on technical data is difficult to acquire, however this kind of knowledge can help develop better solutions. In step 1 information about the host-building can be acquired consulting the museum's archive and, depending on its relevance, historical archives, paintings and photos. This can often help to understand the evolution of the building and to highlight possible critical points (e.g. reconstructions due to collapses, additions and static problems).

Museum description: characteristics of the collection and the exhibition room

The exhibits can be exposed to different level of risk and damage depending on how they are displayed. Step 2 focuses on analysing the exhibition design. The aspects to consider are: the host building's characteristics, the display conditions and the exhibits' features. These aspects intertwine with each other and therefore they should be considered altogether. A simplified assessment method for environmental and energy quality in museum buildings has been proposed [32]. The method suggests to acquire specific information in order to develop accurate models. The information can be directly obtained through survey and measurements or consulted through literature and the national and international standards. In particular, the characteristics of the building (e.g. indoor environmental parameters), the characteristics of the display (e.g. the museums' opening hours; lighting systems; control and management systems) and the characteristics of the collection (e.g. the exhibits' materials, properties and photosensitivity) should be defined.

Enforced rules state of the art

Historical buildings may be subjected to different standards based on their cultural value, however there are international standards for conservation [15] and for user's visual comfort [33,34], which designers can refer to. The requirements may vary between national and international standards, if this occurs, it is advisable to refer to the most restrictive ones. Step 3 helps to understand the enforced rules state of the art, and it concludes the cognitive phase. It should be noticed that conservation standards often differ with visitors' comfort ones: the first ones ignore the presence of an observer, while latter just set minimum lighting levels for workplaces. These lighting levels are not even specified for museums, on account of conservation being fundamental (see Supplementary Materials). In addition, designers cannot refer to the lighting levels set by standards for categories similar to the museum (see Supplementary Materials). In fact, those minimum lighting levels are already higher than the maximum ones required for conservation (see Supplementary Materials). A new approach, evaluating both exhibits' conservation and visitors' comfort, is needed.

D-modelling for simulations

Step 4 allows to analyse a higher number of lighting sceneries, as simulations integrate various aspects together to be analysed in experimental studies whilst reducing the evaluation time. Some researches present employing such simulation-techniques in museums [35,36,40]. There are recent and comprehensive researches [31,37–39] about daylight simulation modelling utilizing dynamic daylight metric (DDM), and climatic data, overcoming and proposing new solutions for shortcomings of the conventional and static metric (i.e. Daylight Factor, DF). It is necessary to integrate these metrics into a new approach to assess the daylighting performance in museums. Unfortunately, the most common simulation software does not implement these analyses yet, so currently they can be run only using particular engines (e.g. *Radiance* via plugins for *Grasshopper*).

Measurement grid definition

Step 5 defines the measurement grid hence the accuracy of the evaluation. The novel procedure comprehends two kind of analyses: one aimed to assess the overall lighting conditions (step 7), and one to evaluate light's damages on exhibits (step 8), therefore two different grids may be needed. The minimum number of measurement points and their spacing can be defined accordingly to [33] for the former, based on the geometry of the room (see Supplementary Materials). The latter instead depends deeply on the nature, dimensions and positioning of the exhibits, hence universal guidelines cannot be provided. In fact, in literature there are best practices but no specific standards, hence it is suggested to refer again to the standards set by [33]. To assess the accuracy of

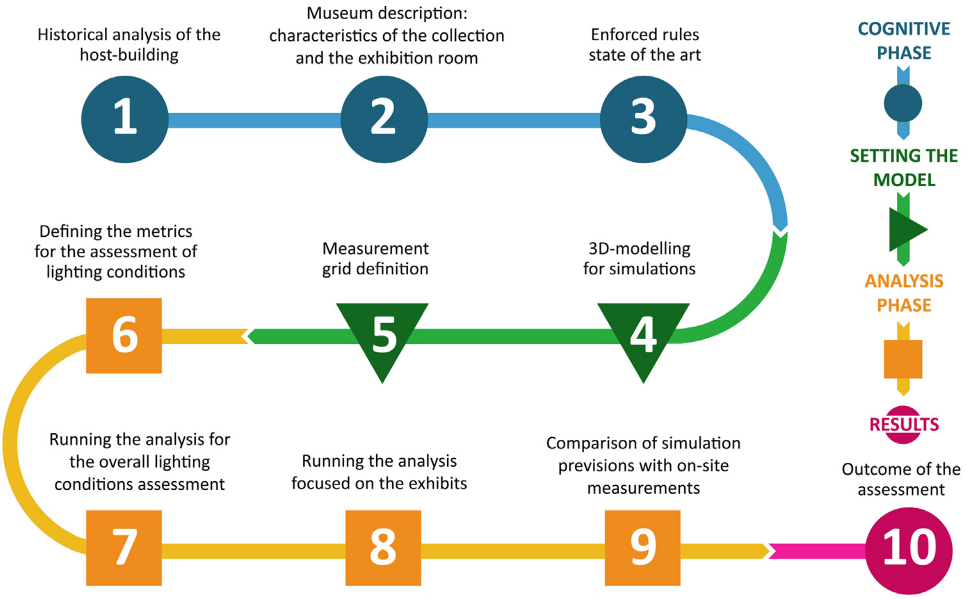


Fig. 1. Schematic flow of the steps of the novel procedure; (top right) schematic description of the phases.

the simulations, an additional grid for the on-site measurements campaign needs to be defined. For the comparison, to be as significant as possible, it is advised to use the same grid both for the on-site measurements and the simulations.

Defining the metrics for the assessment of lighting conditions

Almost all metrics described in standards to assess lighting conditions are illuminance-based. By far the most common is the DF. As the overcast sky rarely corresponds with the predominant sky condition, and due to daylight hourly and seasonal changes, it is suggested using DDM, thus avoiding any flaws and simplifications of the DF approach [40,41]. Daylight autonomy (DLA), Continuous Daylight Autonomy (cDA), Useful Daylight Illuminance (UDI) and Spatial Daylight Autonomy (sDA) are the DDM which permit more accurate and thorough evaluations [31,42–44]. Step 6 helps designer to evaluate which metric is more useful to address the case in exam. DDM allow to integrate information about time and space to illuminance, and to construct relations between illuminance and glare [45]. Unfortunately, the calculation process is complex. Regarding exhibits' conservation, the metrics to refer are the maximum illuminance (E_{max}) and the annual luminous exposure (LO). The main disadvantage is that many lighting software do not implement dynamic daylight analysis. In addition, since the calculation procedure is too complex to be performed manually, the only alternative is measuring the illuminance values with a datalogger on-site. The datalogger could provide hourly illuminance values on a year basis, then those values could be used to calculate the DDM. Such a procedure would be more reliable than simulations, but it would be time and money-consuming, and it would provide operative challenges. On the contrary, the DF can be calculated manually and it is implemented in every lighting software.

Running the analysis for the overall lighting conditions assessment

Lighting analysis can be performed using various tools (e.g. *Honeybee+* for *Grasshopper*, a *Radiance*-based simulation plugin). The simulations in step 7 allow to assess if the exhibition room is too bright or too dark, if it is prone to glare occurrence and if its geometry can guarantee adequate light levels or if an artificial lighting system is needed. First instances analyses can be performed in solstices and equinoxes, in order to acquire general knowledge about the lighting conditions, for more through information annual analyses should be run. Some software implement both Point in Time (PIT) and annual analyses. In PIT ones the user sets the date, hour and sky condition, while annual simulations require climate-based data. These data, provided by meteorological stations, form the typical meteorological year (TMY) for the site in exam. TMY is composed by the succession of the most recurrent weather conditions observed during the recording period [42,46]. In annual simulations the user chooses the time step for calculations, but the sky conditions vary accordingly to the TMY. While PIT analyses are supported by most simulation software, annual ones are not, but they are necessary to calculate DDM.

Running the analysis focused on the exhibits

Step 8 is one of the most important steps of the novel procedure, as it provides information on the exhibits' conditions. It has been said that museums must promote exhibits exposition (so that more public can admire cultural heritage) but without endangering it. In order to acquire precise data on the risks which exhibits are exposed to, additional simulations (focused on the exhibits) are needed. These simulations should be performed using annual analysis, as the damage caused by light is cumulative and non-reversible. Usually, to perform this kind of analysis it would be necessary to carry out annual on-site measurements campaigns, with the novel procedure instead, it is sufficient to run annual simulation analysis and then validate the results through a comparison with fewer on-site measurements. This allows to greatly reduce the time and expenses of prolonged measuring campaigns. Furthermore, it is advised to run annual simulations, because they allow a more accurate estimation of LO and E_{max} (provided that the model is calibrated), by using climate-based data. In addition, using annual analysis allows to calculate the DDM. These metrics can be used to monitor the exposure danger, for example the percentage of time in which the illuminance surpass the limits set by the standards can be inquired. Moreover, designers can inquire which are the most dangerous periods in terms of exposure (by comparing the results for different analysis spans) and they can even evaluate the efficacy of potential interventions. Clearly, these evaluations are preliminary analyses, they will need to be integrated with additional considerations (e.g. economic factors and management aspects).

Comparison of simulation previsions with on-site measurements

Simulations assist designers in their choices while reducing the measurements campaign's length and expenses, however they have to be validated through on-site measurements. The measured and software-simulated values should be compared: in order to have a significant confrontation, the values to compare should correspond to the same date and time and point of the grid. Step 9 helps designer to evaluate the accuracy of their previsions. As measurements require longer time to be performed it is suggested to compare a significant number of values without covering all the grid. Nonetheless, the standards set by [33] for the minimum number of measurement points need to be met. On-site measures are PIT values; therefore, they should be compared to PIT values. That can be done either conducting PIT analyses (specifying the sky condition) or extrapolating PIT results from the annual analysis. In this case, the user selects the wanted outcomes, these outcomes can be found by entering the exact date and time when the measurements were taken.

Outcome of the assessment

Finally, after the analyses, in step 10 it is possible to express a judgment on the adequacy of the exhibits display setting. The possible outcomes are: the setting is adequate and the exhibits are not exposed to danger; the setting is partially inadequate, mild risks exist, and an intervention to safeguard the exhibits is needed; the setting is inadequate, the exhibits are subject to grave danger and an intervention is essential. The procedure and the final judgment should be applied to all the exhibition rooms of the museum. For each one, based on the outcome, different intervention may be possible and have to be evaluated. For example, it could happen that an exhibition room would reveal to be inadequate to host exhibits, and, as no intervention may be applied, these should be moved. It could also happen that a vacant room of the historic building has adequate exposing conditions and therefore the exhibits can be transferred in there. Clearly, if the majority of the exhibition rooms are inadequate these exchanges become more difficult, and thus the probability of having to move the entire collections rises. However, the final overall judgment should be given, once the procedure has been applied to all the historical building's rooms. Moreover, as it often happens, not every exhibition room has the same attractiveness and effectiveness in gathering tourists. Applying the procedure lighting designers can provide scientific results to the museum curator, which can enforce the most appropriate course of action integrating these data with economical and managerial considerations.

Application of the procedure to a case study

The case study is the Cetacean Gallery of the Monumental Charterhouse of Calci, near Pisa (Fig. 2). The Charterhouse was chosen for its value as an historical building, for the importance of its unique collection [47] and for the great amount of daylight entering the space.

Cognitive phase

Historical analysis of charterhouse of Calci

The Charterhouse of Calci (Fig. 2) is a Carthusian monastery founded in 1366. Its original composition was lost after centuries of enlargements [48]. Modifications continued as the Charterhouse was disbanded twice, first due to the religious organizations' disbandment, commanded by Napoleon in 1810, and then in 1866 with the Savoy royal decree n°3036, which handed all of its property to the new-born Italian government. In 1870, the government turned the Charterhouse into an educational building. Most of the monks' cells were transformed into classrooms demolishing the partition walls. The monastery was further altered during WWI and WWII: it was partially occupied by the 32nd Field Artillery (1893–1915), then turned in a backup military hospital (1915) and later into a storage for artworks (1939), even if, in 1923, it was declared a historic landmark. In 1972 the few last monks left the monastery conceding its free and perpetual usage to the University of Pisa which inaugurated the Natural History Museum in 1981. The museum is recognized throughout the world: in 2014 it was one of the most voted in Italian Environment Fund's survey "*FAI–I luoghi del cuore*" [49] and in 2017 the International Council of Museums (ICOM) rewarded it as one of the ten noteworthy museums of the year [50]. The exhibitions are housed on ground, first and second floor. The Cetacean Gallery corresponds to the ex-barn on the second floor.

Description of the Cetacean Gallery and its exhibition

The Gallery (Fig. 2) houses the most important cetacean skeleton collection in Italy, worldwide it is the only one displaying the skeletons of the three biggest non-extinct animals [47]. The exhibition is composed of 28 skeletons, 8 fossils, 47 life-sized and scale models, and 9 thematic areas with horizontal information boards. During the research for every exhibit a sheet was compiled reporting inventory indentation, specimen's dimensions and position, year and cost of acquisition (Fig. 3). The data include photographical report, IUCN Red List classification and specimens' photosensitivity. The Gallery has a rectangular plan, measuring 110 × 7 m, with a floor area of 699 m^2 and a net volume of 3426 m^3, it is the largest exhibition space of the entire Museum. It is organized in 21 bays, divided by brick columns. To each bay corresponds a full-height window on both north and south oriented façades. There are 42 such windows and a large arched one facing west. The ratio of window to floor area is 67 %. Each window consists of a 10 mm thick float glass with a visible transmittance of 0.89 and 2 mullions formed by 3 tempered glass (8 + 10 + 8 mm) with a visible transmittance of 0.75. There is a UVB filter on the arched window. The gable roof is formed by the original wooden beams and brick roof tiles. When the Gallery was converted into an exhibition space, steel beams and steel grates were added on the eaves, however they are not airtight, so there are great thermal changes during the year. The predominant source of light is daylight even though there is artificial lighting, its usage is limited to the winter evening hours when the sun sets before the museum closes. The artificial lighting system comprehends 22 halogen spotlights and 15 LED luminaries.

Italian Normative state of the art

Regarding exhibit's conservation in Italy designers can refer to the Decree of the Minister for Cultural Heritage and Activities [17], 'Guideline on the technical-scientific criteria and on the management and development standards of museums' (May 2001), that replaced the Italian technical standard UNI 10,819 [16], 'Works of art of historical importance–Ambient conditions or the conservation–Measurement and analysis' (July 1999). Italian and international standards for conservation vary depending on the photosensitivity of the exhibits (for a brief review of the normative state of the art in Italy, see also the Supplementary Materials). In the case study, for bone exhibits, the conservation limit values indicated by [17] are: $E_{max} = 150$ lx and LO = 0.5 Mlx hours/year (see Supplementary Materials). Regarding the visual

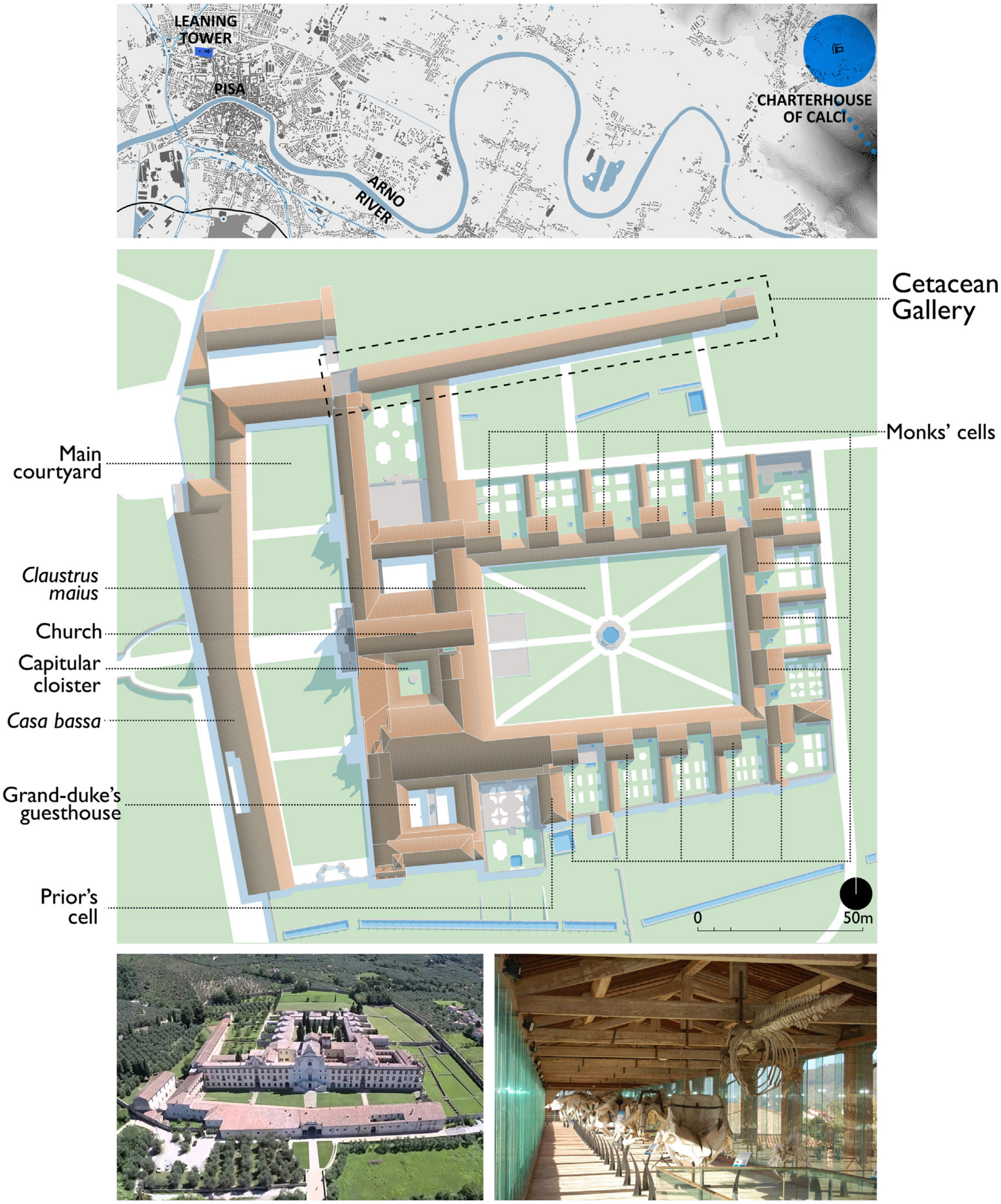


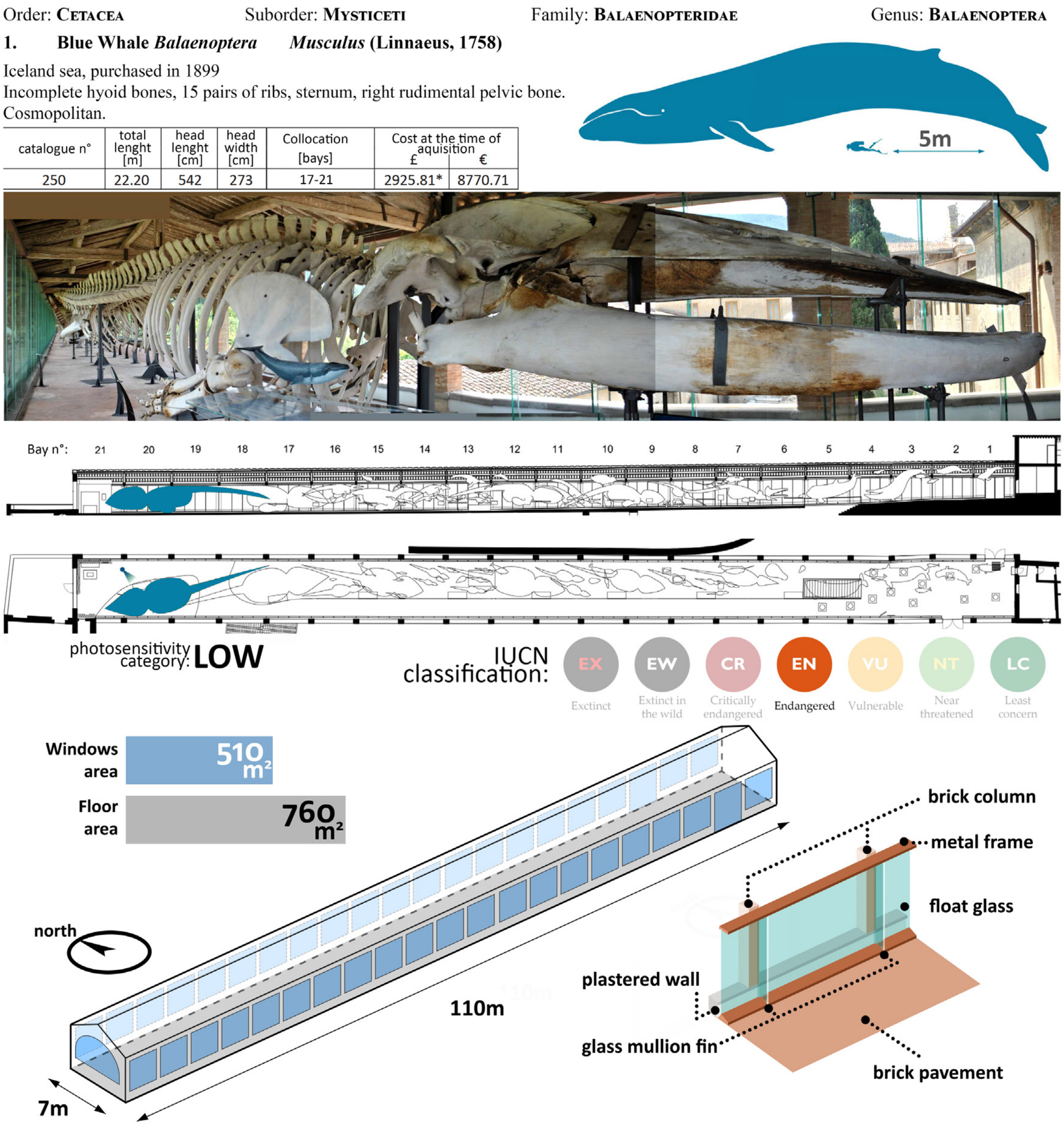
Fig. 2. Monumental Charterhouse of Calci: (top) Territorial analysis; (center) Planimetric view; (bottom left) Aerial view; (bottom right) Cetacean Gallery. The graphic elaborations (top and center) were made by the Authors, while the photos at the bottom are taken by the Museum website (rearranged by [51]).

comfort, requirements are set by the aforementioned international standards [33,34].

Setting the model

D. modelling of the cetacean gallery

The Gallery was modelled with Rhinoceros, on account of its direct interaction with Honeybee+ and Ladybug, and then imported in Grasshopper. "Ladybug allows to import climatic data into Grasshopper while Honeybee + connects Grasshopper to four validated simulation engines, specifically, Energy Plus, Radiance, Daysim and OpenStudio, which evaluate building energy consumption, comfort, and daylighting" [52]. The model (Fig. 4) is based on architectural survey conducted by the University of Pisa. Fig. 4 (bottom) shows the step used to assign the glass-material properties to the modelled geometries. The four components, Fig. 4 (bottom), allow users to choose from a material library or to define custom settings, considering the Gallery's peculiarity, the second option was chosen, therefore materials were defined based on elements' colour, roughness and specularity through Colour-picker-for-Radiance [53] (Table 1). The reflectance was estimated using the RAL colour fan method. The model was geo-referenced using Ladybug for climate-based data assignment. The climate data used for annual simulations were recorded by the Pisa weather-station between 1982 and 1997 [54].



Order: **Cetacea** Suborder: **Mysticeti** Family: **Balaenopteridae** Genus: **Balaenoptera**

1. Blue Whale *Balaenoptera* *Musculus* (Linnaeus, 1758)

Iceland sea, purchased in 1899

Incomplete hyoid bones, 15 pairs of ribs, sternum, right rudimental pelvic bone.

Cosmopolitan.

catalogue n°	total lenght [m]	head lenght [cm]	head width [cm]	Collocation [bays]	Cost at the time of aquisition £	€
250	22.20	542	273	17-21	2925.81*	8770.71

Fig. 3. Cetacean Gallery: (top) Exhibit's data sheet; (bottom) Case study geometry.

Table 1

Geometries' characteristics per material.

	Windows (panels)	Windows (fins)	Tiled Floor	Plastered Walls	Tiled ceiling	Wooden beams	Metal frame	Metal beams
R reflectance	0.75	0.89	0.356	0.364	0.8	0.32	0.34	0.295
G reflectance	0.75	0.89	0.269	0.155	0.731	0.254	0.126	0.312
B reflectance	0.75	0.89	0.225	0.097	0.708	0.232	0.103	0.395
Specularity	–	–	0	0	0	0	0.3	0.3
Roughness	–	–	0	0	0.095	0.2	0.2	0.2
Average diffuse transmittance	0.75	0.89	–	–	–	–	–	–
Average diffuse reflectance	1.52	1.52	0.289	0.206	0.747	0.27	–	–

Definition of the grid for the analyses and the on-site measurements

Through *Honeybee_Generate-test-points* two kind of measurement grids were defined: one horizontal (Fig. 5) and two verticals. The horizontal one is composed of 285 points, spaced 1.75 × 1.5 m, placed 0.80 m above floor level (the same height of the horizontal information boards of the thematic areas). The vertical ones are composed 124 points (6 points per bay for bays 1–20, and 4 points for bay 21) as large as the windows. The vertical grids correspond to the imaginary dividing line between the exhibits and the passing area of visitors. The division corresponds with the alignment of points 8–227 (Fig. 5) for bays 1–18, and it corresponds with the alignment of points 54 and 60 (Fig. 5) for the last three bays. The first grid is used for analyses in step 7 whereas the second ones are used for analysis in step 8. Reduced versions of these grids (with lower number of points) will be used for on-site measurements in step 9.

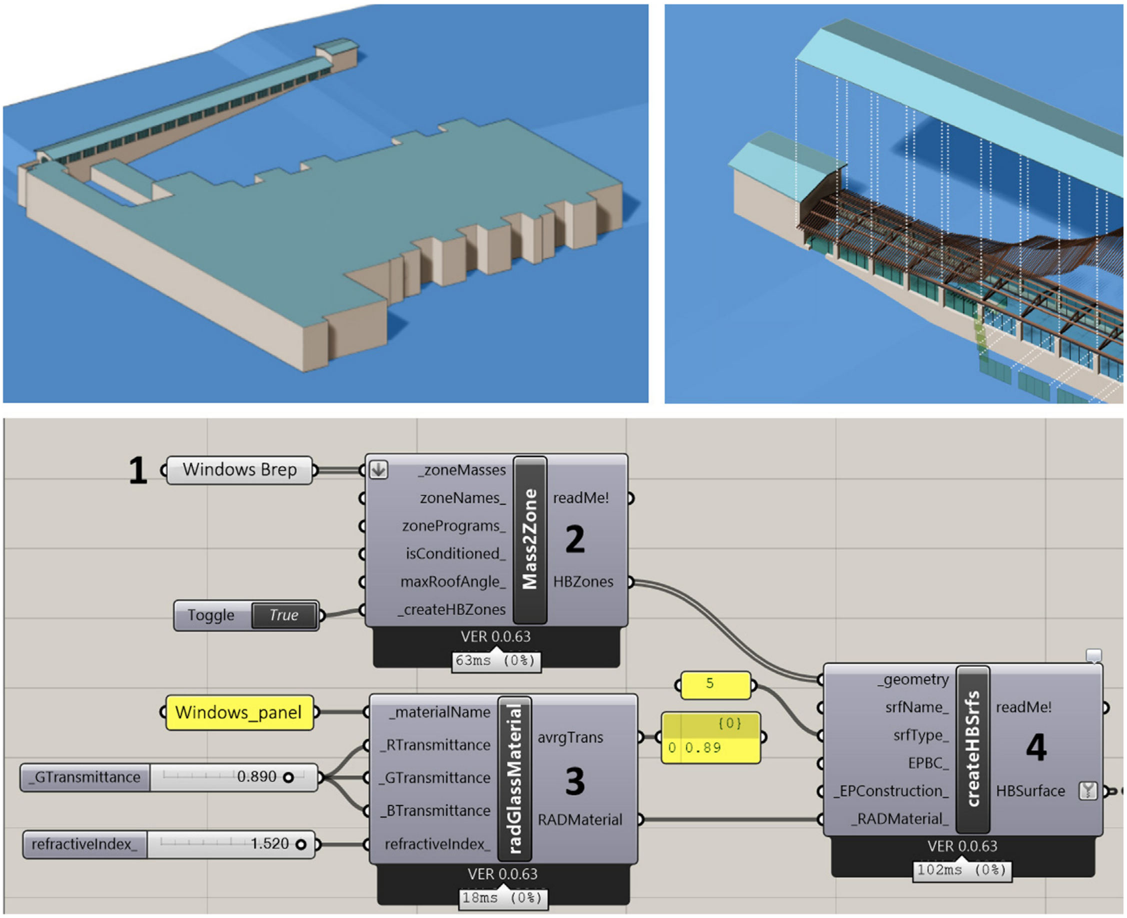


Fig. 4. Cetacean Gallery: (top left) 3D model; (top right) Exploded view; (bottom) Glass material definition: component 1, *Windows_Brep*, imports *Rhinoceros* geometries into *Grasshopper*; comp. 2, *Honeybee_Mass2Zone*, converts them in *Honeybee_zones*; comp. 3, *Honeybee_Radiance-Glass-Material*, defines the material properties; comp. 4, *Honeybee_Create Honeybee Surfaces*, assigns the material properties to the geometries.

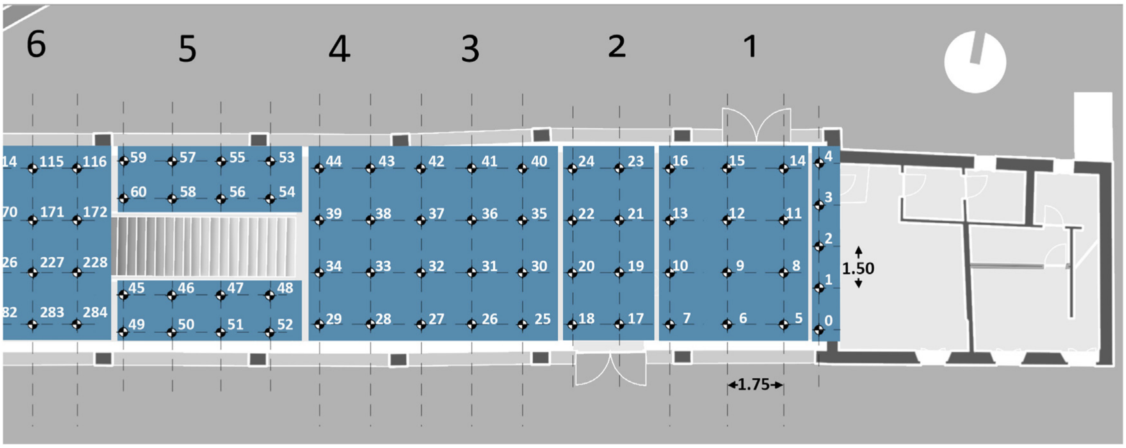


Fig. 5. Cetacean Gallery: Horizontal grid with measurement points (bays 1 to 5).

Analysis phase

Choice of the metrics for the simulations

As the DF approach is too simplistic, the novel procedure uses DDM. For case study the analysis period covers the entire year, thus, it was necessary to calculate 2’496’600 illuminance values for each metric (285 grid points per 8760 hours). For glare evaluation in [33] it is proposed to use Unified Glare Rating (UGR) whilst [34] suggests using the Daylight Glare Probability (DGP), the choice between the index depends on the light sources. In this research DGP was used on account of UGR not being applicable to this case, and considering that DGP is the most robust index for evaluating glare from daylight [55]. To be rigorous, DGP has been developed to evaluate glare in office-like environments. Nevertheless, it was applied in the case study (a museum), considering that glare in the Cetacean Gallery is not due to potential reflections on the artworks. Glare is evaluated from the visitors’ point-of-view: looking ahead towards a window (which it is similar to an office-like tasks).

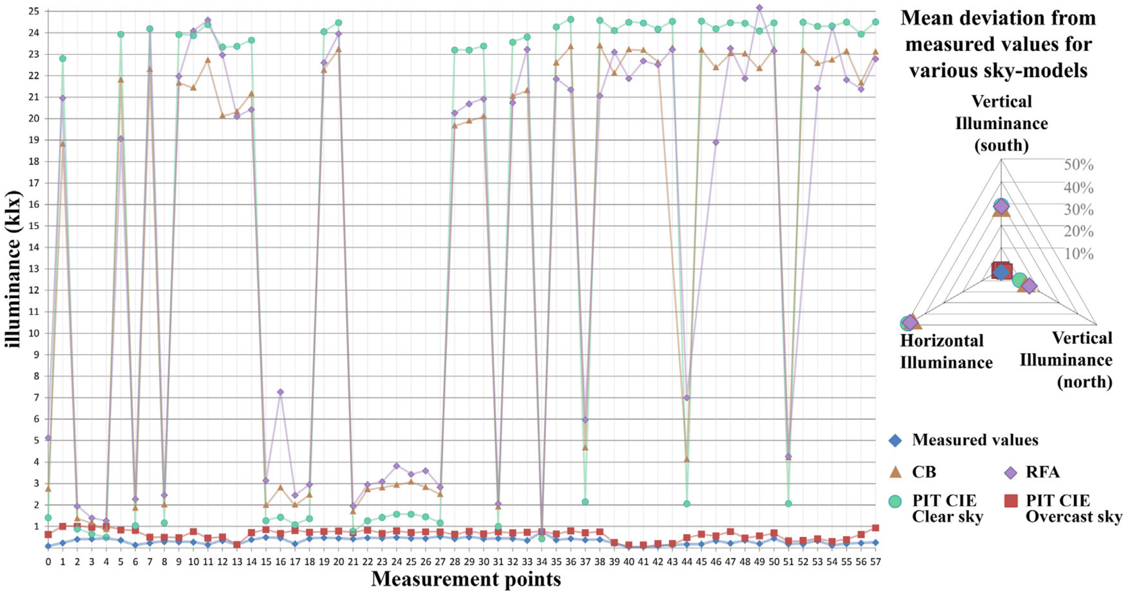


Fig. 6. Simulated and measured values confrontation: (left) Horizontal illuminance; (right) Mean deviation from measured values for various sky models.

Running the analysis focused on the exhibits

Regarding cultural exhibits, conservation is fundamental. In order to accurately calculate E_{max} and LO annual analyses with climate-based data were run. The analyses period corresponded with the entire year (from January the 1st to December the 31st from 00:00 to 23:59), as currently exhibits are exposed to daylight every day since the sun rises until it sets.

On-site measurements to validate simulation predictions

In order to verify the accuracy of the predictions, simulation results were compared to on-site measurements. On-site measurements can be considered as PIT values; therefore, they were compared to PIT results. In *Grasshopper* the *Honeybee+_Hourly Values* component can be used to read PIT values from climate-based annual analyses (RFA, read from annual). In addition, using *Honeybee+_Climate-based sky* and *Honeybee+_CIE standard sky* ulterior PIT analyses with CIE overcast sky, CIE clear sky and climate-based sky (CB) were run. The results were compared to the RFA values and the measurements. Measures were conducted using a Delta Ohm 2102.2 photoradiometer equipped with LP 471 PHOT probe. The probe range is 0 lx–20000 lx, with a resolution of 1 lx and a linearity deviation lower than 1%. Considering the time management operative issues during the measurement process, the comparison did not cover all the points of the simulation grids. It was decided to take one measure every five simulation grid points, the complete grid can be consulted in the Data in Brief article [56]. A set of 58 measurement points was used for the comparison. Both horizontal and vertical illuminance were measured on each point. Vertical illuminance was measured twice: both in north and south directions in accordance with the windows orientations. Measures were performed on December the 6th, from 10:25 to 12:25. The comparison of the results (Fig. 6) shows that model predictions are reliable. More in depth confrontations are shown in the Data in Brief article [56]. It should be noticed that the best fit surprisingly does not occur for climate-based values. That is due to the simulation algorithms. Climate-based analyses rely on the TMY to define the most probable sky condition for a certain date and hour. However, the TMY is a statistical elaboration, therefore it involves a certain degree of uncertainty. While performing climate-based analyses, it implicitly accepted that the TMY is the best representation of the actual sky conditions for a certain site, but that does not imply an actual correspondence. As a matter of fact, even if the CB analyses should have been the most reliable [57], they do not match the measurement results. Instead a strong trend of affinity between RFA, CB and PIT CIE Clear values can be noticed (Fig. 6). That is due to clear sky being the most probable sky condition for this date and hour in the TMY. However, on December the 6th, when measures were performed, the sky condition was overcast. The simulation results under the overcast sky conditions fit almost perfectly with the measurements (Fig. 6). This fact pointed out the importance of measurement campaigns, as exclusively relying on simulations can lead to errors. Nevertheless, simulation models remain a great tool of work for designers, and if well-calibrated, can provide solid information. Fig. 6 shows that the mean differences between simulation predictions (under overcast sky condition) and on-site measurements is scarce, meaning that the model is well-calibrated. Therefore, simulation predictions are a reliable base for analysing potential interventions.

Simulations' results and discussion

Overall lighting conditions

The simulations show that the Gallery is over-lit (Scenery 0 in Tables 2, 3 and 4). Night-time hours compose half of the analysis period, so "DLA = 47 %" means that in the Gallery daylight provides more than 300 lx for almost every daytime hour of the year. "UDI > 2000 = 37 %" means that illuminance is mostly higher than 2000 lx during this period. Those lighting levels indicates serious danger for the exhibits. For what concerns visitors' comfort UDI central area indicates that the Gallery is perceived as well-lit just for the 13 % of the year. DGP was calculated in bay 11 at 1.60 m height from floor level on equinoxes and solstices. This height corresponds with the average male and female eye height [58]. The chosen point represents a common setup inside the Cetacean Gallery as it is placed in the middle of visitors' passing area, at the centre of the Gallery. From this position, facing north both exhibits and a thematic area can be seen; facing south the exterior context can be seen instead. Such characteristics represents a typical situation of the actual visiting experiences, as they remain almost constant throughout all the Gallery. DGP analyses were repeated both in north and south directions. Results (Fig. 7) showed that the phenomenon occurs 57 % of times for south-oriented windows on

Table 2
Exposure sceneries.

Scenery	Period	Time interval	Scenery	Period	Time interval
0 (current)	01/01–12/31	00:00–23:59	8	01/05–31/05	08:00–20:00
1	01/01–12/31	08:00–20:00	9	01/06–30/06	08:00–20:00
2	01/01–12/31	09:00–11:00	10	01/07–31/07	08:00–20:00
3	01/01–12/31	15:00–17:00	11	01/08–31/08	08:00–20:00
4	01/01–31/01	08:00–20:00	12	01/09–30/09	08:00–20:00
5	01/02–28/02	08:00–20:00	13	01/10–31/10	08:00–20:00
6	01/03–31/03	08:00–20:00	14	01/11–31/11	08:00–20:00
7	01/04–30/04	08:00–20:00	15	01/12–31/12	08:00–20:00

Table 3
Mean dynamic metrics values for various annual analysis periods.

Scenery	DLA	cDA	UDI < 100	100<UDI<2000	UDI > 2000	sDA
0 (current)	47 %	49 %	50 %	13 %	37 %	0%
1	82%	85 %	14 %	17 %	69 %	100 %
2	99 %	100 %	0%	15 %	85 %	100 %
3	94%	97 %	1%	21 %	78 %	100 %

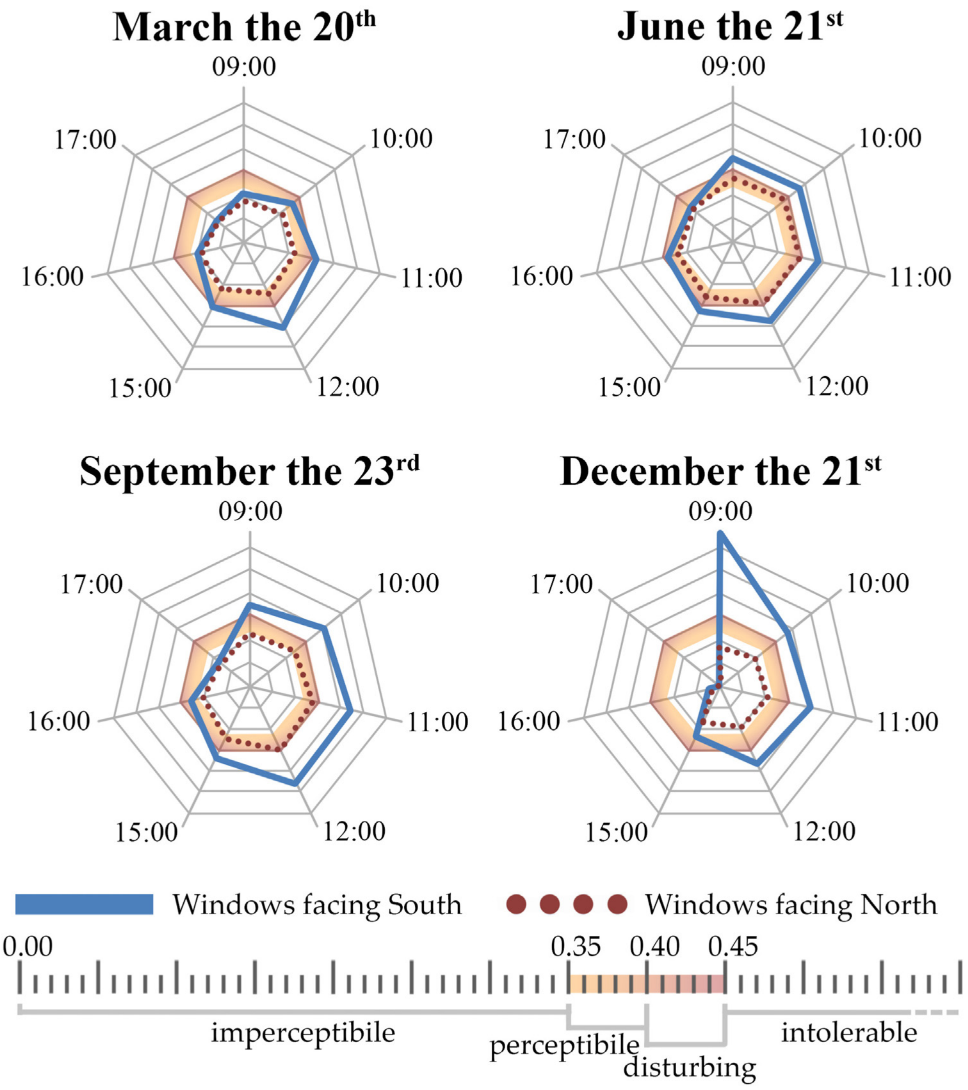


Fig. 7. DGP analysis results (DGP values rise with the radius from the centre to the perimeter).

20th March (DGP = 0.41, disturbing, at 10:00; DGP > 0.45 intolerable, from 11:00 to 15:00) and 29 % of the times for the north-oriented ones. On 21st June the phenomenon always occurs (intolerable from 9:00 to 15:00, disturbing at 16:00 and perceptible at 17:00) for south-oriented windows, while it was perceivable 86 % of times (disturbing from 9:00 to 11:00 and at 15:00, intolerable at 12:00 and perceptible at 16:00) for the north-oriented ones. Obviously, glare occurrence depends on the position of the sun in the sky:

Table 4
Mean annual luminous exposure (LO) and deviation from the conservation standard.

Exposure scenery	Current windows				More performing windows			
	LO (Mlx h/year)		Mean deviation		LO (Mlx h/year)		Mean deviation	
	facing north	facing south	facing north	facing south	facing north	facing south	facing north	facing south
0 (current)	12.7	27.2	+24.4	+53.4	8.99	19.3	+17.0	+37.5
1	11.8	26.0	+22.7	+51.0	8.37	18.4	+15.7	+35.8
2	4.06	10.7	+7.12	+20.4	2.87	7.51	+4.73	+14.0
3	2.42	3.31	+3.84	+5.61	1.71	2.41	+2.42	+3.82
4	0.61	2.49	+0.21	+3.99	0.42	1.78	−0.15	+2.56
5	0.77	2.65	+0.54	+4.30	0.54	1.91	+0.09	+2.82
6	0.99	2.13	+0.98	+3.26	0.70	1.50	+0.40	+2.01
7	1.06	1.74	+1.13	+2.47	0.75	1.23	+0.51	+1.46
8	1.30	1.80	+1.61	+2.60	0.92	1.28	+0.85	+1.56
9	1.39	1.77	+1.77	+2.54	0.99	1.26	+0.97	+1.53
10	1.38	1.79	+1.75	+2.57	0.98	1.27	+0.96	+1.55
11	1.25	1.88	+1.50	+2.77	0.88	1.33	+0.76	+1.67
12	0.99	1.90	+0.99	+2.80	0.70	1.35	+0.40	+1.69
13	0.89	2.63	+0.77	+4.26	0.63	1.88	+0.25	+2.75
14	0.63	2.55	+0.26	+4.11	0.44	1.81	−0.12	+2.63
15	0.59	2.61	+0.18	+4.21	0.41	1.84	−0.18	+2.68

during winter its elevation is smaller, therefore glare occurs the morning hours (intolerable till noon). Hence visitors are likely to be disturbed by glare during over all the year. In conclusion, currently the Cetacean Gallery's daylighting conditions are inadequate to house exhibitions, neither in conservation nor in visitors-comfort terms.

Exhibits conservation

The simulations show that under the current exposure conditions (Scenery 0 in Table 2, exhibits exposed in every daylit-hour of the year) the LO greatly surpasses the national and international standards (Scenery 0 in Table 4). LO reaches 12.7 Mlx h/year for the north oriented windows and 27.2 Mlx h/year for the south oriented ones (Table 4). Exhibits have been continuously receiving damage by light since their settlement in the Gallery.

Possible future interventions

The application of the procedure demonstrated that the Gallery' current configuration is inadequate to house artwork exhibitions due to uncontrolled and high amount of daylight. As light damage is cumulative and irreversible, exhibits' conservation issues need to be solved, or the collection should be moved. The operation is not simple and it needs to consider a variety of factors (e.g. economic aspects and visitors' preferences) as well as the exhibits' conservation; an in-depth multidisciplinary study is needed. Such a study goes beyond the proposed procedure; however, the obtained data can be used to simulate potential interventions. This would provide a preliminary evaluation. Based on the pros and cons of the preliminary scenarios, designers can decide which intervention is worthier of ulterior in-depth analyses, or even decide to evaluate different courses of action. In the Cetacean Gallery four courses of action were analysed: *a*) Exposure time reduction and substitution of current windows with more performing ones; *b*) Sensor-controlled automatic shades installation; *c*) Total shading of daylight and realization of an artificial lighting system (maintaining 150 lx constantly); *d*) Shading devices placement to reduce the amount of daylight entering the space. Simulations were run to execute each action and to figure out the daylight performance.

Action (a): Exposure time reduction and windows improvement

As first attempt 15 additional sceneries were analysed to evaluate how diminishing the exposure time affects the results (Table 2). The exposure can be limited by shutting daylight with curtains except for specific intervals, e.g. during museum visiting hours (8:00–20:00), the morning (9:00–11:00) or the afternoon (15:00–17:00) or for just one month per year. It should be noticed that, as daylight is the only light source in the Gallery, shading the windows would mean closing the hall to visitors, as it would remain in total darkness. Simulations showed that the negative trend persisted (Table 3), meaning that daylight amount remained excessive. Parallel to exposure time variations simulations were reran implementing the windows' characteristics with a glazing system with a 99 % UV filter and a lower thermal transmittance (1.4 W/m^{2}K). The new analyses (Table 4) showed that almost none comply to the technical standards, neither changing the exposition time nor changing the windows characteristics. The only three exceptions correspond with November, December and January, when daylight-hours are at their minimum.

Action (b): Installation of sensor-controlled shades

For both the new analyses described above, E_{max} was considered in addition to LO. Simulations were repeated placing a sensor per bay, the sensor activate the shading if the illuminance surpass the threshold of 150 lx. Results show that this happens almost every daylight-hour of the year (Fig. 8, top); therefore, shadings should operate constantly (with current windows: 90.9 % of the daylit hours for the north-oriented ones and 89.6 % for south-oriented windows; with more performing windows: 88.7 % of the daylit hours for the north-oriented ones and 87.0 % for south-oriented windows). In Fig. 8 there are 8760 boxes, one for each hour of the year, in blue the hours in which shadings should operate, in yellow the few ones in which illuminance do not exceed the maximum limit. Simulations were run for all 21 bays both in north and south directions.

Action (c): Daylight total substitution with artificial lighting

Since the previous option wasn't acceptable, the renovation of the artificial lighting system was considered. If using the artificial lighting 150 lx can be maintained and never exceeded, then the Gallery could be illuminated for 9 h per day throughout all the year. Fig. 8 (bottom) is a visual representation of this concept. Obviously the daylight can be used instead of artificial lighting, if it does not exceed 150 lx.

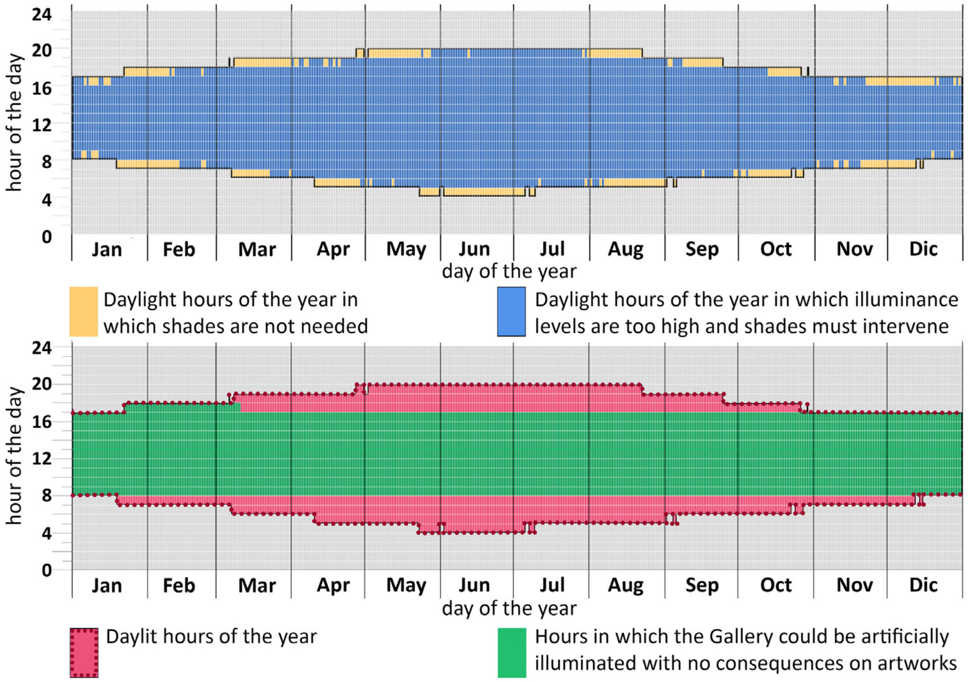


Fig. 8. Annual analysis for bay 1, north orientation: (top) Shadings intervention frequency in a year; (bottom) Hours in which the Gallery could be artificially illuminated with no consequences on artworks.

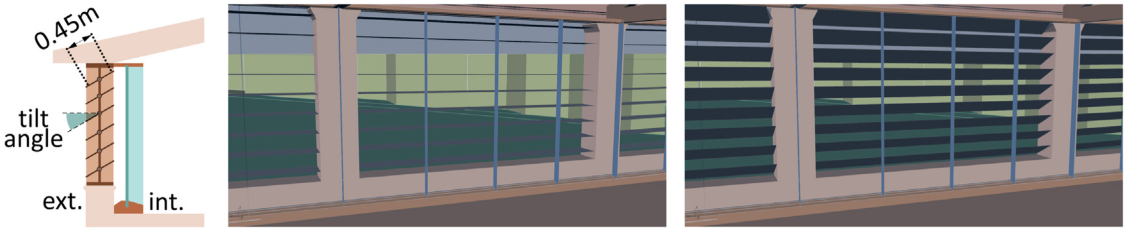


Fig. 9. Adjustable shadings: (left) Shading system; (centre) 3D model with horizontal slats; (right) 3D model with 30° tilted down slats.

Table 5
LO percentage deviation (%) from scenery 1, due to the shadings system.

Bay	Horizontal slats		Slats tilted 30° down	
	facing north	facing south	facing north	facing south
1	−27.2	−39.5	−79.3	−82.9
2	−27.0	−38.1	−76.9	−79.8
3	−27.0	−40.9	−75.6	−81.9
4	−28.1	−43.2	−74.9	−81.7
5	−28.0	−43.4	−74.4	−82.5
6	−28.8	−44.8	−75.0	−83.2
7	−30.8	−45.3	−77.5	−83.4
8	−30.8	−45.3	−77.9	−83.7
9	−30.7	−45.1	−77.1	−83.4
10	−31.0	−45.5	−77.0	−83.7
11	−30.5	−45.5	−77.6	−84.0
12	−30.1	−45.6	−76.7	−83.3
13	−31.0	−45.6	−76.4	−83.1
14	−31.0	−45.6	−75.4	−83.4
15	−30.7	−45.9	−75.6	−83.4
16	−29.8	−46.2	−75.8	−83.6
17	−30.0	−46.4	−75.3	−83.9
18	−30.4	−47.2	−76.2	−84.1
19	−35.2	−38.1	−72.3	−82.4
20	−35.1	−38.9	−72.5	−82.9
21	−36.1	−38.9	−72.8	−84.1
Mean deviation from LO of scenery 0 (current)	−30.4	−43.6	−75.8	−83.1
Mean deviation from LO set by [17]	+15.4	+28.1	+4.78	+7.79

Action (d): Reduction of the amount of daylight with shadings

Additional simulations were run to test if an adjustable shading system could reduce the daylight amount inside the Gallery. The system is formed by rectangular 0.45 m wide slats, rotatable on their longitudinal axis (Fig. 9). The system is placed external to the windows between the brick columns of each bay, it was chosen for its low reduction of the view outside and its low impact on the structure of the historical host-building, in this casuistry interventions must be sustainable, reversible and they should not impair the host-building characteristics. Two configurations were analysed: horizontal and 30° tilted down slats. Table 5 shows the mean deviation in LO between exposure scenery 1 and the two configurations. If a spot-on control system were developed, daylight could be allowed in the Gallery while reducing its amount (and thus safeguarding the exhibits). Anyway, results in Table 5 show that LO diminishes when the tilt angle augments, therefore confirming that daylight needs to be strongly reduced in order to meet the conservation requirements.

Comparison of the four courses of action

Even if more in-depth multidisciplinary studies are needed to properly evaluate the most appropriate course of action, the preliminary analysis provides the basis for some multidisciplinary considerations. For instance, if considered only economic aspects are considered, *action a* would appear the most appealing (on account of being the least expensive). However, *action a* and *b* are not recommendable, as simulations show their low efficacy in reducing LO (Table 5). Thanks to the lower transmittance of the new glazing, *action a* presents thermal advantages (thus economical and conservation-related), but it has no influence on glare control, thus not resolving visitors' visual comfort issues. On the other hand, *action b* and *c* are equally effective in diminishing glare occurrence frequency. Nevertheless, simulations show that in *action b* E_{max} is always surpassed, and therefore shadings should operate for the majority of the year, (meaning that the Gallery would be closed, on account of being in total darkness). For these reasons *action d* seems preferable, in fact it allows to maintain daylight in the Gallery while reducing its potential damage, however simulations shows that conservation requirements are not met. After an overall evaluation, the most recommendable solution is *action c*. In fact, from the economic point of view, this solution does not involve losses (due to the reduction of the opening hours of *actions a* and *b*), it does not require an investment for complex automatic or adjustable shading systems (*actions b* and *d*) or new more-performing windows (*action a*). The only costs would be those linked to the artificial lighting system design and implementation. From visitors' comfort point of view, *action c* would guarantee the absence of glare phenomena (provided a correct design of the lighting system). Finally, for what concerns the exhibits conservation, designers could establish the amount of light on the exhibits, meaning that they can directly control the annual light exposure. That allows to reduce the uncertainty of the risk of danger for the exhibits.

Conclusions

This study proposes a novel procedure to assess daylight performance in historical buildings turned into museums. The exhibits' conservation needs and the visitors' visual comfort needs are considered in the assessment. Exhibits need to receive the right amount of light: enough so that visitors can see them, but in a controlled amount (depending on the exhibit's characteristics) so that damages do not occur. Visitors in museums have two principal needs: seeing the exhibits and moving inside the space. In order to achieve that, lighting should guarantee the recognition of the space, consequently visual discomforts (such as glare) should be controlled and reduced to a minimum (if unavoidable).

The procedure uses climate-based simulations and DDM to evaluate the daylighting conditions. For the simulations climatic data are used, these data represent the most recurrent meteorological condition for a certain site. Climatic data provide a TMY that can be consulted in order to know the most recurrent illuminance level due to daylight in any hour of the year for the analysed site. Implementing the climatic data in simulations guarantees a more accurate results (both in terms of exhibits' conservation and visitors' visual comfort). This approach allows to accurately estimate E_{max} and LO, without the need of annual measurement campaigns, and glare effects. The validity of the proposed procedure is demonstrated through its application on a relevant case study: the Cetacean Gallery of the Natural History Museum of the University of Pisa, housed in the Monumental Charterhouse of Calci, near the town of Pisa.

Regarding the current daylight performance of the Gallery, climate-based simulations showed that for the majority of time the illuminance level is greater than 300 lx (DLA = 47 %). This percentage almost corresponds with every daylit hour of the year, as the climate-based simulations cover the entire year from 00:00 to 23:59. In fact from the analysis of UDI < 100 it can be found that illuminance level is lower than 100 lx for the 50 % of the analysis period (i.e. the night hours). Moreover, the UDI > 2000 analysis shows that the Gallery is greatly over-lit (UDI > 2000 = 37 %). Such high illuminance levels can induce visual discomfort problems and they can have detrimental effects on the exhibits' conservation. Glare was evaluated using DGP; it was calculated 1.60 m above floor level in the middle of the visitors passing area, changing the direction of view once north and once south (corresponding with the two fully-glazed sides of the Gallery). The analyses were repeated in equinoxes and solstices at 9:00, 10:00, 11:00, 12:00, 15:00, 16:00 and 17:00 o'clock. Results shows that glare occurs very excessively especially for south-oriented windows. Glare is perceptible ($DGP \geq 0.35$), and often intolerable ($DGP \geq 0.45$), in March (57 % for south-oriented windows, 29 % for north-oriented ones), June (100 % for south-oriented windows, 86 % for the north-oriented ones), and September (86 % for south-oriented windows, 71 % for north-oriented ones). Even though a peak at 9:00 o'clock (DGP = 1), the phenomenon gets less intense during winter (71 % for south-oriented windows and null for the north-oriented ones).

Considering the high illuminance levels, more in-depth analyses to assess the exposure levels on the exhibits were performed. Using climate-based data illuminance levels were calculated, the maximum value was compared to E_{max}, while the sum of the values was compared to LO. Both the analyses were repeated for south and north-oriented surfaces. E_{max} (150 lx for the exhibits displayed in the Gallery) was surpassed for 90 % of the analysis period on the north-oriented surfaces and for 91 % on the south-oriented ones. LO (0.5 Mlx h/year for the exhibits displayed in the Gallery) was always surpassed (12.7 Mlx h/year on north-oriented windows and 27.2 Mlx h/year on the south-oriented ones). In the case study four possible corrective interventions (*actions*) were analysed: *a*) reducing the exposure time while improving the glazing characteristic; *b*) placing sensor-controlled-shading; *c*) completely substituting daylight with artificial lighting; *d*) placing adjustable slats to diminish the amount of daylight. Simulations showed that *action a* is not advisable, as to meet LO standard for conservation, in addition to the cost of the glazing substitution, the exposure time should be limited to just one month per year (chosen among winter months). Similarly, in *action b* the shading would operate almost constantly (90 % of the daylit hours of the year). *Action d* would reduce the amount of daylight in the Gallery, and hence the risk for the artworks, but LO would be still surpassed. In addition, simulations showed that LO is inversely proportional to the tilt angle, meaning the more the view outside is shut the more LO diminish. *Action c* would be the most recommendable, as its application would allow to safely lit the exhibits for 9 h per day with an easier control of glare.

Based on the case study results, it is correct to assume that the novel procedure is applicable the majority of the historical buildings used as exhibition spaces, whenever daylight is the main light source. The novel procedure is a tool to help museums' curators assess the exposure settings. If they are found to be inadequate, the procedure can be used to compare possible corrective interventions. Clearly, the final choice requires more in-depth and multidisciplinary analyses. However, a first instance study can be performed using this procedure, as it delivers accurate information on daylight conditions, thus providing a solid base for the decision-making process.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.culher.2020.06.010.

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