Daylight Modelling of a Portuguese Baroque Library

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Abstract

The XVIII century baroque King John's Library is one of the most important buildings of the University of Coimbra, which was declared World Heritage patrimony by UNESCO in 2013. As one of the main touristic attractions, it has been object of study on the assessment of the books and furniture conservation. One of the aspects that affect their preservation is the exposure to daylight, which degrades the shelves finishing and the books covers and paper. To prevent the continuous degradation of the patrimony, this work presents a study of the indoor daylight conditions. The software Radiance is used in order to generate accurate annual illuminance maps and detailed daylight indoors images. The results show that natural lighting is a threat to most of the patrimony and must be reduced. This analysis is a contribution to determine an appropriate and comprehensive preservation strategy leaving space to further investigation within this field.

Keywords: *Daylighting simulation, Indoor light, Illuminance maps, Heritage buildings*

1 Introduction

Nowadays, according to International Council of Museums (ICOM) [1], the definition of museum can be applied to a historical library, which mostly "conserves, researches, communicates and exhibits the tangible and intangible heritage of humanity". The conservation of such patrimony can be endangered by excessive exposure to light. For this reason, sunlight must be controlled by avoiding high illuminance levels and direct exposure on books and furniture [2]. However, lighting conditions must be suitable to allow visitors to clearly view exhibited material and satisfy visual comfort [3].

As a radiant source of energy, light causes non-reversible damages in more delicate type of materials such as, colour fading or surface cracking [2], [4].The degradation process is cumulative and mainly caused by the heating expansion (physical damage) and the changing of materials molecule structure (chemical damage) of more sensible materials due to incident radiation [4]. From guidelines and standards [4]–[6] it is known that damage on materials depends on its properties, light intensity and the annual exposure time. Therefore, a proper lighting quantification and damage assessment are crucial in sparing the lifetime of heritage patrimony. Therefore, several research work have been made contributing with methodologies for proper lighting in museums and evaluate damage risks on artefacts via measurement analysis [7], numerical simulation of annual light [8] and both [9]–[11].

A correct lighting strategy should lay on several procedures to evaluate its effectiveness. As the first step, it should be done an assessment of natural daylight conditions via both measurement and numerical analysis. As said by the Illuminating Engineering Society of North America (IESNA) [5], "Calculations are useful, but mockups are most informative". This idea reinforces the importance of measurement analysis, but does not take credit to daylight modelling. The latter represents the foundation to following studies within the whole process of designing or refurbishment. In this perspective, the present study has three main objectives: i) to correctly model the historical library, taking into account most of the geometry complexity, materials and details of the building; ii) to run an annual daylight simulation using Radiance; and iii) to compare the results obtained with the recommended thresholds of guidelines and standards to evaluate which are the most endangered books and shelves.

With the given objectives stated and achieved, this research work becomes an auxiliary tool for the initial phase of refurbishment of a historical library. Some changes must be implemented in order to protect heritage patrimony, such as books and shelves. Therefore, the work is described in a cohesive structure starting with a brief introduction on the importance of conserving sensible artefacts and controlling natural light in a historical library. In Section 2, the lighting requirements for the conservation are described as well as the case study. The strategy of research was stated along with the lighting simulation tools used. The results were presented and discussed in the next Section 3. Finally, Section 4 concludes the article with the main topics highlighting the importance of preliminary studies and further research opportunities on the refurbishment or even design process.

2 Methodology

This research work has followed a work plan divided in two phases: identification of the most recent and used guidelines and standards to evaluate the most endangered artefacts; and simulation of daylight inside a case study of a historical library using Radiance software.

2.1 Lighting requirements

To ensure artefacts conservation, relevant guidelines and standards have to be satisfied in terms of light requirements. Among all the guidelines available, CEN/TS 16163:2013 [6] and IESNA 2011 [5] were used because are the most recent, complete and used nowadays. Both follow and ensure the research alignment from the previous ones within this field.

CEN/TS 16163:2013 [6] follows CIE:157 [12] directive and defines four material classes of sensitivity: highly sensitive (silk, highly fugitive colourants, most graphic art and photographic documents), moderately sensitive (most textiles, manuscripts, draws, prints, paintings and most natural history objects) , slightly sensitive (undyed leather and wood, horn, bone, ivory and some plastics) and insensitive (most metals, stone, glass, ceramic and most minerals). IESNA [4] guideline of 2009 contemplates only three materials classes: highly susceptible (textiles, cotton, natural fibers, furs, silk, writing inks, paper documents and wool), moderately susceptible (oil paintings, wood finishes, leather, textiles with stable dyes and some plastics) and least susceptible (metal, stone, glass, ceramic, most minerals). In 2011, IESNA updated the guideline by changing the light sensitivity categories' names (high, low, no) but maintaining the materials in the same category as before. In the case of historical libraries, books and bookshelves are included in the moderately sensitive category (CEN/TS 16163) and highly susceptible category (IESNA 2011). For a simpler representation of the conservation categories, another nomenclature was used: A, B, C, D and E.

In terms of light intensity, CEN/TS 16163:2013 [6] establishes that limit illuminance level of both classes (highly and moderately) is the same, 50 lux, once it is the threshold for visibility. However, IESNA 2009 [4] states that "for particularly susceptible materials, illuminance can be reduced to 35 lux and still provide for satisfactory viewing" if the brightness levels are low. Later on, IESNA 2011 [5] introduced a new specification by discretizing the recommended illuminances levels depending on the visual ages of observers. The values presented are recommended to people with visual ages between 25 and 65 years. It is also important to note that the recommended values address to maximum limits and, preferably, those should be lower.

As the damage effect of light on materials is cumulative, guidelines also recommend annual exposure limits that are calculated as the "product of illuminance levels by the total annual exposure time" [2]. In other words, the principle of reciprocity is applicable in this case meaning that the damage caused by 50 lux for 1000 h is similar to one with 500 lux for 100 h. Both recommended illuminance levels and annual exposure limits according to materials' susceptibility are presented in *Tab. 1*.

Tab. 1 *Recommended limits according to light sensitivity categories*

Guidelines / Light sensitivity		CEN/TS 16163		IESNA			
		Illuminance (lux)	Light exposure (lux·h·year^{-1})	Illuminance (lux)		Light exposure (lux·h·year^{-1})	
Highly sensitive	A	50	15 000	50[a]	50[b]	50 000[a]	150 000[b]
Moderately sensitive	B	50	150 000	200[a]	-	480 000[a]	-
Slightly sensitive	C	200	600 000	-	200[b]	-	600 000[b]
No sensitive	D	-	-	-	1000[b]	-	-
No conservation	E						

[a] IESNA 2009; [b] IESNA 2011

2.2 Case study

The baroque library started to be built in the 18th century and is located at the University yard. The city where the building is located has the following coordinates: latitude 40°12′20″ N and longitude 8°25′10″ O. The main room has a useful area rounding 550 m^2 divided in three spaces (Space 1, Space 2, Space 3) with a height of 11.50 m. Each space has a balcony surrounding the space that creates two floors with shelves (bottom floor BF and upper floor UF). The entrance door faces East with an angle of 78° E relatively to the North. Despite existing other library spaces in lower floors, the main room was the object of study since it is "richly decorated where the wood shelves are painted with gold leaves storing historical and valuable books" [13], being the most delicate room from conservation perspective. The bottom and upper floor plans (BF and UF) and bookshelf numbering inside the historical library are presented in the *Tab. 2* and *Fig. 1*.

Tab. 2 *Numbering of bookshelves*

Space	Floor	Bookshelf
1	BF	1 to 10
	UF	11 to 16
2	BF	17 to 26
	UF	27 to 32
3	BF	33 to 42
	UF	43 to 48

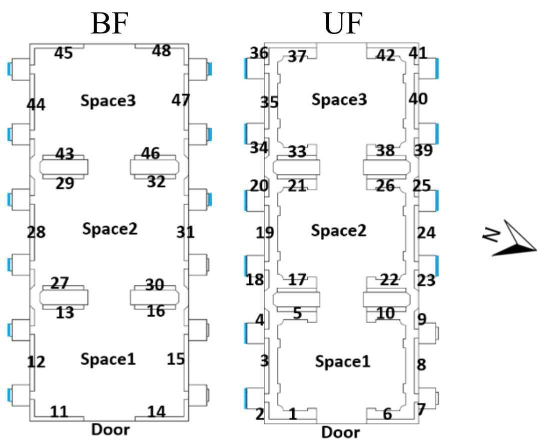

Fig. 1 *Top view of bottom floor (left) and upper floor (right)*

The historical library has 19 windows represented on *Fig. 1* by blue markers, 12 facing South (*Fig. 2)* and 7 facing North. BF and UF windows have the following dimensions: 1.00 x 1.13 m^2 and

2.40 x 5.20 m^2, respectively. All are single glazing with 0.03 m of thickness. The windows reveals were considered by a shading object with e the same shape of the windows and 0.30 m of depth.

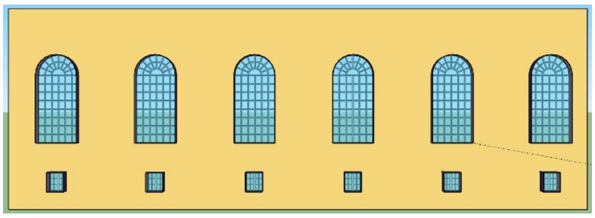

Fig. 2 *South façade - window representation*

2.3 Daylighting simulation

The simulation process was based on a sequential set of tasks. Firstly, the study required several technical visits in order to take up geometry measurements, materials information and lighting distribution inside of the historical library. All the information was needed to model and simplify the 3D geometry in SketchUp software [14]. 3D model was converted to a Radiance [15], [16] scene file using a SketchUp script, OpenStudio Plugin [17], that also runs the daylighting simulation using Radiance engine. However, OpenStudio Plugin does not support material change for Radiance simulations and due to the complexity of the geometry, the model was very heavy what required that the historical library was divided in three spaces, as represented in *Fig. 1* and *Fig. 3.*

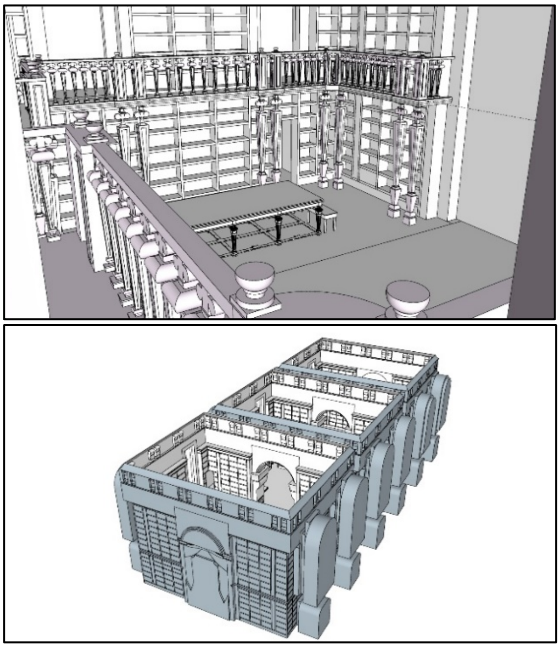

Fig. 3 *3D model of the historical library*

The three spaces were designed in SketchUp and then converted, attached and simulated using Radiance. In addition to the scene files was required to detail more information: surface properties, weather and maps of points where lux was measured (illuminance maps). The illuminance maps were produced by an auxiliary script that created a grid of points distanced approximately 0.10 m from the bookshelves' surfaces. From the annual simulation, hourly illuminance maps were produced as the output of each bookshelf. This data was processed and presented in the following Section.

3 Results and Discussion

The results of the annual daylighting simulation were processed seeking a comprehension of the most endangered shelves and books. Firstly, a global analysis was made pointing average values of illuminance levels and light exposure over one year. Furthermore, worst case scenarios were presented: season (divided by solstices and equinoxes), space, floor and section. Secondly, every bookshelf was analysed individually where the average and maximum values were calculated as well as the average of the annual light exposure of every point in a bookshelf. In addition, the worst season in terms of light exposure for each bookshelf was analysed. All values were presented in *Tab. 3* and coloured according to CEN/TS 16163 limits. Finally, the percentage of simulated points distributed according to standard conservation thresholds in terms of illuminance values and annual light exposure are presented in *Fig. 5*. Only Space 1 and Space 2 results were presented since represent the least and most endangered ones, respectively.

Statistically, the mean average value of illuminance is 156.93 lux over one year for every bookshelf during sunlight period. This value assigns a conservation class of C for the whole historical library. However, when evaluating the mean average light exposure, 725 939.69 lux·h·year^{-1} is the corresponding value over one year for every bookshelf, which exceeds the higher threshold of both standards of 600 000 lux·h·year^{-1} (class E = no conservation). Therefore, these indicators highlight the need to control and reduce natural light inside of the library in order to achieve a conservation class appropriated for books, paper and painted wood. Desirable conservation classes are different for standards: B for CEN/TS 16163 and A for IESNA 2011 but both with a 50 lux threshold. These values are only indicative and should be analysed individually for every bookshelf to really understand the class distribution in the historical library.

Generally, Winter (between 21st of December and 20th of March) is the most damaging season followed by Spring. It is understandable that during this period, the sun is in a lower position, which allows more sunrays to penetrate inside of the historical library. However, considering the weather patterns, Winter will be the season with several overcast skies what in the reality reflects in lower illuminance values inside. Moreover, sectioning the library relatively to the cardinal directions, the North section of bookshelves is the one that is the most vulnerable receiving more light during a year what is explicable by the fact that the building has windows facing South. Light rays enter directly in the library and land on the bookshelves of the North section. Contrarily, South section is the least damaged by light exposure since it is backwards from where the direct light enters what means that there is no direct light exposure of the bookshelves. East and West have similar distributions. However, when looking for the different spaces, Space 2 is the most endangered because it has more windows than the Space 1 and receive reflected rays from both Spaces 1 and 3. It has a similar light behaviour of Space 3 but the latter does not have reflected rays coming from two spaces as Space 2 has. Also, the bigger windows in UF endanger more bookshelves on this floor, which means that UF has higher risks of book degradation than BF.

Due to document restrictions the results presented on *Tab. 3* are only referring to Space 1 and 2 (least and worst situation) for one of the conservation standards, CEN/TS 16163. The colouration of used for the two indicators, annual average of illuminance level and annual average of light exposure, is according to the scale defined in Section 2.

Tab. 3 *Daylighting analysis for CEN/TS 16163 standard limits conservation. For each bookshelf of Space 1 and 2, there are presented: the respective direction, season corresponding to the largest light exposure, hour in which the maximum illuminance is achieved, annual average of the illuminance map and the annual average of light exposure.*

Overall	Worst Section	Worst Season	Most Endangered Space	Most Endangered Floor
	North	Winter	Space 2	UF

	Bookshelf	Direction	Worst Season	Peak Hour	Annual Average [lux]	Annual Average light exposure [lux·h·year^{-1}]
Space 1	1	E	Winter	13:00 19/12	352.96	1 632 774.99
	2	S	Winter	13:00 18/01	41.33	191 177.68
	3	S	Winter	12:00 19/12	51.77	239 494.62
	4	S	Winter	10:00 19/12	43.53	201 366.86
	5	W	Winter	10:00 19/12	390.00	1 804 157.49
	6	E	Winter	12:00 19/12	69.41	321 081.48
	7	N	Winter	12: 00 23/12	142.40	658 752.43
	8	N	Winter	10:00 31/12	204.49	945 985.54
	9	N	Winter	09:00 19/12	145.18	671 604.06
	10	W	Winter	09:00 18/01	75.08	347 304.18
	11	E	Winter	13:00 03/03	49.52	229 066.68
	12	S	Winter	11:00 19/12	20.70	95 749.97
	13	W	Winter	10:00 01/10	52.10	241 028.63
	14	E	Winter	12:00 30/12	85.71	396 502.63
	15	N	Winter	11:00 19/12	252.36	1 167 411.08
	16	W	Winter	11:00 30/01	92.19	426 492.17
Space 2	17	E	Winter	13:00 30/12	385.01	1 781 061.59
	18	S	Winter	13:00 31/01	121.10	560 211.85
	19	S	Spring	10:00 31/10	159.27	736 796.37
	20	S	Winter	10:00 24/02	121.24	560 836.96
	21	W	Winter	10:00 10/02	406.34	1 879 715.70
	22	E	Spring	12:00 23/12	181.94	841 677.07
	23	N	Winter	12:00 16/12	146.69	678 602.19
	24	N	Winter	10:00 30/12	209.33	968 358.97
	25	N	Winter	09:00 19/12	150.63	696 811.10
	26	W	Spring	09:00 18/01	192.54	890 684.73
	27	E	Winter	13:00 03/03	73.85	341 645.79
	28	S	Spring	11:00 18/11	112.31	519 543.88
	29	W	Winter	10:00 01/10	72.01	333 115.21
	30	E	Winter	12:00 30/12	99.19	458 843.23
	31	N	Winter	11:00 19/12	259.38	1 199 881.85
	32	W	Winter	11:00 31/01	103.12	477 011.74

As expected from the global analysis, the annual mean illuminance distribution where the mean illuminance punctually over a year, it represents better the trends when compared with annual light exposure values, which is confirmed by looking to the individual values of every bookshelf. Indeed, category C is predominant for both spaces for annual average of illuminances values. However, the most important concept to conservation, annual light exposure, decreases to class E (undefined by guidelines), which reveals an extremely high risk of degradation by light exposure regarding the type of material. The same argument results from the analysis of both graphs in *Fig. 5*, where class A and B have acceptable percentages for punctually illuminance vales but unacceptable (almost null) for annual light exposure. Thereby, the idea of increasing the control of the available natural light gets stronger.

Space 1 has lower incident light on bookshelves because there are no windows in the northern façade what also contributes to no direct radiation on southern bookshelves. In Space 2 and 3 the same does not happen what puts in danger the southern bookshelves. Both Spaces, 2 and 3, have higher illuminances values and identical light distribution.

Bookshelf 12 is the least endangered and 21 the most. Furthermore, as the three spaces are similar, the light distribution inside the library is similar to the corresponding bookshelf of every space. In other words, the example of bookshelves 5, 21 and 37 show that all have the same position relatively to each space, same western direction and same dimensions, which reflects in a very identical behaviour in terms of light exposure during the year. Identically, the same occurs with the rest of the bookshelves.

The peak hour period is between 9:00 and 13:00 depending on the bookshelf. This period corresponds to lower sun positions where rays are focusing on the bookshelves with a considerable lux intensity. Especially in days close to the Winter solstice justifying the existence of a tendency for the peak hours to occur near Winter solstice. On the other hand, occasional occurrences of peak hours distributed during Spring or Autumn are explained by the fact of those bookshelves not being exposed to direct sunlight which peak hours occur for the biggest reflection scenario (mostly in the BF that is more protected).

The results prove the need to control the light levels inside the library. This must be seen as a priority by applying several techniques and tools for the effect. Measures should cover changes in the windows' glass, a simple glass with 0.30 of thickness does has a high transmission of radiation (Visible and UV) and must be changed for a glass type that eliminates all wavelengths lower than 400 nm or at least apply UV filter stickers to the such windows. Thus, an internal diffusion element should be mounted in order to diffuse light avoiding the direct exposure to the reminiscent light that enters. Nevertheless, these measures can affect the visual conditions of the interior for visitors, even though vision perception depends mostly on contrast and not illuminance intensity. For this reason, a proper artificial lighting system should be designed to complement natural lighting. This system must have both efficiency and efficacy in terms of energy and viewing conditions. Artificial lights should not produce heat and must emit as less UV radiation as possible. Regarding the visiting period, historical libraries "should incorporate a method for completely restricting daylighting when the galleries are closed to the public" [5].

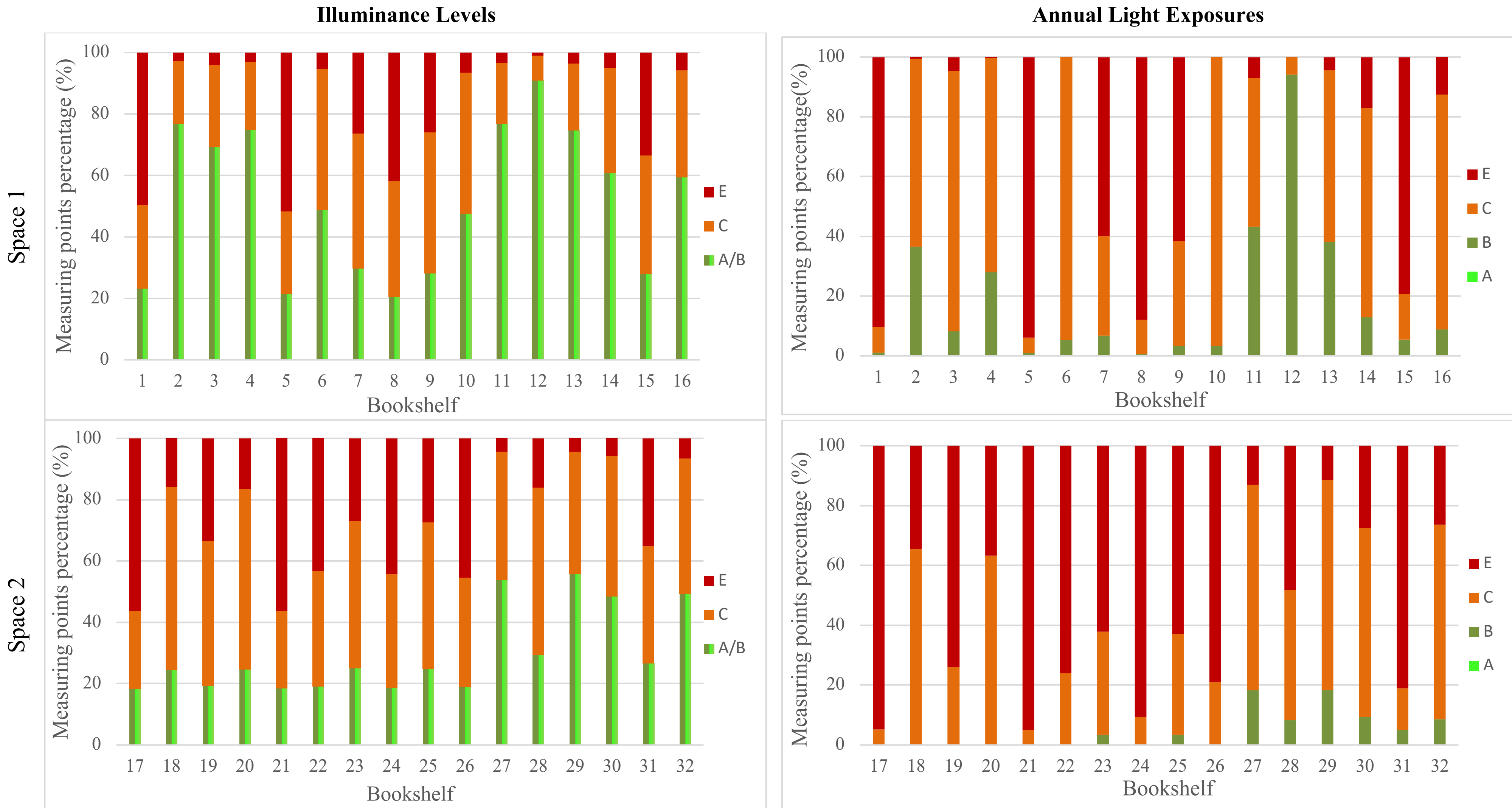

Fig. 4 *Conservation classes distribution for CEN/TS 16163 standard limits*

4 Conclusion

The present research work is a first approach in the design and model process of the 3D of a baroque library that is used for the simulation of annual daylighting conditions with Radiance software. The study represents the preliminary assessment of natural daylighting conditions and was carried out to evaluate the most endangered bookshelves seeking the proposal of preventive actions in the lighting strategy of the case study.

From the results, it was concluded that natural lighting is a threat to most of the patrimony and must be controlled by reducing the amount of ray penetration inside of the baroque library. Several measures can be applied to reduce light incidence. The aim of the study allowed to develop a model that can be used to test and evaluate the impact of these measures allowing further investigation on the topic. Moreover, Radiance is a complex software that requires a detailed modelling to achieve quantitative results bringing simulation come closer to reality. A continuously improvement of small details as well as a validation of the model leave space for future research work to be done.

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