


Article

An Approach for Lighting Calculations in Indoor Mirrored Facilities Based on Virtual Twin-Spaces

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Abstract: The presence of walls with different reflectance in indoor facilities is a problem when designing their lighting installations. This problem becomes more serious when one or more walls are mirrors, a common situation in medical, sport, educative and many other indoor facilities. Even if some programs can work with different approaches, the results are far from exact and, in many cases, designers ignore the mirrors and work by eye, with results that are frequently excessive in terms of illuminance on the working planes, glare and energy consumption and use of materials. These deviations from the intended results are due to the direct or indirect estimation of reflectance remarkably lower than 1 in the mirrored walls. In this framework of uncertainty, this work is presented with the objective of developing an intuitive theoretical model based on the consideration of virtual twin-spaces behind the mirrors. This proposal is not just an approach, but a useful tool providing the input for any kind of calculation ranging from the lumen method, used in quick pre-dimensioning, to the most complete calculations with computational methods. In addition, apart from calculating the number of luminaires and photometric parameters, the use of virtual twin-rooms also takes into account the extended field of vision of the users, including objects behind, and virtual luminaires. This advantage has no precedent in the literature up to date.

Keywords: indoor lighting; lumen method; lighting simulation; required illuminance



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1. Introduction

Indoor lighting design is a complex task due to several major issues:

- (1) Lighting installations generally operate during hours including both daytime and nighttime, which dramatically changes their conditions of work because natural light reinforces the lighting levels and/or impairs the visual task due to glare, loss of contrast and other factors. Due to the variability of the relative position of the window/sun, the levels of natural luminous flux also vary across the days, seasons, etc. All these circumstances make effective and ergonomic integration of daylight in indoor facilities a non-solved and extremely difficult task [1,2].
- (2) Indoor spaces frequently change their configuration (furniture), utility and use during their lifetimes. Due to the important role of the light reflected in the different elements of the room [3,4] and their role in the creation of shadows [5], lack of uniformity, influence on the illuminance levels on the working plane, performance of the visual task, etc., we find that the projected installations usually do not meet the needs they were initially designed for. This influence is similar to that of groves on street lighting [6], which results in frequent disagreements between projected and measured luminance/illuminance levels and uniformity.
- (3) The influence of lighting on the users of the installations goes beyond visual performance to enter complex paths intimately related to hormones, which have an impact

on psychological aspects of human life and performance (mood, anxiety, health, insomnia, etc.). This influence is especially acute in indoor lighting, whose very basis and applications are currently under deep revision [7–10] after the recent and ongoing advances in the comprehension of the non-visual paths of light in the human retina and neurological system to produce and regulate non-visual effects [11–13], so lighting of indoor spaces and the maximization of the performance there is a matter of active research.

In addition to this complexity, the intimate relationship between lighting and visual performance, with vision being the sense providing us with about 80% of our total information, makes good lighting a must for human activity. Furthermore, accurate lighting is a transversal factor whose influence on a vast variety of activities makes it a key factor to keep in mind when talking about such different targets as: decreasing violence in sports facilities [14], recovery of people after physical or psychological trauma [15], increasing industrial, farming or livestock efficiency [16,17], improving the visual ergonomics at workstations [18] and, in general, achieving truly sustainable development.

Due to this importance, the necessity of precise and reliable calculations when designing lighting installations is indisputable [19]. In the case of indoor facilities, the target of this work, precise forecasts in average illuminance, uniformity and glare allow us to accurately plan the activities to be carried out. This is necessary to predict productivity and performance in factories and other activities as well as energy consumption in most of the indoor facilities.

Furthermore, the complexity of the visual tasks to be carried out have made indoor spaces more and more complex, which makes it common to find asymmetrical rooms with very different reflective properties and high impact on the visual tasks of the users.

The use of mirrors of large dimensions occupying a whole wall is frequent in a wide variety of indoor facilities with multiple purposes: allowing the users to see themselves for aesthetical reasons, improving corporal tasks, making the room appear larger and many others. In spite of their utility, the inclusion of big mirrors presents some problems due to their very high reflectance compared with the rest of the walls in that same space ($\rho \approx 1$) and, even more important, the reflected pattern, which is a specular reflection in the case of mirrors as opposed to the Lambertian-like pattern of many standard walls. All these circumstances make it difficult to design the lighting installation of indoor facilities with precision while ensuring the required illuminance and uniformity as well as avoiding glare.

In the next sections, a sequential approach to the lighting installations in indoor mirrored spaces will be carried out, departing from one key parameter: the coefficient of utilization. Finally, a new approach to indoor lighting design in mirrored facilities, based on symmetry considerations, is presented and developed. As result, the arrangement of the luminaries in indoor spaces with one or more mirrored walls can be easily estimated with the consequent effectiveness to achieve accurate illuminance levels without oversizing the installed power.

2. Coefficient of Utilization as a Key Factor in the Design

When approaching the design of an indoor lighting installation, the designer needs some preliminary data:

- (1) The activity to be carried out.
- (2) The required average illuminance and uniformity on the working plane, as well as how to limit glare on the user's eye for this activity. These requirements are generally established in national regulations and international standards such as the European standard EN 12464-1:2021, "Light and Lighting. Lighting of Work Places. Part 1: Indoor Work Places" [20].
- (3) The characteristics of the light needed for the visual task to be performed, mainly spectral distribution, color temperature (T_c) and color rendering (R_a).
- (4) The dimensions and shape of the room.
- (5) The reflective properties of the walls to determine the coefficient of utilization C_u .

Once these data are known, the designer can make an approximate idea of the luminaries and light source to be used, as well as the power needed to achieve the requirements.

The abovementioned data are easy to know except for one factor: the coefficient of utilization of a given installation, which is defined as the ratio between the luminous flux received on the working plane and the total luminous flux emitted by all the lamps in the luminaries [21]. This coefficient is absolutely necessary to estimate the illuminance levels on the working plane.

The definition of the International Commission on Illumination (CIE) is equivalent to Equation (1):

$$C_u = \frac{\varphi_{WP}}{\sum_i \varphi_{LS-i}} \quad (1)$$

where φ_{WP} is the luminous flux reaching the working plane and φ_{LS-i} is the luminous flux emitted by the i -th light source.

C_u is easy to measure once installations are already working since the value of φ_{LS-i} is available in the datasheet, and φ_{WP} can be calculated by multiplying the average illuminance measured with a lux-meter by the total surface of the room.

However, the situation is different during the design phase, because the calculation of φ_{WP} greatly depends on our knowledge of the reflective properties of walls and ceiling.

Even if we know that a standard indoor space with white walls has a utilization factor around $C_u = 0.7$ – 0.9 , the estimation of the illuminance on the working plane, and hence the arrangement of the luminaries, that is, the positions and distances between each other and to the walls, is not easy, because in general, the reflection on the walls is not isotropic, but follows a complex pattern. If we adopt the well-known Lambertian approach, which assumes that the luminance reflected is the same in all the directions, or another finer approach [4], a reasonable guess about the illuminance on the working plane becomes more difficult in the very frequent case of rooms and spaces where not all the walls have the same reflective properties. If the difference between reflective properties of the different walls is too high, involving not only the reflectance but also the whole pattern, an average coefficient will lead to incorrect results.

This is the case of indoor spaces where one or more walls are completely mirrored (Figure 1), as in a wide variety of locations such as gyms, medical and physiotherapeutic facilities, some kinds of classrooms in schools and many others.

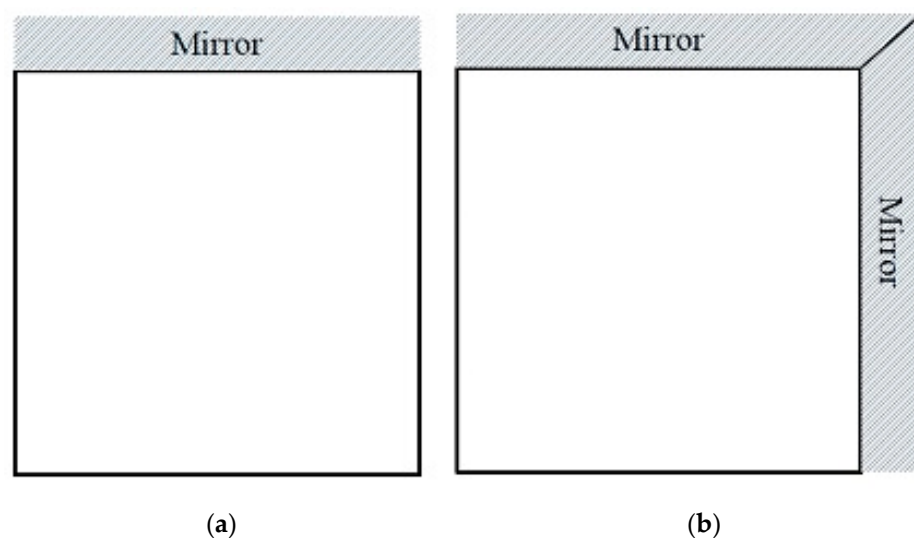


Figure 1. Room with: three similar walls and one mirrored wall (a) and two similar walls and two mirrored ones (b).

In this situation, it is not possible to use an average reflectance or any other approach to determine the C_u , because the value of this parameter depends on the whole installation:

walls, ceiling and luminaries, but the reflection pattern will greatly vary from one wall to another.

All these considerations highlight that indoor lighting calculations lose precision in mirrored spaces and that the distribution of luminaries, including their distance to the walls, must be determined in a non-exact way, with the consequent differences between planned and actual illuminance values on the working planes. These differences lead to oversized installations in terms of installed power and hence consumed energy, money, raw materials and emissions.

3. A Simple Model Based on Virtual Twin-Spaces to Design Lighting Installations in Mirrored Indoor Facilities

The proposed model will be introduced departing from a concrete example whose complexity will be progressively increased.

Let us first consider the design of the lighting installation of a rectangular room in a gym or similar indoor facility with three standard white walls and a mirrored one. Its dimensions may be 10×15 m as shown in Figure 2.

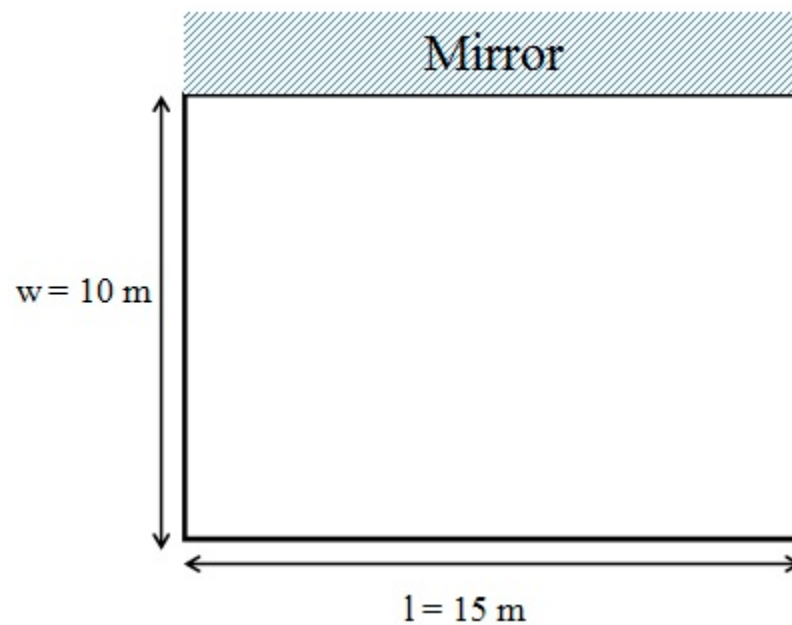


Figure 2. Rectangular 10×15 m indoor space with one completely mirrored wall.

Let us suppose standard neutral LED luminaries ($T_c = 4000$ K, $R_a = 80$, $P = 18$ W) with a luminous flux of 2000 lm and maintenance factor $C_m = 0.9$ as the best option.

According to the European Standard on lighting of sport facilities [22] and the European Standard on lighting of workplaces EN 12464-1:2021 [20], the required average illuminance (the ratio between the luminous flux received on one surface, and the area, dA , of this surface) on the floor of gym facilities is $E_m = 300$ lux, whereas the average illuminance uniformity, U_0 (the minimum measured illuminance in a grid of points divided into E_m), must be $U_m > 0.6$.

Since the walls that are not mirrored are painted with a standard white paint, it can be estimated in a good approach that the utilization coefficient, if all the walls were the same (no mirrored one), would be $C_u = 0.8$.

Departing from these data, the following assumption is proposed: if we consider the room reflected by the mirror, that is, the virtual space behind it, a new twin symmetric space arises. Its dimensions are doubled in the direction of the mirror (Figure 3). The walls of the new space would all be physically similar to the original white ones, so we can ignore the mirror as long as we suppose its reflectance is $\rho = 1$, which is not a strong requirement.

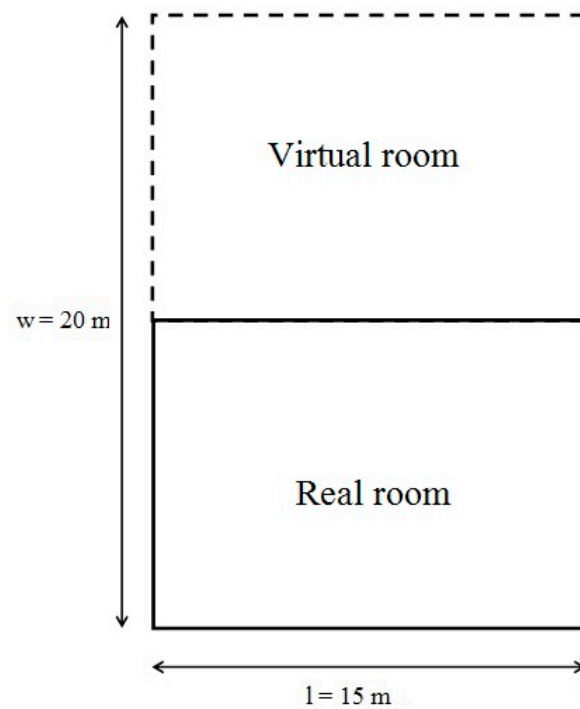


Figure 3. New room adding the virtual twin-space reflected by the mirror.

Furthermore, one virtual luminary in the virtual room corresponds to each real luminary in the real room as shown in Figure 4.



Figure 4. Gymnasium with one totally mirrored wall reflecting the real luminaries, the furniture and the opposite wall.

Departing from this model, the data of the resulting space, real and virtual twin, can be used as input in any calculation method. Since the target of this paper is demonstrating the accuracy of the virtual space in order to avoid the asymmetry introduced by the mirrors, the final installation will be calculated by the easiest and quickest method, which is a pre-dimensioning with the lumen method. In the same way, they could be used as input

by DIALux [23] or any other software providing additional parameters such as average uniformity, glare, etc.

Hence, the calculation with the lumen method (Equation (2)) is enough to estimate the necessary number of luminaries demonstrating that the assumptions of the virtual twin-space is valid.

$$E_m = \frac{N\Phi C_u C_m}{lw} \quad (2)$$

In this equation, E_m is the average illuminance required in the working plane (floor), N is the number of luminaries necessary to achieve it, Φ is the luminous flux emitted by each lamp, C_u is the coefficient of utilization, C_m is the maintenance coefficient, l is the length of the room and w is its width including both real and virtual rooms, that is, double the width of the real room.

The following examples will show how the generalities above can be used to design the lighting installations of mirrored installations of increasing complexity. Once more, the lumen method will be used since, as stated above, the target of this paper is demonstrating the accuracy of the virtual twin-space model, not the well-known accuracy of different software.

Case 1: room with one mirrored wall

According to the hypothesis, one room with one mirrored wall would give place to a new real + virtual space with double length in the mirrored wall, that is, $2 \times 10 \text{ m} = 20 \text{ m}$.

Introducing these data in Equation (2), the number of luminaries is $N = 62$. In a room with 20 m length and 15 m width, a reasonable arrangement of luminaries would be 64:8 in width by 8 in length (Figure 5). According to Equation (1), the total illuminance on the working plane $E_m = 307 \text{ lux}$, which is just 2.3% over the requirements established by EN 12464.

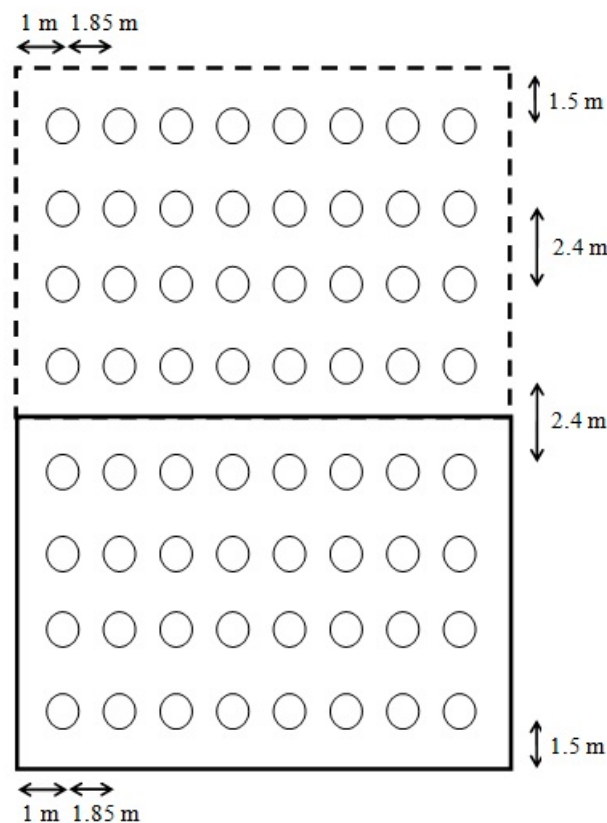


Figure 5. Arrangement of luminaries in the real + virtual room.

After obtaining this arrangement, which mixes real and virtual rooms, the following step is to erase the virtual part of the project with the result of a real room with 15 m length and width and 10 m width and 32 luminaries divided into four rows and eight columns (Figure 6). The average illuminance in the working plane is now $E_m = 307$ lux again.

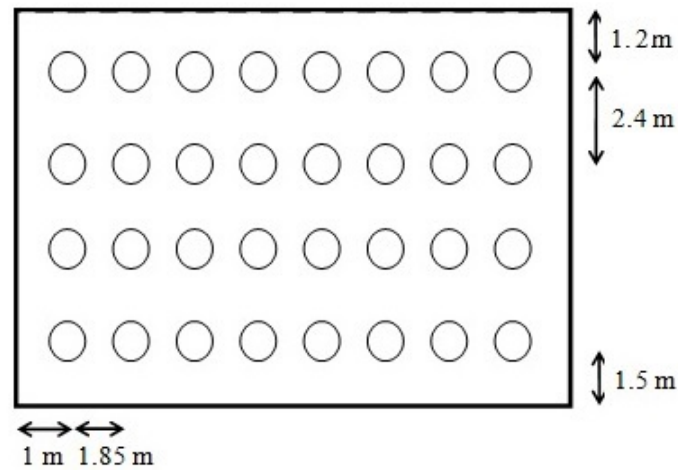


Figure 6. Arrangement of luminaries in the resulting real room.

Case 2: room with two mirrored walls

As a second and more complex example, let us consider one rectangular room with two standard white walls and two mirrored ones as shown in Figure 7.

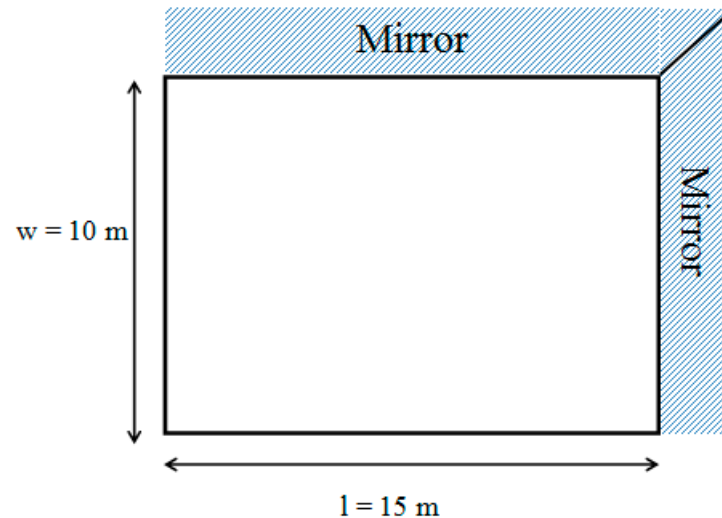


Figure 7. Rectangular 10 × 15 m indoor space with two completely mirrored walls.

Proceeding as in case 1, the dimensions are doubled behind the mirrors, which are eliminated in the resulting real+virtual rooms as shown in Figure 8:

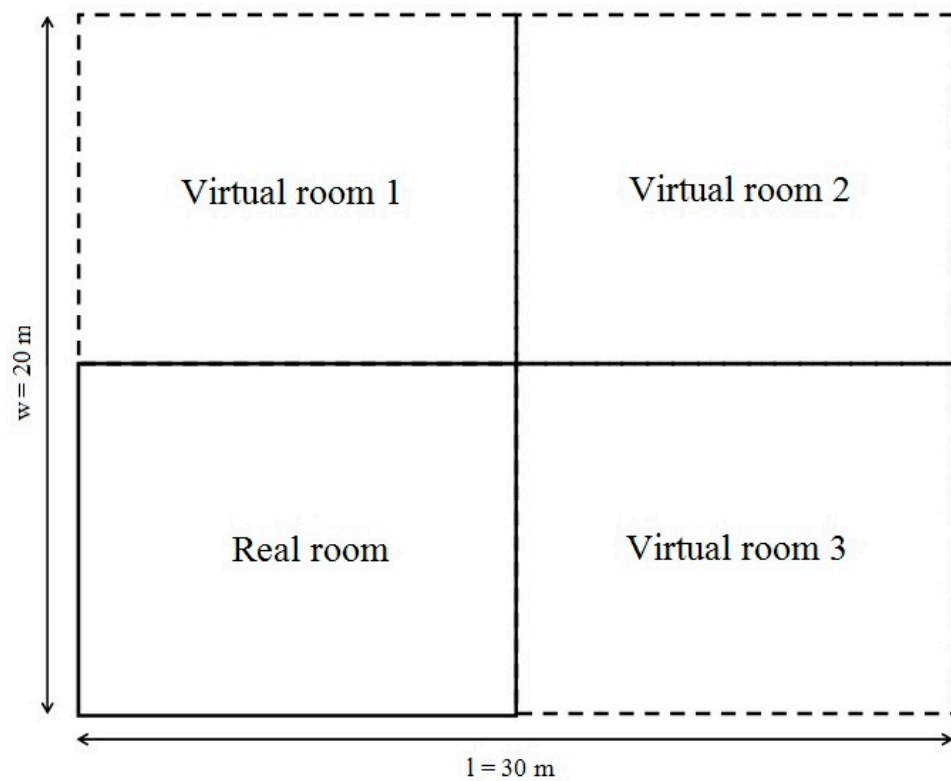


Figure 8. Real + virtual room adding the virtual spaces reflected by each mirror.

According to the proposed model, one room with two mirrored walls would give place to a new real+virtual space with double length and double width, that is, $w = 2 \times 10\text{ m} = 20\text{ m}$ and $l = 2 \times 15\text{ m} = 30\text{ m}$.

Introducing these data in Equation (2), the number of luminaries is $N = 125$. Since the number must be odd, two different possibilities can be considered:

- (1) $N = 126$: A total of 14 rows of luminaries in length and 9 in width, giving an average illuminance on the working plane $E_m = 302.4\text{ lux}$, just 0.8% above the 300 lux required by regulation EN 12464 [20].
- (2) $N = 128$: A total of 16 rows of luminaries in length and 8 in width, giving an average illuminance on the working plane $E_m = 307.2\text{ lux}$, just 2.4% above the 300 lux required by regulation EN 12464 [20].

Among these two options, $N = 128$ seems more realistic since the final step of dividing dimensions by 2 to work in the real space required odd values. Thus, the resulting installation has the same arrangement as in the case with one mirror as shown in Figure 6.

4. Discussion

The presented model allows calculations to be carried out with any tool (software or analytic methods) without assuming average reflectance or utilization coefficients. A quick glance to the above could suggest that the mirrors have no effect on the installation because the same arrangement could arise if the mirrors were not considered. Furthermore, doubling the spaces and then dividing the resulting number of luminaries could seem self-tricking since figures will finally remain unaltered.

However, the essence of the proposed model is much deeper: the rooms with mirrored walls are much more than rooms having one or more walls with higher reflectance; they are actually singular spaces where the area of sight is multiplied. The visual task is doubled and inverted, giving the users perspectives of objects behind them that they could never perceive without the mirrors.

Furthermore, it can be said that the frequent calculations assuming that the coefficient of utilization is the same independent from the presence of mirrors are unconsciously working with the present model since they are actually multiplying by two in both numerator and denominator. Otherwise, the coefficients should be higher.

In generally accepted situations where mirrored indoor spaces have been treated like standard rooms with a higher reflectance or coefficient of maintenance, this work presents them as non-standard spaces whose characteristics are included in the definitive design of the lighting installation (DIALux, pre-dimensioning methods, etc.) by taking into account the virtual twin spaces created behind the mirrors and, of course, the virtual luminaries in these spaces.

5. Conclusions

Spaces with mirrored walls are quite special and paradoxical from the perspective of visual perception because the visual field of their users does not end in the wall, but continues, virtually doubling lengths, whereas the electrical installation is physically interrupted just before reaching the wall. In addition, the reflection of the objects behind the users increases the visual load, whereas the added difficulty of a spatial inversion left to right and right to left also arises.

The proposed model, based on the assumption of twin virtual spaces, is more than a rule of thumb to estimate the number of luminaries or calculate some photometric parameters. It adds a total perspective of the visual task by considering the virtual spaces created behind the mirrors: it considers the real room and the virtual one reflected by the mirror that contains planes and objects where visual tasks will be performed. Then, the geometric output of this theoretical model is introduced as input in the standard tools for calculations.

More specifically, the symmetry consideration behind this model can be applied in both quick pre-dimensioning with the lumen method (as shown in the examples in this work), which has the limitation of not providing the average uniformity and the glare, and also in computational calculations with DIALux or similar programs that provide average illuminance, average uniformity, glare and other parameters. In this last case, it is enough to consider the virtual spaces behind the mirrors and then, for the real installation, consider only the number of luminaries and their dispersal in the real space, as done in this work. Thus, the proposed method is completely general and applicable in any situation involving mirrored walls.

As the main limitation of the model, a perfect reflectance of the mirror is adopted, which obviously is not completely true. However, in most cases they reflect almost all the luminous flux and, more importantly, create a perfect and symmetric image of each luminary, which is supposed to be real in the first step of the proposed method.

Furthermore, regular geometries of the rooms and only one type of luminary are supposed. Future research will approach non-rectangular or irregular facilities through geometric methods as well as facilities using more than one model of luminary.

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