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Multi-Disciplinary Analysis of Light Shelves Application within a Student Dormitory Refurbishment

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Abstract: The achievement of sustainable cities and communities is closely linked to an accurate design of the buildings. In this context, the transparent elements of the building envelope have a crucial role since, on one hand, they are a bottleneck in regards to heat and mass transfers and sound propagation, while, on the other hand, they must allow daylight penetration. Thus, they are responsible for occupants' thermal and visual comfort and their health. Considering passive solutions for windows, the light shelves can improve natural light penetration, reducing the lights' electricity demand and controlling windows' related thermal aspects. The scientific literature is characterized by several studies that analyze this topic, which, however, focus only on the daylight field and sometimes the energy saving for lights. Moreover, they often refer to fixed sky type for the simulations. The aim of the present study is to analyze the application of the light shelves with a multi-disciplinary approach, by means of dynamic simulations, in the EnergyPlus engine, for a whole year. A new methodological approach is presented in order to investigate the technology under different fields of interest: daylight, lighting energy, cooling and heating needs, and thermo-hygrometric comfort. The case study chosen is an existing building, a student dormitory belonging to the University of Athens. It is subject to a deep energy renovation to conform to the "nearly Zero Energy Building" target, in the frame of a European research project called Pro-GET-onE (G.A No. 723747). By means of the calibrated numerical model of this HVAC–building system, ten different configurations of light shelves have been investigated. The best solution is given by the application of an internal horizontal light shelf placed at 50 cm from the top of the window with a depth of 90 or 60 cm. It has been found that despite the reduction in electricity demand for lighting, the variation in heating and cooling needs does not always lead to a benefit.

Keywords: light shelves; energy refurbishment; daylighting; dynamic simulations; EnergyPlus

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Citation: Ruggiero, S.; Assimakopoulos, M.-N.; De Masi, R.F.; de Rossi, F.; Fotopoulou, A.; Papadaki, D.; Vanoli, G.P.; Ferrante, A. Multi-Disciplinary Analysis of Light Shelves Application within a Student Dormitory Refurbishment. *Sustainability* **2021**, *13*, 8251. https://doi.org/10.3390/su13158251

Academic Editors: Marc Alier and Mohan Lal Kolhe

Received: 5 June 2021
Accepted: 19 July 2021
Published: 23 July 2021

1. Introduction

The design of high-energy-performance building envelopes is crucial for the achievement of the Sustainable Development Goals set by the United Nations [1,2]. In particular, the transparent elements of the building envelope play a key role in the heat and mass transfer control and also in natural light penetration, sound insulation, the thermal and visual comfort of the occupants and their health, and the improvement of aesthetic features [3]. The challenge for the designers of new or refurbished buildings is to minimize cooling and heating energy need and electric demand for lights, increasing the amount of daylight entering the rooms and its uniformity, avoiding glare and overheating. This is not always possible since the objectives are conflicting with each other. For this reason, novel design techniques such as multi-objective optimization are currently being developed, aimed at window components [4,5]. Light shelves (LSs) are passive solutions for improving daylight penetration, reducing the related lights' electricity demand, and controlling windows' thermal aspects [6]. They are horizontal or inclined shelves, fixed or movable, placed on the outer or on the inner side of the windows. LSs have optical and spectral surface features able to reflect sunlight onto the inner ceiling, which is further reflected into the room environment, evenly and deeply, with the result of avoiding a dark zone in the back of the room or possible glare near the window.

There are several factors that affect the LSs' performance, such as their geometry, material type, and surface reflectance; their position and inclination; the surfaces' characteristics of the room and its layout; the outdoor climatic conditions; and the user behavior. Considering these parameters, the papers published in the main prestigious journals will be described below.

Warrier and Raphael [7] carried out an experimental campaign showing that an external horizontal light shelf can increase the illuminance in the inner zone by 21% on average. On the other hand, by means of numerical simulations, they found some design configurations of horizontal LSs for which the improvement of daylight penetration or the reduction of glare has not been observed. Claros and Soler [8] in their experimental study showed that the LS can bring the same shading effect of the overhang, providing, at the same time, more light in the back part of the analyzed room. By means of radiance software, Meresi [9] showed that the best solution for both protecting from glare and improving the daylight distribution is made of the combination of an external light shelf (0.80 m width), placed at 2.00 m from the floor, inclined by 10° and 20° (external part higher), with a reflection index of 90% and movable external semi-transparent blinds. Considering only internal LSs, in the study [10], the energy consumption and the thermal comfort have also been evaluated by means of sensitivity analysis and multi-objective optimization. It has been found that, for the west orientation, the optimum angle is 24.37° and the depth is 0.571 m with a decrease in the total energy consumption of 27.819 kWh/m^2 if five shelves are used. According to Kim et al. [11], the application of mobile LS with dimming control and user-awareness is more effective for saving lighting energy and developing pleasant environments compared to the horizontal fixed LSs and On/Off control.

Since the layout of the investigated room also affects the LS performance, the studies [12,13] propose a new concept of a room with a different ceiling shape. The light level in the back of the room can increase by 52% and 30% for curved and chamfered, respectively, compared with a flat ceiling; meanwhile, the illuminance level in the front of the room is reduced by 27% and 30% for curved and chamfered ceilings, respectively, compared to a flat ceiling. Considering bigger rooms, Mangkuto et al. [14] analyzed an open-plan room of a dental hospital, with east- and west-facing windows. By means of a genetic algorithm, the best LS configuration found is, for the east façade, external LS width 0.90 m (tilt angle 5°) and internal LS width 0.40 m, and for the west façade, external LS width 1.20 m (tilt angle 25°) and internal LS width 0.30 m. The spatial daylight autonomy at the perimeter area is increased to 89.1%. On the other hand, Xue et al. [15] investigated the influence of clerestory window structures on the performance LSs in terms of the interior illuminance level and uniformity distribution.

New studies carried out in recent years [16,17] focus on innovative configurations, such as the combination of LS and photovoltaic modules. According to [16], the optimal solution is achieved by internal LS, curved, with a height of 1.3 m from the floor, 30 cm reflector on the top of a window, and the full PV coverage, which reduces the energy consumption by more than 85%. With reference to [17], different LS-PV solutions have been tested in a full-scale testbed. The results highlighted that increasing the light shelf angle increased the amount of natural light coming into the room, and it saved lighting energy and maximized the PV generation during summer and mid-season. On the other hand, in wintertime, the installation of LS was unsuitable for saving energy compared to not installing an LS. The latter authors, in other experimental studies, proposed the use of different surfaces (prism sheets [18] or crystal face [19]) in order to study the refraction and reflection of LSs or also the perforated surface [20] for improving the LSs' wind resistance. Finally, Moon et al. [21] provide operation guidelines for a daylight dimming control system in an office with LSs:

- Under clear and partly cloudy skies, it is recommended that the photosensor should be at least partially shielded and positioned at the center of the ceiling.
- For all sky conditions, the no-shielding sensor is not recommended because the control system could generate over-dimming due to the excessive daylight detection.

Moreover, they found that:

- Under the overcast sky conditions, the effect of the energy saving is insignificant, owing to insufficient daylight.
- For the clear and partly cloudy sky conditions, the energy savings are not significantly different.

In order to develop a critical and comparative method providing a complete and exhaustive state of the art, Table 1 has been carried out, collecting detailed information of all analyzed papers. In detail, the type of the study (if experimental or numerical) with the used software is shown; the internal environment (use and geometry) and external boundary conditions (site latitude, orientation, sky type), the layout and materials of the LS, and the fields of investigation are presented. The term "thermal need" means both cooling and heating need.

From the overview in Table 1 it is evident that the studies in the literature regard above all the analysis of the application of LS in building for increasing the illuminance levels [7–9,12–15,22] and in some cases the connected reduction of the electricity for the artificial lighting [11,13,16,18,19,21,23] by using daylight control devices. However, this technology can also affect aspects related to the heating and cooling need and the indoor thermo-hygrometric comfort, since it modifies not only how the solar gains through the windows are distributed in the room, but also their penetration depth, light intensity, which disrupts the indoor thermal conditions, and the comfort sensation of the people, as stated by [10,17]. For a comprehensive analysis, in addition to daylighting illuminance level and lighting energy savings, the thermal aspects and the related comfort should also be investigated, as performed by [4]. This study, however, takes into account different window scenarios (changing geometry and materials) with only one variable regarding one configuration of LS, so it is not properly focused on the LS system.

Moreover, it can be seen that the studies often refer to fixed sky type for the simulations [9,13,14,21,23]. For the deep investigation that the authors intend to do, as discussed above, taking into account sky conditions dynamically changing over the whole year could be better [16].

Thus, in order to overcome the limitations pointed out, the aim of the present study is, in the first instance, to define a methodological approach to analyzing the LS application under different domains: daylight, lighting energy, cooling and heating needs, and thermo-hygrometric comfort. This concept has been also treated by a recent review paper [24] explaining that a multi-domain study analyzes at least two different domains, e.g., visual and thermal. EnergyPlus engine has been used: it is able not only to integrate different domains such as thermal, airflow, building services, and daylight [25] but also to run dynamic simulations for a whole year. The case study chosen is a university student dormitory placed in Athens and subject to a deep energy renovation to conform to the nZEB target in the frame of a European research project called Pro-GET-onE.

Table 1. Summary of prior light shelves studies.

Paper	Site (Latitude, Longitude)	Type of Study	Tool	Width, Depth, and Height of the Environment	Use of the Environment	Type of LSs	Orientation	Type/Model of Sky	Field of Investigation
[4]	Cairo, Egypt (30°3′ N 31°14′ E); Munich, Germany (48°8′ N 11°34′ E)	Numerical	Radiance; Daysim; EnergyPlus	4.00 × 6.50 × 3.00 m	Office	Fixed Horizontal Internal or external	South	-	• Daylighting illuminance; • thermal need; • lighting energy; • thermal comfort.
[7]	Chennai, India (13°04′ N 80°16′ E)	Experimental; numerical.	Radiance	1.40 × 2.00 × 2.00 m; 7.00 × 7.00 × 3.20 m.	Test cell	Fixed Horizontal or inclined Internal or external Aluminum or glass mirror material	All; South	Sunny and cloudy (standard CIE overcast)	• Daylighting illuminance.
[8]	Madrid, Spain (40°30′ N 3°40′ W)	Experimental	-	0.60 × 0.60 × 0.28 m (1:10 scale model)	Scale model	Fixed Horizontal Internal or external Metacrilate or glass mirror material	South	-	• Daylighting illuminance.
[9]	Athens, Greece (37°58′ N 23°43′ E)	Experimental; numerical	Radiance	7.00 × 7.00 × 3.20 m	School classroom	Fixed Horizontal or 30° inclined Internal or external with differed width	South	CIE overcast sky type or clear sky using climate data.	• Daylighting illuminance.
[10]	Mashhad, Iran (36°18′ N 59°36′ E)	Numerical	Energy plus	5.83 × 10.69 × 3.20 m; 4.53 × 6.08 × 3.20 m; 12.98 × 7.50 ×3.20 m on average	Residential	Fixed Horizontal or vertical or 30° inclined Internal with different depth	West, South, East	Dynamically weather conditions (EPW File)	• Thermal need; • lighting energy; • thermal comfort.
[11]	-	Experimental	-	6.60 × 6.60 × 2.50 m	Residential	Movable External	South	Artificial sunlight 15-day standard for each season.	• Daylighting illuminance; • lighting energy.
[12]	Jordan (31°57′ N 35°56′ E)	Numerical	Radiance	6.00 × 8. 00 × 3.25 m with curved ceiling	-	Fixed Horizontal or curved Internal or external	South	One year sky condition	• Daylighting illuminance.
[13]	Jordan (31°57′ N 35°56′ E)	Numerical; experimental	Radiance	6.00 × 8. 00 × 3.25 m with curved ceiling	-	Fixed Horizontal or curved Internal or external	South	CIE clear skies conditions	• Daylighting illuminance.

Table 1. *Cont.*

Paper	Site (Latitude, Longitude)	Type of Study	Tool	Width, Depth, and Height of the Environment	Use of the Environment	Type of LSs	Orientation	Type/Model of Sky	Field of Investigation
[14]	Bandung, Indonesia (6°55′ S 107°36′ E)	Experimental; numerical	Radiance	14.20 × 19.00 × 2.77 m	Dental hospital	Fixed Horizontal or inclined Internal or external	East, West	Overcast sky	• Daylighting illuminance.
[15]	Hong Kong, Cina (22°18′ N, 114°10′ E)	Numerical	TracePro	6.00 × 8.00 × 3.20 m	Residential	Fixed Horizontal Internal or external with aluminum sheet	South	One year sky condition	• Daylighting illuminance
[16]	Ha'il, Saudi Arabia (27°31′ N, 41°41′ E)	Numerical	Radiance	8.00 × 4.60 × 2.00 m	Office	Fixed Horizontal or curved Internal or external with different PV coverage	South	One year sky condition by climate file	• Daylighting illuminance; • lighting energy
[17]	Seoul, South Corea (37°33′ N 126°59′ E)	Experimental	-	6.60 × 4.90 × 2.50 m	Full-scale testbed	Fixed Horizontal or inclined External with PV	South	Artificial sunlight and external temperature during mid-season	• Daylighting illuminance; • thermal need
[18]	Seoul, South Corea (37°33′ N 126°59′ E)	Experimental	-	6.60 ×4.90 × 2.50 m	Full-scale testbed	Fixed Horizontal or inclined External prism sheet	South	Artificial sunlight and external temperature during mid-season	• Daylighting illuminance; • lighting energy
[19]	Seoul, South Corea (37°33′ N 126°59′ E)	Experimental	-	6.60 ×4.90 × 2.50 m	Full-scale testbed	Movable Internal and external with diffused reflection surface	South	Artificial sunlight and external temperature during mid-season	• Daylighting illuminance; • lighting energy
[20]	Seoul, South Corea (37°33′ N 126°59′ E)	Experimental	-	6.60 ×4.90 × 2.50 m	Full-scale testbed	Fixed Horizontal or inclined External with perforated surface	South	Artificial sunlight and external temperature during mid-season	• Daylighting illuminance; • lighting energy

Table 1. *Cont.*

Paper	Site (Latitude, Longitude)	Type of Study	Tool	Width, Depth, and Height of the Environment	Use of the Environment	Type of LSs	Orientation	Type/Model of Sky	Field of Investigation
[21]	Seoul, South Korea (37°33′ N 126°59′ E)	Numerical	Lightscape	5.00 × 10.00 × 3.00 m	Office	Fixed Horizontal External	South	Clear, partly cloudy, and cloudy (overcast) skies, three representative days for the sun positions in a year	• Daylighting illuminance; • lighting energy
[22]	Toronto, Canada (43°42′ N 79°20′ W)	Numerical	AGi32	15.00 ×10.00 × 3.00 m	Office	Fixed Horizontal Internal and external	South	Perez All-Weather	• Daylighting illuminance.
[23]	Jakarta, Indonesia (6°12′ S 106°49′ E)	Numerical	Dialux	36.00 × 22.85 × 3.10 m	Office	Fixed Horizontal Internal aluminum with white coating	All exposures	Overcast sky	• Daylighting illuminance; • lighting energy

2. The Case Study: A Dormitory in Athens

The student dormitory, belonging to the National and Kapodistrian University of Athens (37°58′ N 23°45′ E), is named B Building FEPA and it was built in 1986 (Figure 1a). Athens has a hot-summer Mediterranean climate, *Csa* classification according to Köppen et al. [26], with alternation between prolonged hot and dry summers and mild to cool winters with moderate rainfall.

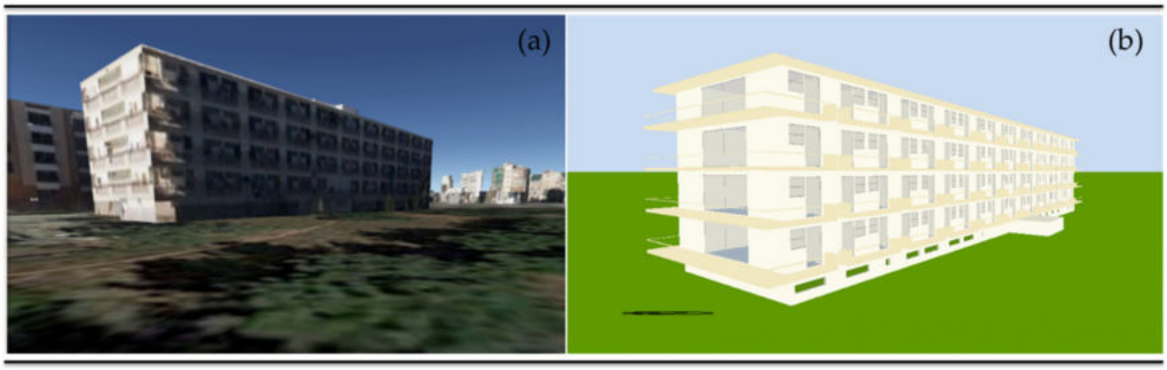


Figure 1. The real building (**a**) and the render view of the model in Design Builder (**b**).

For this HVAC–building system, a deep energy audit has been carried out by means of site inspections, energy data measurements, and interviews with the occupants, described with all details in [27]. The building structure, made of reinforced concrete, has a rectangular shape (56.6 × 15.4 m) with four floors above ground and a basement. It hosts 138 single-bed rooms for students, with a global gross building area of around 3642 m^2 and a heated floor area of about 2584 m^2. The total window to wall ratio is equal to 32%. Each floor, with an area of 725 m^2, hosts 36 student rooms, except for the ground floor, which hosts 30 rooms. External walls consist of plaster (2.5 cm) on both sides and brick (double wall without insulation). The basement is made of 3 cm of marble and 20 cm of concrete, while the roof is composed, from the outer side to the inner side, by asphalt cover (6 mm), perlite-bitumen bonded (3 cm), concrete (20 cm), and plaster (2.5 cm). Windows and glazed doors are made of single glass with an aluminum frame (5 cm width). For heating purposes, the building is equipped with two gas boilers, one with nominal power of 988.6 kW and another one with nominal power of 732.7 kW, with nominal efficiency of around 94%. The terminal systems are in-room old static radiators, 0.90 m height, without regulation.

The building, in its existing state (ES), has been modeled by means of EnergyPlus V.9 [28] and its visual interface Design Builder v. 6 [29], which provides a render view of the numerical model developed (Figure 1b). The energy outputs of the model have been compared with the energy billings referred to different years, collected during the audit phase. According to the "Whole Building Level Calibration with Monthly Data" approach of the M&V Guideline [30], the model can be considered calibrated. For instance, the error in the annual electricity consumption is about −1%, and the coefficient of variation of the root mean squared error is approximately +6%.

The building will undergo an energy renovation and seismic retrofitting within a European project that aims to demonstrate the attractiveness and the energy efficiency of a renovation strategy based on new façade additions [31]. The European project, called Pro-GET-onE, is under G.A No. 723747. In order to achieve this goal, among the various strategies designed, such as high-performance materials, home automation, and renewable sources integration, this study focuses on the installation of light shelves.

The present study is conducted for the state of project (SP) of the refurbished building. With respect to the ES, the SP is characterized by substantial geometrical, thermo-physic, and plant differences. First of all, a re-distribution of the internal spaces has been designed; in particular, the hallway is restricted in order to create larger bedrooms, and two double rooms per floor are created. Moreover, one of the Pro-GET-onE goals is to develop innovative volumetric add-ons by means of *inteGrated Efficient Technology*, namely GET. In this new configuration, most rooms (called extra-rooms in the GET system) are characterized by a net floor area of 23 m^2 and one window of 2.7 m^2 with a 0.8 m high parapet. The envelope renovation led to a significant reduction in the heating and cooling loads. Indeed, regarding the HVAC system, in the state of project, a mixed air–water system is proposed. The old radiators have been replaced with two pipe fan coil units (FCU), in each room, characterized by constant water flow and a variable-speed fan. In winter, a natural gas condensing boiler, assisted by climatic compensation, is considered, starting from the total heating design load (240 kW). For the cooling period, an air-cooled chiller (275 kW) with a screw compressor is chosen. Finally, a centralized air handling unit (AHU) is considered with duct distribution for each room. In order to ensure the required level of air quality according to the UNI 10339 standard [32], and thus according to the building's kind of use, 11 L/s per person, the AHUs will process only the external air. Regarding the operating mode:

- The heating system is turned on from 1 November to 31 March (except for Christmas holidays) with a set-point temperature of 20 °C.
- The cooling system is turned on from 15 May to 15 September (except August) with a set-point temperature of 26 °C.
- The ventilation system is available all year (except for Christmas holidays and August):
- in wintertime, from 7:00 to 11:00 and from 18:00 to 22:00;
- in summertime, from 6:00 to 8:00 and from 18:00 to 23:00.

3. Materials and Methods

For the study proposed, two representative rooms, on the west (WR) and east (ER) side of a representative floor (the third one), have been taken into account. Their layout is shown in Figure 2. Their shape, narrow and long, is suitable for the LSs application in order to illuminate the back areas.

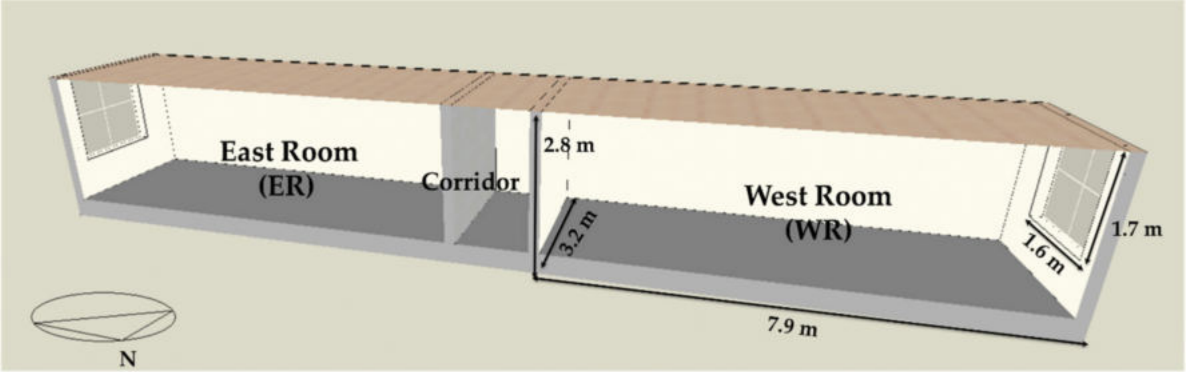


Figure 2. Internal view of investigated rooms.

As regards the SP configuration of the building envelope, only the differences with the ES are listed here. The external walls are made of cross-laminated panels (9.0 cm) insulated with mineral wool panels (7.0 cm) for an overall thickness of 0.2 m and U-value of 0.33 W/m^2 K. The windows are made of triple-clear and selective glass, filled by Argon, with a thermal transmittance of 1.00 W/m^2 K, solar factor of 0.57, and light transmission of 0.75. All other surfaces have been designed as adiabatic since they border with thermal zones with the same schedule of set-point temperature, occupation, and use of equipment. Considering the surface materials of the rooms, the light reflectivity has been set equal to 80% for the ceiling, 70% for the wall, and 20% for the floor and the ground, in accordance with [16,23].

Following the main design criteria found in the literature [6], horizontal light shelves, made of wood with a white coating, have been designed, both internal (LS_in) and external (LS_out), as shown in Figure 3. Ten different geometrical configurations have been taken into account, five on the internal and five on the external side. They are characterized by different distances from the top of the window (y) and width (x), as shown in Table 2. For instance, LS_in_30_60 is the inner LS with a distance from the top of the window of 30 cm and an overhang of 60 cm. The geometrical, spectral, and thermal features of the designed LSs are reported in Table 2. Since fixing the distance of the LSs from the top of the window, the height from the floor is also fixed and provided in the table. This is because, according to several design criteria [6], it is an important parameter to take into account for occupant wellbeing. Indeed, the LSs are usually placed above the eye level of the stand-up occupant in order to prevent the glare from their upper surface.

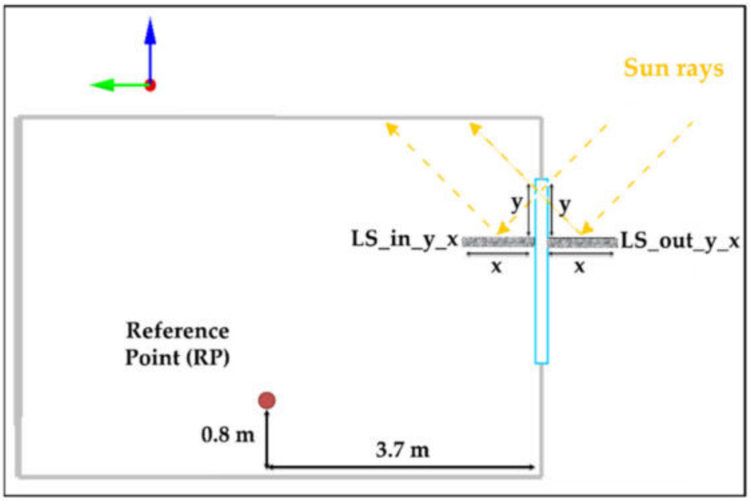


Figure 3. Cross-section view of investigated rooms.

Table 2. Main characteristics of the designed LSs.

Geometrical Features	
Height from floor	1.9 m; 2.1 m
Distance to ceiling	0.9 m; 0.7 m
Distance from the top of the window (y)	50 cm; 30 cm
Width (x)	30 cm, 60 cm, 90 cm
Thickness	0.03 m
Angle with window plane	90°
Spectral characteristics	
Thermal emissivity	0.8
Solar reflectance	0.8
Visible reflectance	0.9
Thermal characteristics	
Thermal conductivity	0.03 W/m K
Density	30 kg/m^3
Specific heat	1000 J/kg K

The lighting system is made of LED lamps equipped with presence- and illuminance-level sensors. The type of control is linear: the lights dim continuously and linearly from maximum electric power (5 W/m^2) to minimum electric power as the daylight illuminance increases. It is the "daylight-integrated lighting control system" discussed in [33]. Figure 4 depicts the illustration of the relationship between the artificial light illuminance and electricity as fractions of maximum light output and electric power, respectively. When the daylight is null, the electric power and the light output of the LED system are maximum; then, the fraction linearly decreases as the daylight illuminance increases. The minimum fraction of the electric power is the lowest power the lighting system can dim down to, and the minimum fraction of artificial light is the lowest lighting output that the system can dim down to. The lights remain at their lowest electric power with a further increase in daytime illuminance. This behavior is active every day, from 7:00 to 24:00. The reference point (RP) for the control is placed in the room's center 0.8 m from the floor (Figure 3), assuming that the student's desk is located there. The artificial lighting system, when switched on, guarantees 500 lux on the RP.

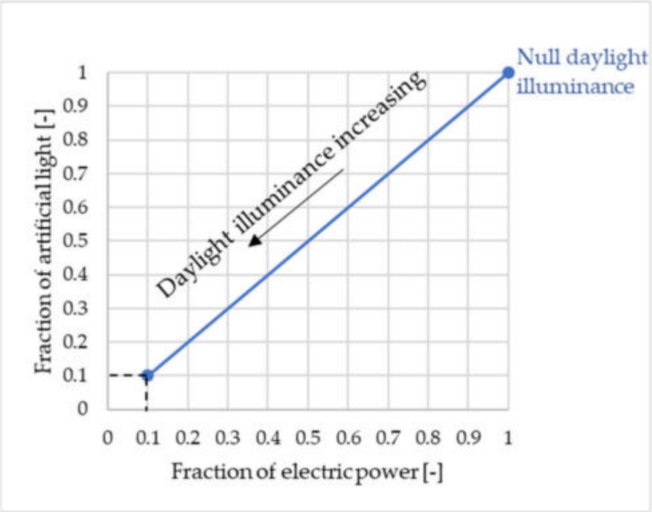


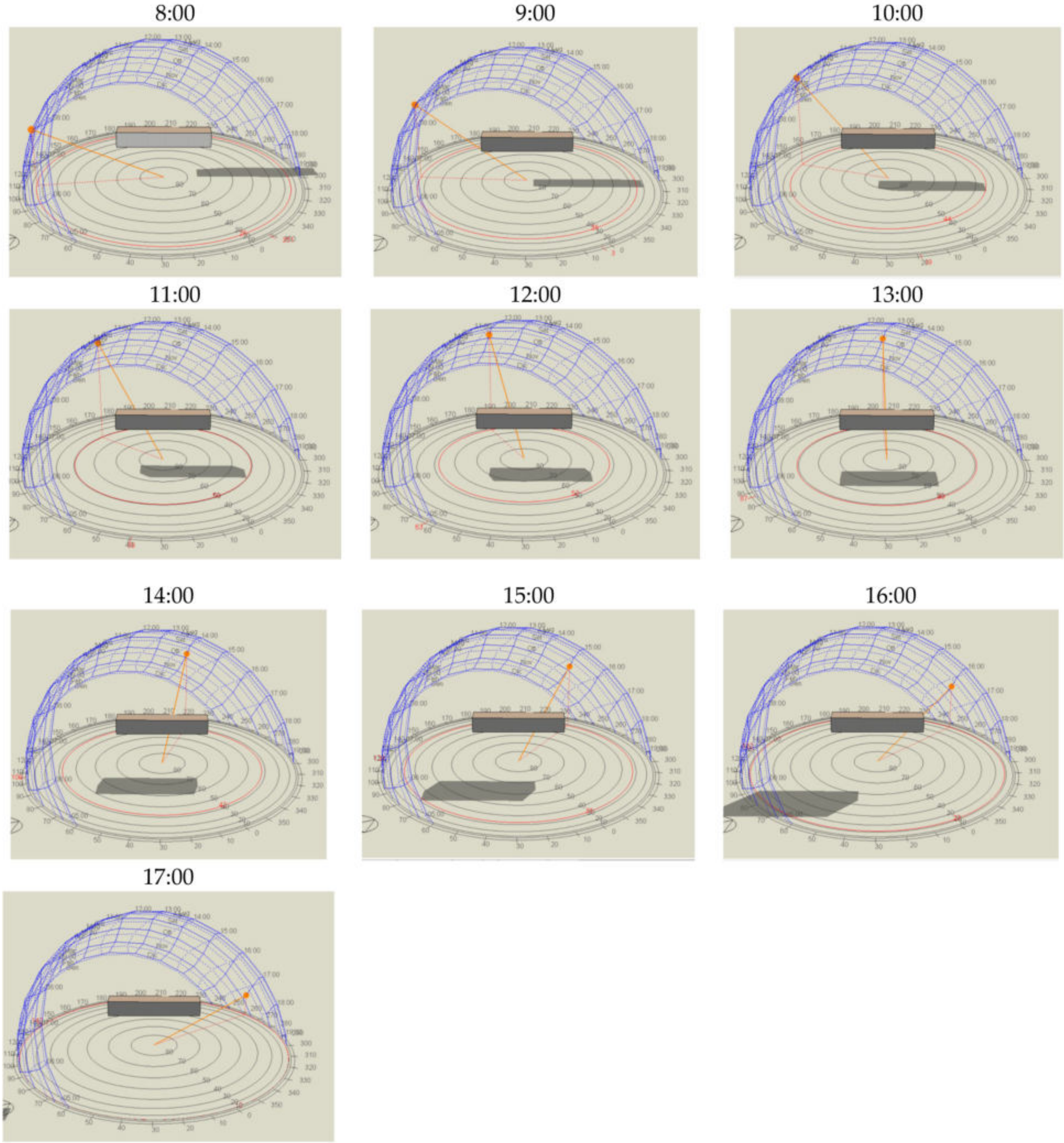
Figure 4. Continuous dimming control.

Within EnergyPlus capability, the LSs are simulated for daylighting and for the zone heat balance separately. The daylighting model used is the *SplitFlux* method, in conjunction with the *Conduction Transfer Functions* algorithm for the thermal analysis [34]. In the daylighting simulation, the inner LS is modeled in such a way that all light transmitted from the window is converted into diffuse upgoing flux. On the other hand, the outer LS is modeled as a shading surface that blocks part of the view of the ground and so it reduces the flux transmitted through the window due to diffuse ground luminance. With reference to the heat balance simulation, the internal LS is equivalent to a mass placed indoors that interacts convectively and radiatively with the zone air and other zone surfaces. For the outer LS, view factors to the sky and ground are used instead as the daylighting calculation. Briefly, by using the *SplitFlux* method, it is possible to determine the energy impact of daylighting strategies, considering the daylight availability, outdoor conditions, lighting control strategies, and window management.

A specific hourly weather data file for Athens has been used. It is called "Athens 167160 (IWEC)", available on a software website, in the section Europe WMO Region 6—Greece [28]. It defines the sky conditions throughout the year and provides all elements needed during the calculations. For instance, the hourly solar altitude and solar azimuth angles are provided, as well as the global horizontal illuminance. Moreover, also the total sky cover for each hour of the year is present in the climate file. It is the amount of sky dome in tenths covered by clouds or obscuring phenomena (0 is the minimum value, and 10 is the maximum value). It is necessary to carry out both annual and then hourly analysis in order to have a global knowledge of the LSs performance. For the hourly analysis, in this study, four representative days have been chosen:

- 13 September (autumn equinox).
- 22 December (winter solstice).
- 21 March (spring equinox).
- 21 June (summer solstice).

The outdoor sky conditions of the selected days are reported in Table 3, while the sun path during 23 September is depicted in Figure 5. The latter picture has to be considered only for daylight simulations, since for energy simulations, as already specified above, boundary conditions that allow taking into account the whole HVAC–building system have been set.



8:00 9:00 10:00

11:00 12:00 13:00

14:00 15:00 16:00

17:00

Figure 5. Sun path on 23 September.

Table 3. Solar angles and sky conditions.

Hours	Solar Altitude Angle (°)				Solar Azimuth Angle (°)				Global Horizontal Illuminance (lux)				Total Sky Cover (-)			
	21/03	21/06	23/09	22/12	21/03	21/06	23/09	22/12	21/03	21/06	23/09	22/12	21/03	21/06	23/09	22/12
1:00	−50.1	−27.4	−50.1	−72.1	337.2	346.8	343.1	322.5	0	0	0	0	0	4	2	5
2:00	−51.9	−28.5	−51.5	−74.9	6.1	4.2	8.0	15.2	0	0	0	0	0	2	2	4
3:00	−49.3	−26.5	−47.8	−68.8	24.3	17.5	29.4	51.1	0	0	0	0	1	2	2	4
4:00	−42.7	−21.5	−40.4	−58.4	43.8	31.6	47.7	72.1	0	0	0	0	2	2	2	5
5:00	−33.5	−14.3	−30.8	−46.8	58.9	43.9	61.9	84.6	0	0	0	0	4	2	2	5
6:00	−22.8	−5.3	−19.8	−35.0	70.9	54.5	73.3	94.1	0	1800	0	0	5	3	2	6
7:00	−11.3	4.8	−8.3	−23.3	81.0	63.8	83.2	102.4	800	14,100	1700	0	6	3	2	7
8:00	0.5	15.8	3.5	−12.0	90.4	72.3	92.5	110.6	9200	32,800	15,100	200	7	4	2	9
9:00	12.2	27.3	15.2	−1.3	99.8	80.4	102.0	119.3	28,300	49,400	35,300	4600	6	5	3	9
10:00	23.6	39.0	26.5	8.5	110.1	89.0	112.7	129.0	51,900	59,400	51,400	12,500	4	6	4	9
11:00	34.2	50.8	36.8	16.9	122.3	99.2	125.5	140.1	72,300	59,900	63,200	19,200	2	7	5	9
12:00	43.3	62.1	45.4	23.5	137.7	113.7	142.0	153.0	83,200	88,400	74,600	23,500	2	5	4	9
13:00	49.6	71.6	50.9	27.5	157.5	140.2	163.0	167.6	87,000	102,900	79,300	24,700	2	2	3	9
14:00	51.9	75.0	51.9	28.4	181.0	187.4	187.0	183.1	84,600	102,200	77,700	22,700	1	0	2	9
15:00	49.3	69.3	48.2	26.2	204.3	229.4	209.6	198.3	74,800	93,600	67,200	17,900	1	0	2	9
16:00	42.6	59.0	40.8	21.1	223.7	251.2	228.0	212.3	59,400	77,800	49,100	10,800	1	0	2	9
17:00	33.4	47.4	31.1	13.8	238.8	264.0	242.2	224.5	38,500	55,800	28,100	2900	1	0	1	9
18:00	22.7	35.6	20.1	4.8	250.8	273.5	253.7	235.0	16,000	32,900	8200	0	1	0	1	7
19:00	11.3	23.9	8.5	−5.4	261.0	281.9	263.5	244.3	1500	13,000	400	0	1	0	0	5
20:00	−0.5	12.6	−3.3	−16.4	270.3	290.1	272.8	252.7	0	1400	0	0	1	0	0	4
21:00	−12.3	1.8	−15.0	−27.9	279.7	298.7	282.4	260.9	0	0	0	0	1	0	0	4
22:00	−23.7	−8.0	−26.2	−39.7	290.0	308.4	293.0	269.5	0	0	0	0	1	0	0	5
23:00	−34.3	−16.6	−36.5	−51.5	302.2	319.4	305.9	279.8	0	0	0	0	1	0	0	5
24:00	−43.4	−23.2	−45.0	−62.7	317.6	332.2	322.3	294.7	0	0	0	0	1	0	0	6

The main indices carried out are reported and described in depth in Table 4. They refer to three fields of interest: daylighting, energy performance, and thermal comfort. The results will be elaborated and shown for the SP and for all LS developed configurations (i) on a time basis of the whole year (ii) and with an hourly step during the four representative days.

Table 4. Output indices of simulations.

	Index		**Description**
Daylighting	Ill	(lux)	Illuminance level in the RP
	El	(kWh)	Electricity required for the light when the continuous dimming control is used in the RP.
Energy performance	Ec	(kWh)	Total cooling energy need (sensible and latent). Temperature set point (26 °C).
	Eh	(kWh)	Total heating energy need (sensible and latent). Temperature set point (20 °C).
Thermal comfort	To	(°C)	Operative temperature.
	PPD	(%)	Predicted percentage of dissatisfied according to ISO 7730 [35]. Clothing insulation: 0.5 Clo in summer, 1.0 Clo in winter.
	PMV	(-)	Predicted mean vote according to ISO 7730 [35]. Clothing insulation: 0.5 Clo in summer, 1.0 Clo in winter.

The methodological approach is similar to the one defined in [36] but with some novelty elements. Figure 6 shows the flow-chart of the proposed methodology, which could be applied to any kind of buildings with different locations. On the basis of this study, the diagram was conceived in the case that the LS installation takes place at the same time as an energy refurbishment. Indeed, this situation is frequent, since measures that provide envelope building refurbishment are often joint to the whole HVAC–building system refurbishment [37,38]. Obviously, if the refurbished scenarios addition is deleted, then the chart continues to maintain its valence. In this case, the results will be referred to the improvement of the indices, by applying LSs with respect to the existing state of the building. On the other hand, if only the state of project subsists for the building, the calibration section could be avoided. Therefore, the method is easily replicable in other different conditions.

In the downstream section, if each index used in the evaluation has been improved with respect to the ES or the SP, it is possible to find the solutions that guarantee energy efficiency as well as the effectiveness and quality of lighting, visual, and thermal comfort. A limitation of this method could be the great amount of LS configurations to be investigated that make this methodology laborious. Therefore, a further development of this study could be to introduce, downstream of the calibration section, a multi-objective optimization, with three different objective functions, referred to the investigated fields. It is possible to carry this out by means of interfacing EnergyPlus with other calculation tools (e.g., MATLAB [39]) or by using proper tools provided by DesignBuilder [40].

The novelty of the proposed methodology lies in the fact that, by defining a single simulation model within a single-engine environment, it is possible to evaluate the application of LSs under different fields of interest: daylight, lighting energy, cooling and heating needs, and thermo-hygrometric comfort. In addition, this method allows having a whole knowledge of the LSs performance for the case study to which it is applied due to annual outcomes. Finally, thanks to the dynamic simulations and the calibration of the numerical model, the results could be considered strongly representative of reality [30,41].

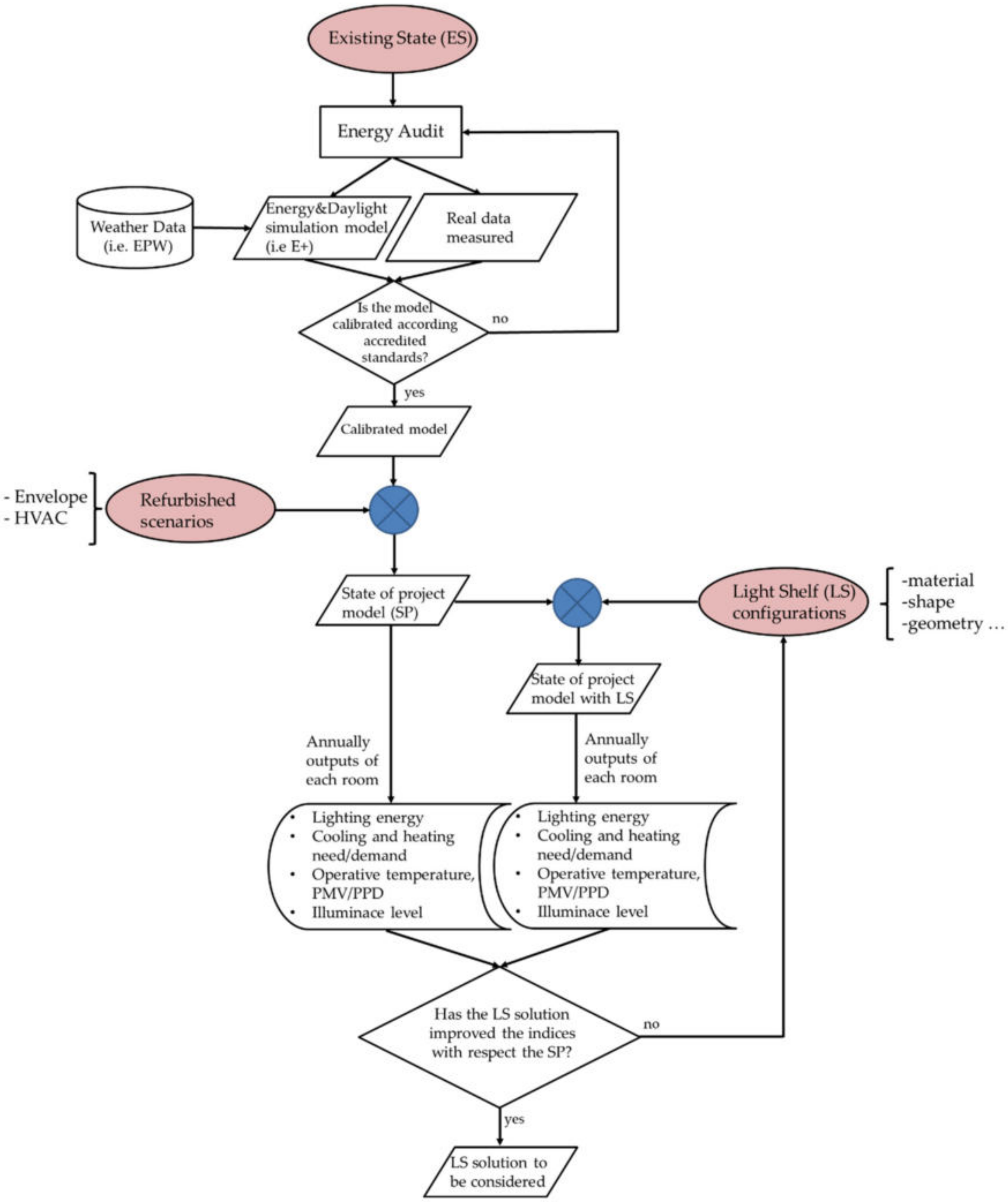


Figure 6. Flow-chart of the methodological approach.

4. Results of Numerical Study

4.1. Daily Analysis

During the autumn equinox, in the ER, the maximum illuminance magnitude (≈1700 lux for SP) is almost double the one in the WR (≈770 lux for SP), as shown in Figure 7, due to the different solar altitude and solar azimuth angles. For the illuminance level, the time period from 8:00 a.m. to 18:00 p.m. is analyzed since it is the time range in which significant differences (with respect to SP) are observed. Moreover, during this period, the desk is occupied.

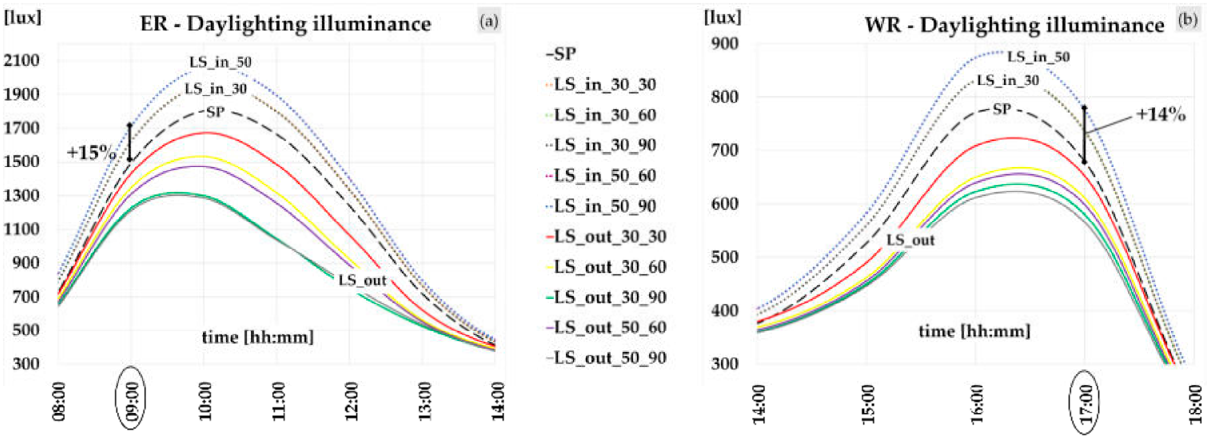


Figure 7. Illuminance level during autumn equinox in the east room (**a**) and west room (**b**).

With respect to the SP, it is possible to obtain a maximum increase in illuminance of +14% ÷ 15% with LS_in_50_60 and LS_in_50_90 in the ER around 9:00 a.m. and with LS_in_50_60 in the WR, at 17:00 p.m. It is observed that LS_out configurations bring a reduction of illuminance level, because, in the simulation model, they reduce the flux transmitted through the window due to diffuse ground luminance. Only LS_out_30_30 can bring an increase in illuminance from +3% to +5% in the ER, during the last sunny hours of the day, and from +2% to +5% in the WR, during the early hours of the morning. This behavior could also depend on the daylight calculation method used in the EnergyPlus tool or on the reference point chosen for the analysis.

Figure 8 depicts the trends of the energy demand for lights by considering continuous dimming control, during the autumn equinox, for the east and west rooms. The maximum energy saving is reached at 14:00 ÷ 15:00 with LS_in_50_90 both for WR (−23%) and ER (−21%). It occurs during these hours because the rooms are occupied.

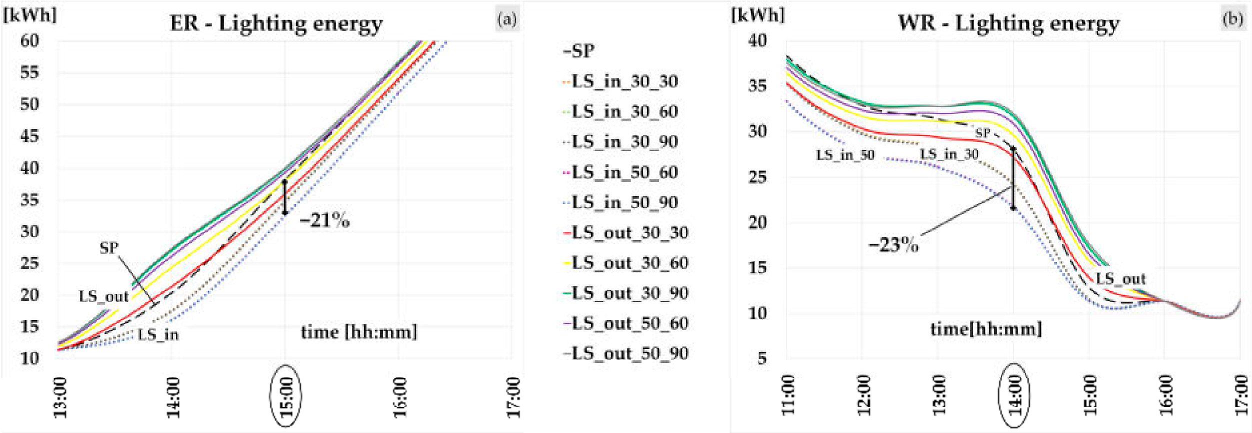


Figure 8. Electricity for lights during autumn equinox in the east room (**a**) and west room (**b**).

Considering the total cooling energy need of the two rooms, Figure 9, during the autumn equinox, the LS_in configurations show an increase in the cooling need. Indeed, looking at the solar diagram in Figure 5, the maximum increase in cooling need happens when the sun shines directly over the LSs, both for ER and WR. Under this condition, there is the maximum efficiency of LSs and so the maximum amount of light penetration [17,42]. In both rooms, with the application of LS_in, a variation of the cooling need with respect to the SP has been observed:

- For the WR, it goes from −7% (at 12:00) to +17% (at 16:00).
- For the ER, it goes from +2% (at 18:00) to +33% (at 10:00).

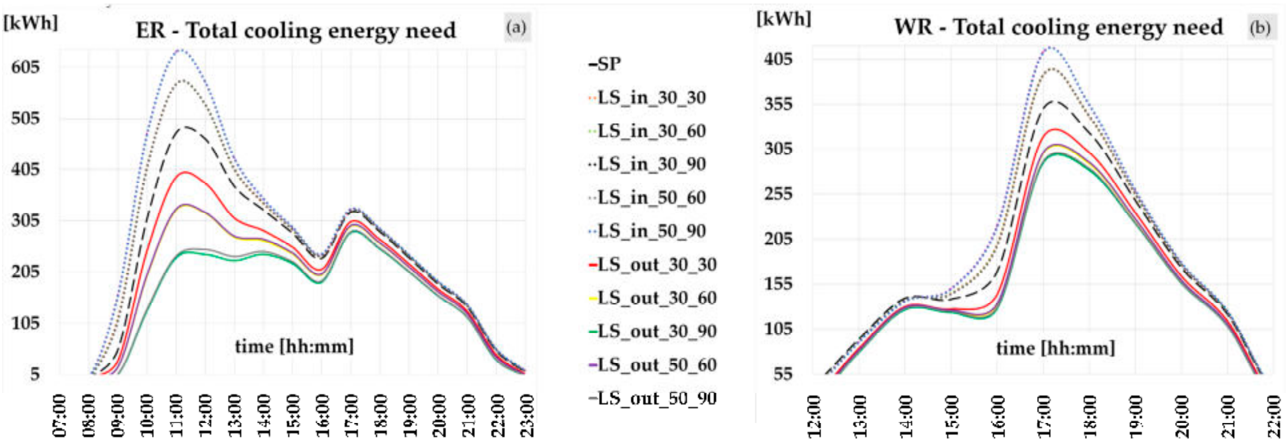


Figure 9. Cooling energy need during autumn equinox in the east room (**a**) and west room (**b**).

Comparing these results with other studies, the increase in cooling need has been observed in an office with the same latitude (37.97° N) by Kontadakis et al. [43], who used an active sunlight redirection system mounted on a light shelf. Lee et al. [19] state that, in the northern hemisphere, varying the tilt of a light shelf can increase the light flux entering the room, increasing the cooling load at the same time.

On the other hand, the LS_out configurations show, for all hours, a reduction of cooling need, because they mainly act as a shading system for the windows. For instance:

- in the WR, the daily median reduction goes from −8% (LS_out_30_30) to −14% (LS_out_50_90 and LS_out_30_90);
- for the ER, the daily median reduction goes from −10% (LS_out_30_30) to −21% (LS_out_30_90).

It can be seen that the maximum cooling need decrease is achieved for the deeper LS_out (90 cm), which confirms their shading action.

For all analyzed days, there is no significant difference in the operative temperature values between the SP and LS cases; this condition is reflected in the PPD trends, as can be seen for the autumn equinox in Figure 10. To better understand the incidence, from the thermal point of view, of the LS-window system with respect to the variation of the operating temperature inside each of the two rooms studied, Table 5 is provided. It shows the median value calculated over each reference day, of the hourly difference between the T_o of the SP and To of each LS case: ΔT_o. If ΔT_o is positive, it means that T_o in the SP is greater than the LS case; otherwise, it is negative. All ΔT_o have module values lower than 1 °C. Mainly for the ER, the presence of internal LS brings an increase in the T_o. This could be explained by the increase of the daylight amount for this configuration, as can be seen in Figure 7. Meanwhile, the LS_out configuration brings, considering the whole day, a T_o reduction, as it is justified by its behavior as a shield. The ΔT_o values during 22 December are lower than the other days. It depends on the lower solar altitude during this day (28° the maximum), which does not allow a direct incidence on the LS. In fact, as stated by Ochoa and Capeluto [42], light shelves have maximum efficiency when the sun shines directly over them. Moreover, the total sky cover during this day is 9 h, from 8:00 to 17:00 (Table 3). As shown by [21], in this case, the effect of the LS on the variation of the thermal environmental condition is insignificant, owing to insufficient daylight. In order to understand how this translates into comfort sensation, Table 6 reports the median value calculated over each reference day of the hourly PMV. On the March, June, and September reference days, the increase in T_o (for LS_in) brings an improvement of PMV with respect to the SP, while in December, the variation is almost null.

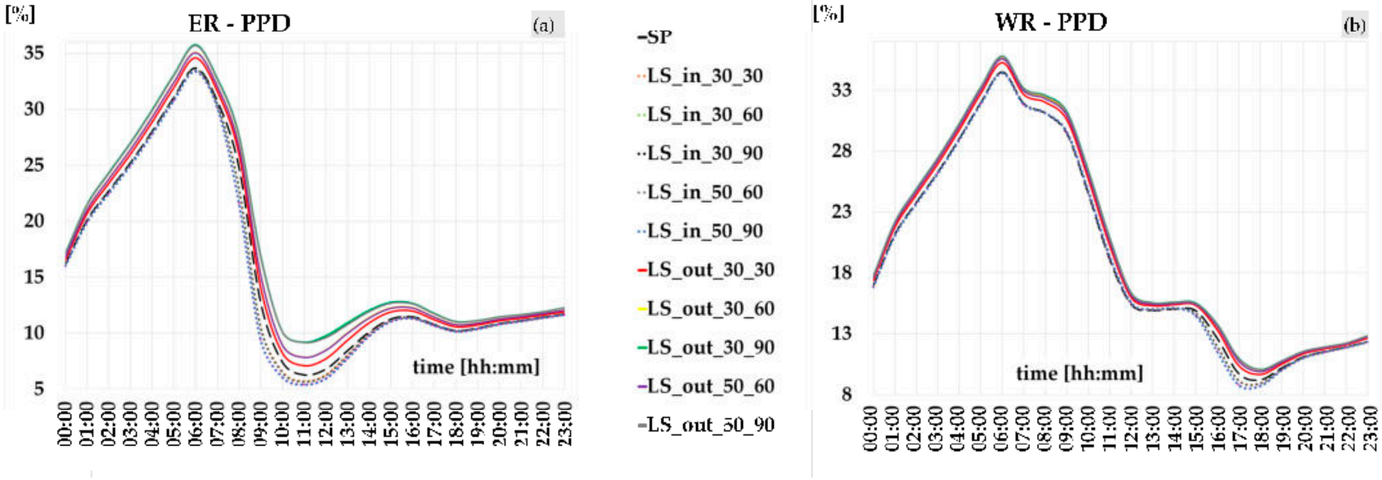


Figure 10. Predicted percentage of dissatisfied during autumn equinox in the east room (**a**) and west room (**b**).

Table 5. Variation in the operating temperature (T_o) with respect to the SP and median value.

	ΔT_o (°C)							
	March 21		**June 21**		**September 23**		**December 22**	
	ER	**WR**	**ER**	**WR**	**ER**	**WR**	**ER**	**WR**
LS_in_30_30	−0.19	−0.01	−0.01	−0.01	−0.01	0.00	−0.02	0.01
LS_in_30_60	−0.19	−0.01	0.00	−0.01	−0.01	0.00	−0.02	0.00
LS_in_30_90	−0.19	−0.01	0.00	0.00	−0.01	0.00	−0.02	0.00
LS_in_50_60	−0.33	−0.01	−0.01	−0.02	−0.02	−0.01	−0.03	0.01
LS_in_50_90	−0.33	−0.01	−0.01	−0.01	−0.02	−0.01	−0.03	0.01
LS_out_30_30	0.34	0.09	0.05	0.05	0.04	0.04	0.07	0.03
LS_out_30_60	0.53	0.13	0.07	0.08	0.07	0.06	0.10	0.04
LS_out_30_90	0.74	0.15	0.10	0.10	0.10	0.07	0.14	0.04
LS_out_50_60	0.51	0.12	0.07	0.08	0.07	0.05	0.09	0.03
LS_out_50_90	0.72	0.14	0.09	0.10	0.10	0.06	0.14	0.04

Table 6. Median value of PMV.

	PMV (-)							
	March 21		**June 21**		**September 23**		**December 22**	
	ER	**WR**	**ER**	**WR**	**ER**	**WR**	**ER**	**WR**
SP	−1.37	−1.86	−0.27	−0.24	−0.55	−0.73	−1.84	−1.93
LS_in_30_30	−1.30	−1.84	−0.26	−0.22	−0.55	−0.73	−1.83	−1.94
LS_in_30_60	−1.30	−1.84	−0.27	−0.22	−0.55	−0.73	−1.83	−1.94
LS_in_30_90	−1.30	−1.84	−0.27	−0.22	−0.55	−0.73	−1.83	−1.94
LS_in_50_60	−1.25	−1.83	−0.26	−0.20	−0.54	−0.73	−1.83	−1.94
LS_in_50_90	−1.25	−1.83	−0.26	−0.20	−0.54	−0.73	−1.83	−1.94
LS_out_30_30	−1.50	−1.89	−0.30	−0.26	−0.57	−0.74	−1.86	−1.95
LS_out_30_60	−1.56	−1.90	−0.31	−0.28	−0.58	−0.75	−1.87	−1.95
LS_out_30_90	−1.64	−1.91	−0.30	−0.31	−0.60	−0.75	−1.88	−1.96
LS_out_50_60	−1.55	−1.90	−0.31	−0.28	−0.58	−0.75	−1.86	−1.95
LS_out_50_90	−1.62	−1.90	−0.30	−0.30	−0.60	−0.75	−1.87	−1.95

Similar results, from a daylighting, energy performance, and thermal comfort point of view, have been achieved during the spring equinox. Only during the spring day in the ER, the application of LS_in_50_90 can bring an increase in operative temperature of 1.0 °C at 12:00, while in the WR, the maximum difference in operative temperature between SP and

LS_in_50_90 is 0.6 °C at 18:00. For this configuration, PMV values closer to the null value and reduction in PPD index have been observed.

During the winter solstice, significant reductions in electricity for the lighting system have been observed, in particular of −40% at 12:00 for the LS_in_50_60 and LS_in_50_90 in the ER. For the WR, the maximum reduction is −9% at 13:00–14:00 in the LS_in_50_60 and LS_in_50_90 cases.

During the summer solstice, the trends of illuminance are similar to the autumn solstice. Moreover, it has been observed that the cooling need in all LS_in configurations is greater than in the SP. The maximum electricity saving is −24%, and it occurs at 9:00 for LS_in_50_60 and LS_in_50_90 in the WR. The same configurations in the other room bring a reduction of about −21% at 13:00.

The results show that the LS_out configurations have a behavior different from the expected one, mainly considering the daylighting analysis. Indeed, an increase in illuminance level was also expected in the case of LS_out. This could be caused by the chosen space positioning of the reference point, and so a spatial distribution of daylight should be considered to investigate this issue further. Moreover, it could depend on a limitation of the model used in EnergyPlus to simulate external LSs.

4.2. Annual Analysis

In Table 7, the number of hours (nh), over the whole year, in which the daylight illuminance is greater than 500 lux is reported. It is evident that the optimal configurations from a daylighting point of view are LS_in_50_60 and LS_in_50_90, both for WR and ER. In addition, considering the energy aspect, the percentage variations (Δ) of the thermal needs and the electricity with respect to the SP are shown in Table 7.

Table 7. Percentage variation of the main indices with respect to the SP.

		SP	**LS_in_3030**	**LS_in_3060**	**LS_in_3090**	**LS_in_5060**	**LS_in_5090**	**LS_out_3030**	**LS_out_3060**	**LS_out_3090**	**LS_out_5060**	**LS_out_5090**
ER	nh	1740	1839	1838	1837	1895	1895	1727	1603	1484	1519	1484
	ΔEc		+4%	+4%	+4%	+7%	+7%	−7%	−13%	−19%	−12%	−17%
	ΔEh		−5%	−5%	−5%	−8%	−8%	+7%	+10%	+15%	+9%	+14%
	ΔEl		−2%	−2%	−2%	−3%	−3%	−1%	+1%	+2%	+2%	+3%
	ΔPPD		−2%	−2%	−2%	−2%	−2%	+3%	+5%	+8%	+5%	+8%
WR	nh	724	810	810	810	863	863	711	634	574	607	567
	ΔEc		+3%	+3%	+3%	+5%	+5%	−5%	−9%	−11%	−8%	−10%
	ΔEh		-	-	+1%	+1%	+1%	+3%	+4%	+5%	+4%	+4%
	ΔEl		−2%	−2%	−2%	−4%	−4%	−1%	-	+2%	+2%	+2%
	ΔPPD		-	-	-	-	-	+2%	+3%	+3%	+2%	+3%

In the WR, the maximum reduction in the electricity for the lights is −4% with LS_in_50_60 and LS_in_50_90. On the other hand, these configurations show an increase in total cooling need of +5% and total heating need of +1%. Therefore, from the energy point of view, this solution could be not suitable for the western exposure.

Considering the ER, the maximum electricity reduction for the lights is observed in the LS_in_50_60 and LS_in_50_90 cases. They also could bring a reduction of the total energy need (heating and cooling).

In general, it can be concluded that, for the case study analyzed and the LS configurations developed, the solutions that show a saving of electricity demand for the light system, due to an increase in the daylight illuminance level, can increase the cooling need and reduce the heating need in the eastern exposure. Therefore, these configurations could be suitable for climate conditions in which the energy demand for heating is comparable or higher than that for cooling.

Evaluating only the lighting energy, considering that the activation of artificial light always guarantees the right level of visual comfort, the best LS configuration coupled to the regulation system of the luminous flux used is LS_in_50_60 and LS_in_50_90 in both rooms.

Finally, considering the thermal comfort aspect, in Table 7, the variations of the mean annual values relating to PPD with respect to the SP (Δ PPD) are shown. They go from −2% to +8%, with no significant percentage variation above all in the cases of LS_in. A discussion in detail has been provided, in Section 4.1, for each reference day. The annual results of the PPD are comparable with the ones carried out by [10], developed for a similar latitude and similar environment, geometry, and orientation (as can be seen in Table 1). Thus, [10] shows that in the studied east room, the application of internal horizontal LS brings an annual increase of PPD of about 1%; while in the same room, for the application of vertical LS, a reduction of 6.5% of PPD has been observed. They do not analyze the external LS solutions.

The presented results did not lead to the univocal definition of an optimal solution of LSs by considering a multidisciplinary approach. If, on one hand, the application of the methodology developed for a real building has a significant scientific value (calibrated model, in-field measurements, interviews, post-retrofit analysis, etc.), on the other hand, this causes a series of constraints due to the pre-existence (height of the room, exposure, etc.). For instance, it was not possible to investigate the other exposures, above all the south one, which seems to be the most suitable one from the scientific literature [6].

5. Conclusions and Further Developments

The study proposes a methodological approach for analyzing light shelves' (LSs) performance over a whole year, considering not only the visual aspects but also the energy performance and thermal comfort of the occupants. The method could be applied to any type of buildings placed in any location, both for existing or project buildings, refurbished or not.

The first step has been the development of the numerical model of the HVAC–building system. The case study is a student dormitory subject to a deep energy renovation to conform to the nZEB standard in the frame of the European project called Pro-GET-onE. Defining two representative rooms of each exposure, in a second phase, the application of different configurations of LSs has been carried out.

As regards this case study in particular, the best solution is to install internal light shelves at 50 cm from the top of the window with an overhang of 90 or 60 cm. This shows:

- under the daylight point of view, an annual increase of illuminance level (+12% approximately);
- considering the energy aspect, a saving of electricity demand for the light system, but an increase of cooling need; and
- regarding the thermo-hygrometric comfort, a small variation of the PPD index (≈ ±2%).

The trade-off between the light electricity reduction and cooling need increase due to the LS application is a topic still discussed and studied in this area [19,43]. A tilt angle equal to 30° might be useful for achieving savings for both lighting and cooling [20], while vertical LSs could bring a greater reduction in the PPD index [10].

General conclusions could be also written. Considering static horizontal light shelves, made of wood, applied to windows of the east- and west-exposed rooms:

- The internal configuration could be suitable for climate conditions in which the energy demand for heating is comparable to or higher than that for cooling.
- The outdoor solution could be suitable for climate conditions in which the energy demand for cooling predominates.
- This latter did not show improvement in daylight.
- The maximum benefit of light shelves' application has been observed in the room with the eastern exposure, with respect to the western one.

In the frame of the shown methodological approach, a further development of this study could be the application of a multi-objective optimization. This could lead to the investigation of a great number of LSs configurations and more significant results. Several variables of the optimization could be used, also combined with each other: material (thus the thermal and optical properties), tilt angle [20], plane position [10] (vertical or horizontal), and operation (fixed or movable).

Author Contributions: Conceptualization, R.F.D.M., S.R., M.-N.A., D.P., F.d.R., A.F. (Anastasia Fotopoulou), A.F. (Annarita Ferrante), G.P.V.; methodology, R.F.D.M., S.R., M.-N.A., D.P., F.d.R., A.F.(Anastasia Fotopoulou), A.F. (Annarita Ferrante), G.P.V.; software, R.F.D.M., S.R., M.-N.A., D.P., F.d.R., A.F.(Anastasia Fotopoulou), A.F. (Annarita Ferrante), G.P.V., validation, R.F.D.M., S.R., M.-N.A., D.P., F.d.R., A.F. (Anastasia Fotopoulou), A.F. (Annarita Ferrante), G.P.V.; formal analysis, R.F.D.M., S.R., M.-N.A., D.P., F.d.R., A.F. (Anastasia Fotopoulou), A.F. (Annarita Ferrante), G.P.V.; investigation, R.F.D.M., S.R., M.-N.A., D.P., F.d.R., A.F.(Anastasia Fotopoulou), A.F. (Annarita Ferrante), G.P.V.; resources, R.F.D.M., S.R., M.-N.A., D.P., F.d.R., A.F., A.F., G.P.V.; data curation, R.F.D.M., S.R., M.-N.A., D.P., F.d.R., A.F. (Anastasia Fotopoulou), A.F. (Annarita Ferrante), G.P.V.; writing—original draft preparation, R.F.D.M., S.R., M.-N.A., D.P., F.d.R., A.F. (Anastasia Fotopoulou), A.F. (Annarita Ferrante), G.P.V.; writing—review and editing, R.F.D.M., S.R., M.-N.A., D.P., F.d.R., A.F. (Anastasia Fotopoulou), A.F. (Annarita Ferrante), G.P.V.; visualization, R.F.D.M., S.R., M.-N.A., D.P., F.d.R., A.F.(Anastasia Fotopoulou), A.F. (Annarita Ferrante), G.P.V.; supervision, R.F.D.M., S.R., M.-N.A., D.P., F.d.R., A.F. (Anastasia Fotopoulou), A.F. (Annarita Ferrante), G.P.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Pro-GET-one Project Horizon 2020 Innovation action—Proactive synergy of inteGrated Efficient Technologies on buildings' Envelopes—under Grant Agreement No. 723747.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

ES	Existing state	
LS	Light shelves	
LS_in	Inner light shelves	
LS_out	Outer light shelves	
SP	State of project	
ER	East room	
WR	West room	
RP	Reference point	
nh	Number of hours in which the illuminance is greater than 500 lux	
Δ	Percentage variations, or simply variation, with respect to the SP	[%]
Ill	Illuminance level in the RP	[lux]
El	Electricity for the light system	[kWh]
Ec	Total cooling energy need	[kWh]
Eh	Total heating energy need	[kWh]
T_o	Operative Temperature	(°C)
PMV	Predicted mean vote	[-]
PPD	Predicted percentage of dissatisfied	[%]

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