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Sizing analysis of interior lighting using tubular daylighting devices

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Abstract

Daylight access and indoor thermal comfort are key issues for high design level of sustainable buildings. In fact, daylight provides energy savings and visual comfort condition that can foster higher productivity and performance. This paper proposes a case study of sizing of daylight devices for zenith light. It enables the decision-making process of the designer to reach high levels of daylight factor. The proposed method is shown with an example of application. For the case study, a room in south of Italy, 24 different solar tunnels configurations and 12 cases with different number of skylights have been evaluated.

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Keywords: Daylighting, Daylight system, skylight, rooflight, solar tunnels, natural light, daylight factor, illuminance, internal comfort, energy consumption, transmittance, reflectance, overhang

1. Introduction

The climate change is considered as one of the main worries of the modern civilization. Starting from the construction sector, it is urgent to reduce the CO_2 gas emissions that cause the greenhouse effect and the temperature rise [1,2]. The recent inclination, encouraged by the European Energy Performance of Buildings Directive (EPBD), is aimed at decreasing energy use in the building sector [3]. The results of correct choices for the design of

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sustainable buildings involves positive environmental effects, reducing the consumption of natural resources and costs and especially ensuring a high quality of service for the end users and the whole community. Several studies have been carried out to give more information about a right choice of technical solutions for high energy performance buildings, focusing on the envelope and on the technical systems [4]. M.T. Ke al. [5] show that the daylight received through windows can significantly contribute to the reduction of lighting energy use in office buildings. It can be considered as a latent passive strategy for reducing the building energy use and bettering the visual comfort without any expensive operational cost and installation. Daylight access and indoor thermal comfort are key issues for a high design level provided that building occupants spend about 80% to 90% of the time in indoor activities [6]. In fact, daylight provides an agreeable and pleasant indoor environment that can foster higher productivity and performance [7]. Many researches analysed the performances of systems for natural lighting through numerical modelling and experimental tests [8]. On the other hand, Danny H.W. Li et al. [2] noted that several final users and designers do not invest in systems of natural light control, due to limited data and studies mainly about innovative devices systems. Tubular daylight device, also known as solar tunnel, is a novel way of using daylight [9]. As for traditional skylight systems, they are a good choice for some places without windows able to transmit daylight. There is a good number of researches made over the last decades on solar tunnels and on design of them (e.g. materials and shape) and on their application. Back in 2001, Zhang et al [10] developed a mathematical model aimed at predicting the daylight performance of solar tunnels with various configurations under all weather conditions in the UK. Robertson et al. [11] analysed four coordinated experimental measurements campaigns in order to provide coherent test data for a wide range of solar tunnel systems. Ciugudeanu et al. [12] presented a field measurements and software simulation results (DIALux, Lux calculator) for a case-study of a passive tubular daylight guidance system installed in a residential building in Cluj-Napoca, Romania. Mohammed Al-Marwaee [13] showed a survey of daylight guidance systems in 13 working buildings in order to have indications of the achieved conditions which are used as the bases for suggested design criteria. In the present study, an example of a correct design of such system providing a high-level daylight in indoor spaces, focusing on solar tunnels with different number and lengths, has been shown. To reach this aim, the authors analysed a case study, i.e. a room (4x4x3m) of a building located in the South of Italy without windows. The results have been compared with the values obtained simulating conventional skylight systems for the same room.

2. Methodology: The case study

In this paper, a sizing analysis of an interior daylight system has been carried out. The analysis has been conducted on daylight systems able to provide a high level of daylight factor [14] inside the buildings using solar tunnels. To reach this purpose, a room of a building located in Lecce has been investigated. The geographical coordinates are 40° north latitude and 18° east longitude and the elevation is 49 m from the sea.

Its size is 4,5 m in length, 4,5 m widths and 3,5 m height and the main facade is oriented towards North-East. The room has no windows.

The building envelope of the case study is shown in Fig 1. It has an inner coating of plaster (reflectance 0.90%, rugosity 0.03%, specularity 0.0%), while the floor has tiles (reflectance 0.90%, rugosity 0.03%, specularity 0.0%). The task plane, where the light properties have been evaluated, is a wooden table placed at the centre of the room characterized by following properties: reflectance 0.66%, rugosity 0.02% specularity 0.05%. Furthermore, the study has been carried out for two typologies of lighting systems with the follow properties:

- Skylights equipped by a double glazing with a light transmittance equal to 78%;
- Solar tunnels system with a Plexiglas outer dome and diffuser with 78% of light transmittance and an aluminium light tunnels with 78% of reflectance (Fig. 1) with two different lengths.
- Skylight and solar tunnel have the same diameter (0,65 m).

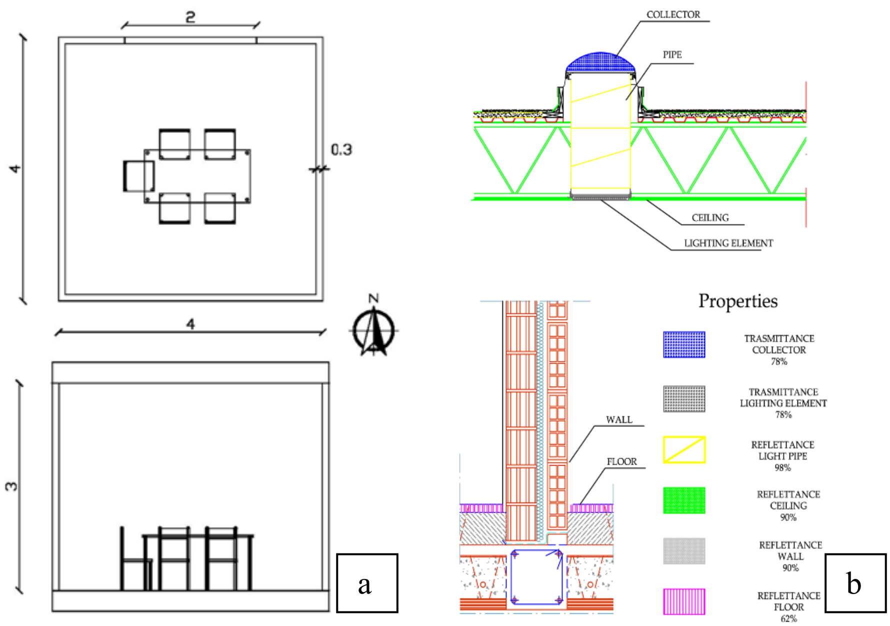

Fig. 1. The section and the plan of the room (a) and the section of the solar tunnel (b).

In order to know the natural light contribution achievable applying different size and number of solar tunnels and skylight devices, many simulations have been performed using the software Daysim [15]. It permits the assessment of the luminance value, illuminance and daylight factor, as well as other useful indicators, depending on the characteristics of lighting system and of the room. The software is able to simulate the natural light in its complexity using the Radiance algorithm that takes into account several parameters such as the shape of the building and at the properties of the used materials. For simulating daylight condition an energy plus weather data file has been used.

Finally, the results have been imported in the software Sketchup [16], used also for developing the 3d model. The sensor has been placed on the table, one in an external correspondent point, at an height of 3,5 m far from the roof. Moreover other 25 sensors have been placed on the floor distant of 1 meter from each other (Figure 2).

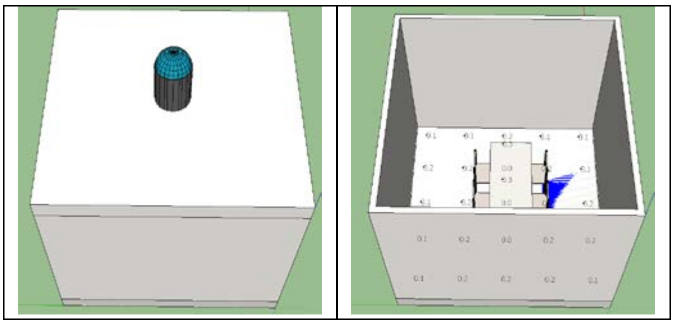

Fig. 2. Some examples of the simulation models interface.

A trial sizing has been performed using a variable number of tunnels starting from one to the maximum that can hold the room. This procedure has facilitated the assessment of the size of the solar tunnels and their precise arrangement, optimizing the performance. For the investigated room, 24 different configurations of solar tunnels and 12 different combinations of skylight have been evaluated. In particular, the following cases have been analysed:

- 12 cases of 1 meters long tunnels (with 1, 3, 5, 7, 8, 10, 15, 20, 25, 30, 35 and 40 tunnels);
- 12 cases of 3 meters long tunnels (with 1, 3, 5, 7, 8, 10, 15, 20, 25, 30, 35 and 40 tunnels);
- 12 cases of traditional skylights (with 1, 3, 5, 7, 8, 10, 15, 20, 25, 30, 35 and 40 skylights).

For each configuration, the following indices have been calculated:

- Daylight factor [%];
- Daylight Autonomy [%];
- Continuous daylight autonomy [%];
- Useful Daylight Illuminance [%];
- Annual light exposure [lx·h].

Indices, such as the daylight factor and the annual light exposure, give a general idea of the daylight contribution. The Daylight Autonomy represents the percentage of the time-in-use that a certain user-defined lux threshold is reached through the use of just daylight [17]. The UDI [18] is defined as the annual occurrence of illuminance values, across the task plane, that are within a range considered “useful” by occupants. DA_{con}, [19] as proposed by Roger’s [18] associates partial credit for daylight levels below a user-defined threshold in a linear fashion. These data can be useful to estimate achievable energy savings for the artificial lighting system [20].

3. Results and discussion

Fig. 3 shows the correlation between the A_{RB}/A_{RG} number of corresponding solar tunnels and Daylight Factor, where:

- A_{RB} is the total area of the skylight/tunnels openings [m^2];
- A_{RG} is the floor area of considered space [m^2].

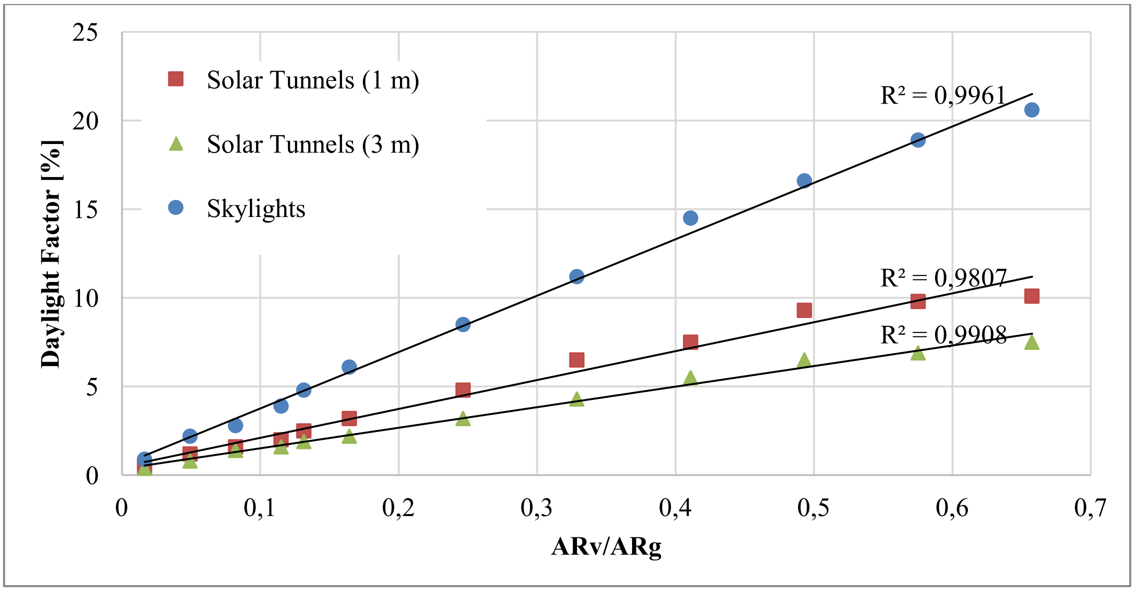

Fig. 3. Calculated Daylight Factors for the three typologies of systems and for variable number of devices.

It can be observed that the contribution of daylight is highest in the cases where the application of the skylights is considered and it is proportional to the numbers of devices (or ratio of roof-light opening area and room ones). Looking at Figure 3, it is possible to note that the line is not perfectly straight, even if it is almost negligible. It is because the daylight factor has been calculated in a point of the table that is in the centre of the room. Only some tunnels are located on the roof in correspondence of the table (with a variable number), while the other are distributed in the rest of the roof. E.g. in the case where DF has been calculated with 30 solar devices, six devices are in correspondence of the table; while, in the case with only 2 and the other 6 are distributed in the rest of the roof. This causes a different distribution of the light.
The Fig. 3 shows that the trend of the daylight factor vs A_{RB}/A_{RG} is linear for all the three types of systems. In particular, it highlights that DF increases linearly, with a deviation of approximately 1.0%, 1.4%, 1.2% respectively increasing the area of skylights, 1 m and 3 m tunnels.

Following tables show the results of a set of daylight indices calculated for each daylight systems typology and configuration.

Table 1. Daylight indices calculated for solar tunnels systems.

N.	DF [%]	DA [%]	DA$_{con}$ [%]	UDI $_{<100}$ [%]	UDI $_{100-2000}$ [%]	UDI$_{>2000}$ [%]	annual light exposure [klx·h]	DF [%]	DA [%]	DA$_{con}$ [%]	UDI $_{<100}$ [%]	UDI $_{100-2000}$ [%]	UDI $_{>2000}$ [%]	annual light exposure [klx·h]
1	0.5	0	12	84	16	0	233	0.4	0	11	86	14	0	208
3	1.2	2	35	28	72	0	673	0.8	0	21	62	38	0	391
5	1.6	9	47	18	82	0	927	1.4	5	39	26	74	0	759
7	2	18	57	48	88	0	1196	1.6	6	41	23	77	0	772
8	2.5	26	63	10	69	0	1551	1.9	10	49	17	83	0	842
10	3.2	38	74	6	94	0	4350	2.2	22	58	13	87	0	1292
15	4.8	63	85	4	95	2	2757	3.2	31	68	6	91	0	1940
20	6.5	76	90	3	88	9	3561	4.3	50	79	4	95	1	2268
25	7.5	82	92	2	77	20	6650	5.5	65	85	3	92	5	3042
30	9.3	88	94	1	70	29	5238	6,5	73	89	3	93	4	3416
35	9.8	86	95	1	73	26	7969	6.9	74	89	3	89	9	3595
40	10.1	86	95	1	72	27	5869	7.5	77	91	3	86	9	4090

Table 2. Daylight indices calculated for skylight systems.

N.	DF [%]	DA [%]	DA$_{con}$ [%]	UDI$_{<100}$ [%]	UDI$_{100-2000}$ [%]	UDI$_{>2000}$ [%]	Annual light exposure [klx·h]
1	0.9	1	33	32	68	0	593
3	2.2	38	71	10	90	0	1549
5	2.8	54	80	6	94	0	3887
7	3.9	73	87	4	82	15	3593
8	4.8	78	89	3	77	20	4249
10	6.1	83	92	3	69	29	4823

15	8.5	88	95	2	57	41	9138
20	11.2	92	97	1	43	56	20093
25	14.5	94	97	0	31	69	19456
30	16.6	95	98	0	24	75	14812
35	18.9	95	98	0	21	78	19080
40	20.6	97	98	0	20	80	27781

In the case of 1 meter long solar tunnel, it would be needed 7 solar tunnels to reach the values of Daylight Factors (2%) suggested by the Standards and Guides [21, 22, 23, 24]. Regarding the cases with the 3 meters long solar tunnels, it would be needed 10 tunnels. Despite a comparison between skylight and tunnel applications is not always meaningful due to several architectural constraints, if we look at the number of devices, able to provide the same value of DF, it can be noted that more solar tunnels than skylight are generally required. Anyway, being the tunnels equipped with a light diffuser, its application ensures lower risks of indirect glare. This can be assumed by the very low values of $UDI_{>2000}$ which could be correlated to the glare probability [25]. In addition, such diffuser increases the luminous uniformity and prevent the room overheating.

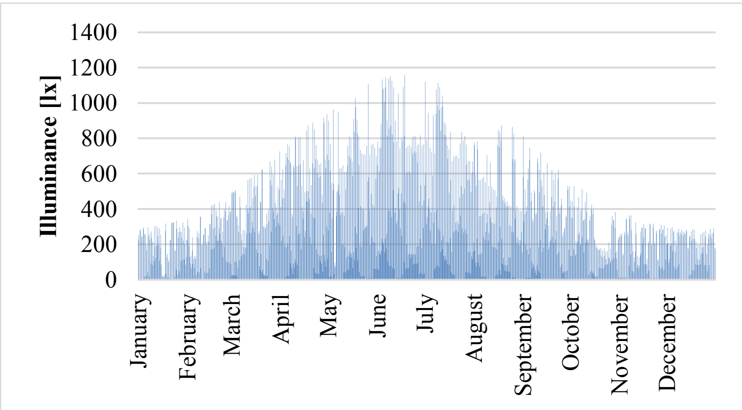

Figure 4: Daylight illuminance distribution over the year for 7 solar tunnels (1 meter long).

The graph in fig. 4, gives an idea of the illuminance frequency distribution during 1 year for the case of application of 7 solar tunnels 1 meter long. In particular, the graph is referred to the illuminance values calculated on the plane, in the same point where DF has been calculated. It can be noted that while during the winter season the task illuminance value of 500 lx is never achieved, during most part of the other seasons it is reached or exceeded. The solar tunnels can be a good solution to avoid direct solar radiation in the room and, therefore, glare discomfort conditions. A further analysis of the indices calculated can provide a method to select the best configuration in terms of visual and thermal comfort and energy savings.

4. Conclusion

This paper comes from the awareness of a lack of scientific studies on the daylight performances of solar tunnels. The following study results as a rough estimation of the solar tunnels performances in a room. It presents a set of data of daylight indices associated to different zenith daylight devices. It enables the designer to have preliminary information to size such devices in rooms with similar characteristics.

On the contrary, it must note that it is important not exceed and oversize the daylight devices of the room in order to prevent risks of glare and overheating.

A case study of a room located in South Italy, placed around the 40° North latitude, has been investigated. This calculation can be applied for different latitudes and buildings. The calculation of the other indices, i.e. the Daylight Autonomy, the continuous Daylight Autonomy and the UDI can provide, useful data to estimate achievable energy savings for the artificial lighting system. In future work, starting from the results shown and applying the results in the Regulation method, it will be possible to improve the performances, detailing the path of light along the tunnel.

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