Daylight performance of the Modified Double Light Pipe (MDLP) through experimental analysis on a reduced scale model.

Paolo Zazzini[1]*, Alessandro Di Crescenzo[1], Roberto Giammichele[2]

[1]Department INGEO, University “G. D’Annunzio”, Viale Pindaro 42, 65127 Pescara, Italy.

[2] Engineer, Via A.Gramsci n°10/A, Vasto (CH), Italy.

* Corresponding author. Tel: +39 854537282

zazzini@unich.it

Nomenclature

DLP	Double Light Pipe
MDLP	Modified Double Light Pipe
r	luminous reflectivity
E_{in}	Internal illuminance (lx)
E_{out}	External illuminance (lx)
E_{avg}	Average Illuminance on the work plane (lx)
E_{max}	Maximum Illuminance on the work plane (lx)
E_{min}	Minimum Illuminance on the work plane (lx)
U_0	Illuminance Uniformity (E_{min} / E_{avg})
$U_0^{'}$	Illuminance Uniformity (E_{min} / E_{max})

Abstract

This paper focuses on the Modified Double Light Pipe (MDLP), an innovative daylighting system set up by the authors in the Laboratory of Technical Physics of the University “G. D’Annunzio” of Pescara (Italy).

The MDLP is an evolution of the Double Light Pipe (DLP), designed by the authors to distribute natural light in two underground levels of a building. It improves the performance of the DLP, thanks to its smaller encumbrance, and the application of a light shelf around the external tube that prevents the occupants of the room from seeing the upper portion of the device avoiding the risk of glare, and reflects light towards the ceiling spreading it more uniformly on the horizontal wok plane.

The authors describe the technological components of the system, as well as the procedure to install it to a brick concrete roof slab and show the first results of an experimental activity carried out by on a 1:2 scale model of the MDLP.

The results can be considered satisfactory in winter climatic conditions both in terms of internal illuminance and uniformity of light distribution and encourage to continue the analysis in summer when they will probably be even better thanks to the more favorable external conditions.

Keywords

Daylight; Natural Light; Light Pipe; Double Light Pipe; Light Shelf.

1. Introduction

Natural light can give a contribution in guaranteeing visual comfort conditions in buildings, even if it involves the risk of some discomfort conditions due to visual glare or veil reflections. Tabadkani et al. (2021) have recently underlined the role of facades equipped with daylight sources (windows) and daylighting strategies able to block or redirect light to get visual comfort condition of the occupants and analyzed a great number of parameters to underline the influence of daylight on visual comfort of occupants.

Visual comfort in internal areas of buildings depends on various physical aspects such as light quantity, absence of glare phenomena, uniformity in illuminance and luminance distribution and adequate view outdoor, as well as psychological factors that influence the occupants’ perception of daylight (Heerwagen and Heerwagen, 1986; Hamedani et al. 2019).

The presence of daylight is particularly important in office buildings, as underlined by Galasiu and Veitch (2006), so much that it can have a positive influence on productivity, as shown by De Carli et al. (2008).

Daylight in buildings is very significant also for sanitary purposes. The lack of daylight can severely penalize human health, producing modification of the circadian rhythms, weakening of the immune system, alteration of mood, and depression (Boubekri et al. 1991; Leather et al. 1998).

Natural light also allows effective energy savings in buildings, thanks to less use of artificial light, taking into account that about 14% of electrical consumption in EU and 19 % in the world is due to the use of artificial light. (Bellia et al. 2015; Bodart et al. 2002; Gago et al. 2015; Mardaljevic et al. 2009; Momani et al. 2009; Pyonchan, et al. 2009).

In many cases, particularly in public buildings, this is partially due to the occupants' bad habit of using artificial light also in presence of natural light taking curtains or blinds shut in order to avoid glare from the windows hit by direct solar radiation (Masoso and Grobler 2010).

The electric energy consumption in EU must be significantly reduced as requested by the European Directives that fixed the Nearly Zero Energy target for buildings and daylight can effectively contribute to achieve this.

For these reasons, the use of natural light in buildings is growing in importance. In this perspective, numerous visual comfort indices have been proposed to quantify the daylight availability in the design process of buildings and thus guide the design choices (Carlucci et al. 2015).

When traditional sources of daylight are absent, such as in underground areas of buildings, or unable to provide adequate light level, such as in large plan area environments (i.e. industrial or commercial buildings), daylight can be introduced and transported by technological light transport systems. Among these, light pipes or similar technological devices are very widespread (Canziani et al. 2004; Jenkins et al. 2005; von Wachenfelt et al. 2015). Obradovic and Matusiak (2019) propose "*a literature study of daylight transport systems aiming at selecting the most appropriate ones for application at high latitudes*".

Although vertical light pipes and similar daylighting strategies are most suitable at high latitudes, being particularly apt to catch zenithal light, and less effective in the Mediterranean latitudes as suggested by Obradovic and Matusiak (2019, 2020), these systems can still make a contribution to energy saving by allowing underground or basement environments to be illuminated with daylight.

In environments equipped with windows, an uneven spatial distribution of natural light usually occurs, with very high values near the window rapidly decreasing away from it. In these cases, light shelves can be effectively used to improve the spatial distribution of light (Freewan et al. 2008; Ganga et al. 2017; Kontadakis et al. 2018; Meresi 2016; Warrier and Raphael 2017; Yaik-Wah and Mohd Hamdan 2015; Zazzini et al. 2020).

Many authors have investigated the performance of daylighting technological devices through numerical or experimental methods (Ahmed et al. 2006; Carter 2002; Dutton and Shao 2007; Li et al. 2010; Oakley et al. 2000; Paroncini et al. 2007; Rosemann and Kaase 2005; Su et al. 2012; Vasilakopouloua et al. 2017).

Experimental data can be collected under real or artificial sky, using the scale model approach. Boccia and Zazzini (2015) propose a critical analysis of the use of the scale model approach, underlying its simplicity and effectiveness but its reduced accuracy due to some accidental factors, as the presence of direct solar radiation.

In previous years, the authors of this paper carried out research on daylight transport systems and they developed an innovative device called Double Light Pipe (DLP). The DLP is an evolution of the traditional light pipe, particularly suitable for large showrooms or museums, able to illuminate contemporarily two levels of underground buildings or of buildings not equipped with traditional daylight sources (Baroncini et al. 2008, 2010).

Recently, they developed the idea of combining the technology of the DLP with that of light shelves and they set up a new system named Modified Double Light Pipe (MDLP), a technological device designed with the aim of improving the performance of the Double Light Pipe (Zazzini et al. 2021).

In this paper, the authors present the technological components of the MDLP and the first results of an experimental analysis carried out on a 1:2 scale model of the system.

2. The Modified Double Light Pipe (MDLP)

The MDLP has been designed to improve the performance of the DLP, a device developed by the authors to distribute natural light in underground buildings (Baroncini et al. 2008, 2010). It can light two hypogeal levels and consists of two coaxial tubes. The internal one brings natural light into the second underground level as a traditional light pipe, while the external transparent one allows the light to enter the intermediate room. The DLP presents some troubles: it has a considerable encumbrance and involves the risk of glare from the upper portion of the system. Moreover, it produces an uneven distribution of light, more concentrated near the tube.

The MDLP has been designed with the intent to solve these problems and improve the performance of the system (Zazzini et al. 2021). The DLP has been modified by fixing to the ceiling a reflecting panel and equipping it with a circular light shelf, 600 mm distant from the ceiling, able to reflect light toward the ceiling and improve the uniformity of light distribution in the environment. The light shelf also prevents the occupants from seeing the upper portion of the device with the highest luminance, avoiding the risk of glare. Furthermore, the encumbrance of thr external pipe is significantly reduced than in the DLP, because the lower portion of the tube is cut.

Fig. 1 shows a comparison between the DLP (Fig. 1.a) and the MDLP (Fig. 1.b), underlying the different visual perceptions of the two devices, the reduced encumbrance of the MDLP if compared to the DLP and a qualitative distribution of light from the two systems.

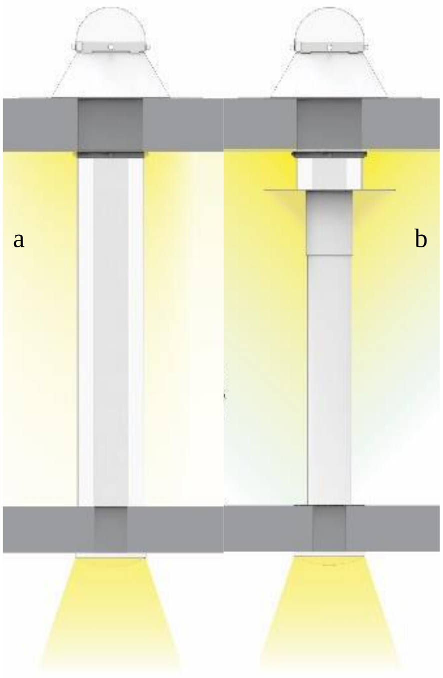

Figure 1: Comparison between the DLP (a) and the MDLP (b)

3. Technological components and installation procedure of the MDLP

The MDLP can be installed in both new and existing buildings. In this paragraph, the authors describe the device applied to a generic brick concrete roof slab as it is the most used in common constructions.

The external tube has a 500 mm diameter and the internal one has a 250 mm diameter.

The first step of the installation process consists in making a hole over the roof slab. It must have a 505 mm diameter to allow easy fixing of the external tube. In the case of an existing building, the hole should be positioned so that only one joist is removed and an appropriate stiffening should be created to restore the structural continuity offered by the joist.

At this point, the fixing surface should be prepared by removing part of the surface layer to “hook” the flashing to the covering screed (see Fig. 2). The flashing should be fixed on the screed by mechanical anchors, which allow a firm grip and high resistance thanks to friction and shape. The fixing of the flashing should be carried out using sealants and sheaths to avoid long-term corrosion phenomena.

The upper part of the system consists of the elements shown in Fig.3, which also displays how it can be fixed to the roof slab, inserting it into the flashing previously prepared. In Fig. 4.a the connection of the system to the intermediate floor is shown, while Fig. 4.b shows the telescopic shelf that is a fundamental element of the system. In addition, it allows to set the shelf at the correct height to facilitate the installation of the apparatus making the system extremely versatile and applicable at different heights

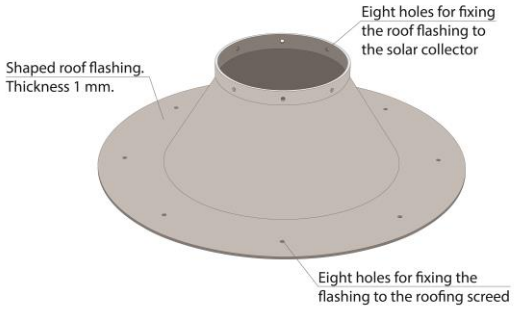

Figure 2. Axonometric view of the flashing that allows anchor the system to the roof slab.

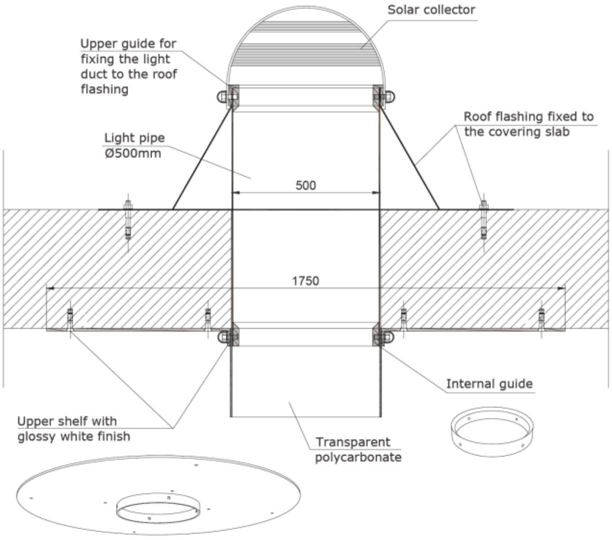

Figure 3. Connection system to the roof slab

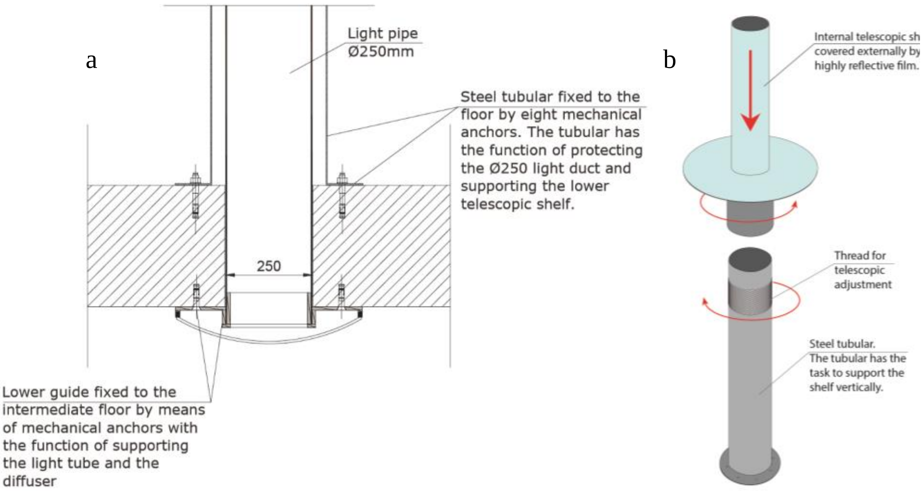

Figure 4. Fixing mode of the system to the inter-floor slab (a) and lower telescopic shelf (b)

Considering that the internal pipe is in contact with the users of the intermediate room, it is necessary to protect it with a steel coating. Overall, the system looks like a long classic tube to which a steel circular protection has been applied to prevent damage. Finally, by assembling the components, the configuration shown in Fig. 5 is obtained.

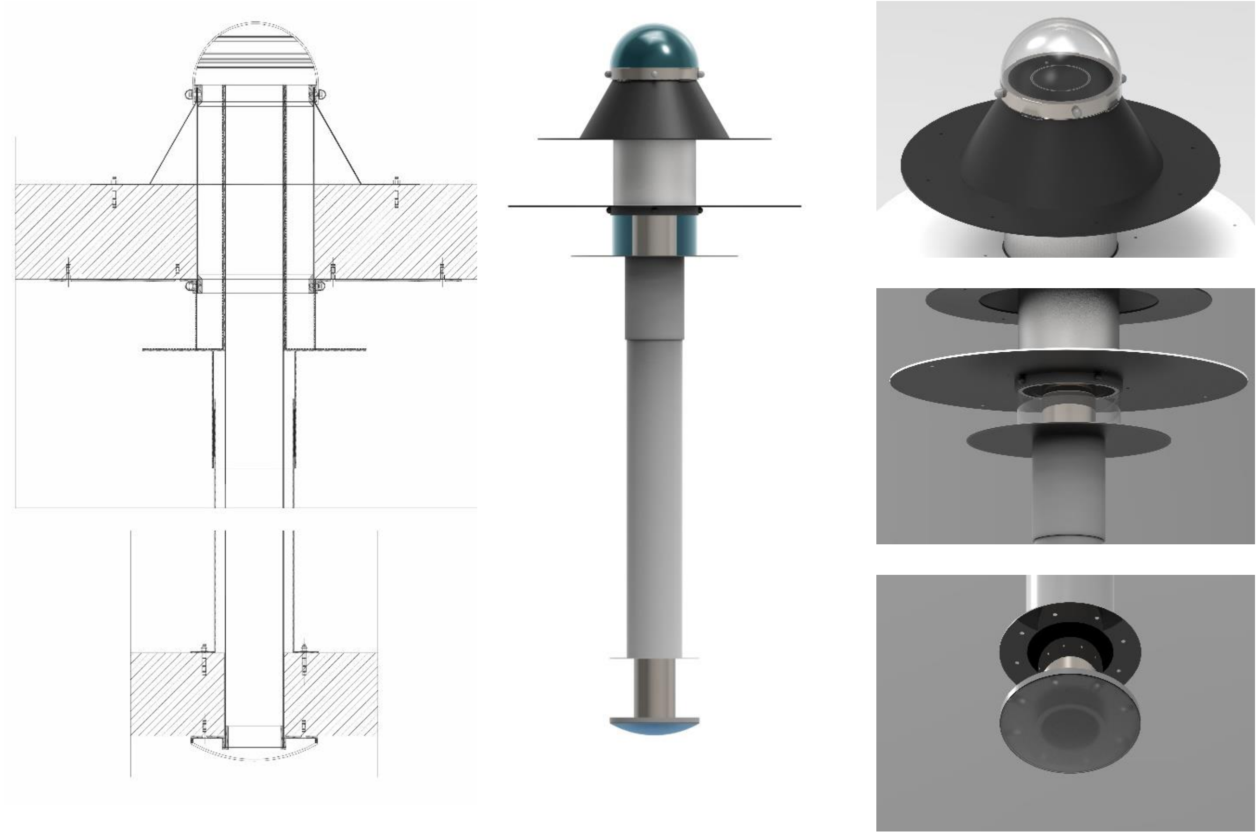

Figure 5. Complete configuration of the MDLP, overall and detailed renderings

4. Description of the experimental apparatus

The authors built a wood 1:2 scale model of a 3.8x3.8 m plan area room, 3.0 m high. The vertical walls are made of unpainted multilayer wood, with a luminous reflectivity equal to 50%. Sheets of grey drawing paper are applied to the floor of the room (luminous reflectivity = 49.1%) and a circular grey panel (100 mm diameter) with the same luminous reflectivity is applied over the ceiling around the external tube. The internal tube of the MDLP is made of PVC. The upper portion of it is externally covered by a reflective film (3 M Radiant Mirror Film LRF) with luminous reflectivity r = 99.5%. The external tube is made of transparent polycarbonate. Fig. 6 shows some photos of the device and the test room.

Figure 6. Some photo of the MDLP

The model simulates the passage room of a two-level hypogeal construction illuminated by the MDLP. The room is not equipped with any window or skylight, so the MDLP is the only source of natural light.

Twelve CIE Lux-meters sensors type LSI-BSR001, range 0–25 klx, accuracy 3% of the reading value for illuminance, have been positioned in the room on a horizontal work-plane (see Fig. 7). This last is 0.4 m high on the floor and simulates a 0.8 m high work-plane in the real scale room. A CIE sensor type LSI-DPA 503, range 0–100 klx, tolerance 1.5%, has been used to measure the external horizontal illuminance (E_{out}).

A data-logger type LSI Lastem ELO 310 has been used to register data.

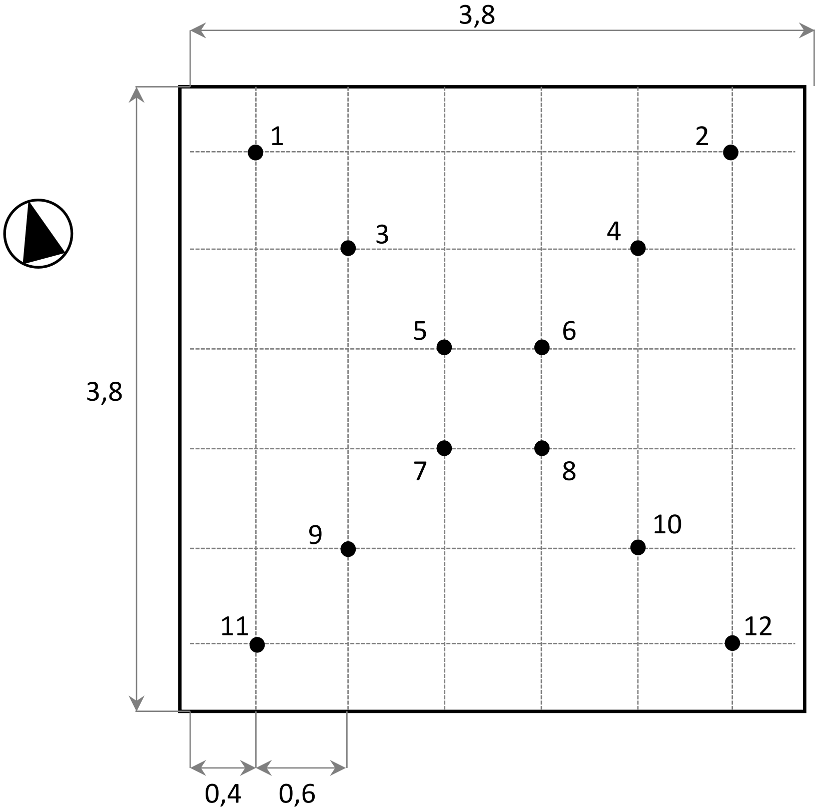

Figure 7. Real scale dimensions of the test room and positions of the luxmeters on the horizontal work plane.

5. Experimental results

The authors carried out an experimental activity from December the 22nd to January the 19th for 24 hours a day, collecting data of illuminance every one minute and elaborating them every ten minutes.

Figs. 8, 9, and 10 show the results of typical situations, respectively: one representative week (5-11 January), a cloudy day (22 December), and a sunny day (5 January).

Under overcast sky (i.e. 22 December) the internal illuminance trend is very similar to the external one. The maximum external illuminance is about 21 klx and takes place at 12.30, while the internal illuminance is generally ranging between about 30 and 60 klx, except for the period from 12.30 to 13.30 during which it significantly decreases due to very low external illuminance values. On the contrary, under clear sky with sun (i.e. 5 January) although the internal illuminance trend generally follows the external one, illuminance in positions 2 and 12 (in the right corners of the room) is significantly higher than in other measure points, and a peak value of about 350 lx takes place in position 12 at 12.30. Moreover, note that while on December the 22nd the external and internal maximum values of illuminance are perfectly simultaneous, on January the 5th there is a time shift of 30 minutes between them.

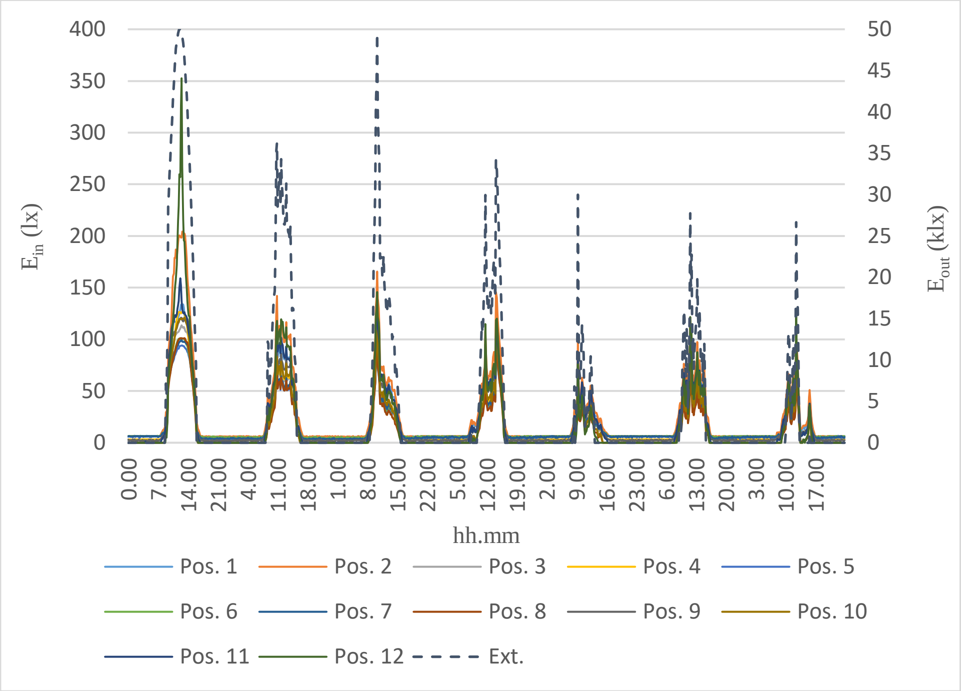

Figure 8. Illuminance data of a typical week (5-11 January) - External illuminance referred to the right axis

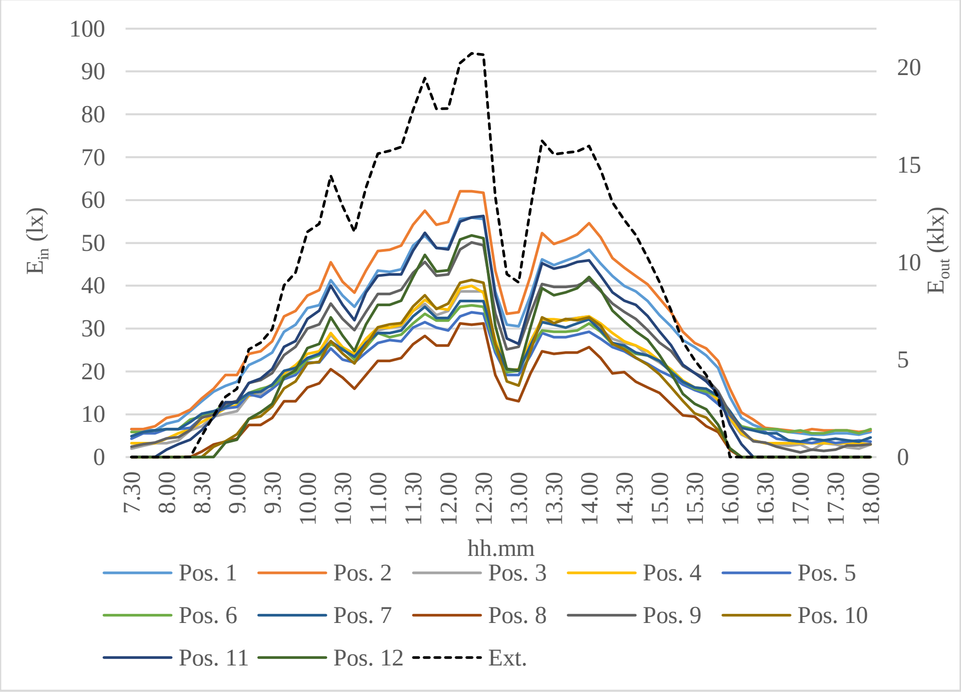

Figure 9. Illuminance data of a typical overcast day (22 December) - External illuminance referred to the right axis

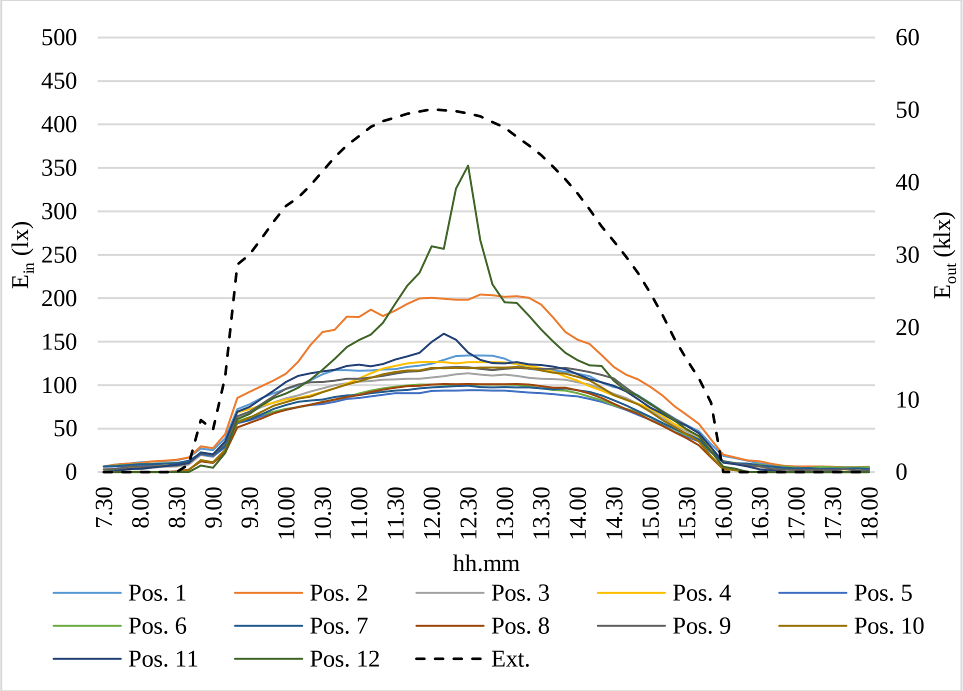

Figure 10. Illuminance data of a typical sunny day (5 January) - External illuminance referred to the right axis

Moving from the previous considerations, the authors analyzed data of all the test days to determine the correlation between internal and external illuminance.

Table 1 shows the internal and external average and maximum illuminance values for each day between sunrise and sunset, the measure positions in which the maximum value happens, and the time shift between internal and external maximum values.

Note that the table is lacking external illuminance data for five days (28 December, 1-3 January, 12 January) caused by an accidental malfunction of the external luxmeter.

Maximum values take always place in positions 2 (13 times) and 12 (16 times), on the right side of the room.

For twelve days, the internal and external values are simultaneous, while for eleven days, there is a time shift between them, six times late and five times early. The maximum delay occurs on January the 15th (70 min), while the maximum advance occurs on January the 18th (60 min). The contemporaneity generally happens with low external illuminance on partially or totally cloudy days, while the time shift generally takes place on sunny days under clear sky with sun, probably caused by the presence of direct solar radiation.

Table 1. Average and maximum illuminance values, measure positions of maximum values and time shift between internal and external maximum illuminances.

			E_{in} (lx)				E_{out}(lx)			
	Sunrise	Sunset	Avg	Max	Pos.	hh.mm	Avg	Max	hh.mm	Δt (min)
Dec 22	07:29:55	16:33:48	23.3	62.0	2	12.10/12.20	9.5	20.7	12.20	0
Dec 23	07:30:23	16:34:22	62.6	262.4	12	12.20	22.1	43.2	11.40	40
Dec 24	07:30:48	16:34:57	74.4	335.1	12	12.20	23.1	41.9	12.10	10
Dec 25	07:31:11	16:35:34	19.4	102.0	2	14.00	4.6	25.2	14.00	0
Dec 26	07:31:32	16:36:14	16.0	51.3	2	13.30	5.6	15.5	13.30	0
Dec 27	07:31:50	16:36:55	30.1	132.5	2	11.40	11.1	38.1	11.40	0
Dec 28	07:32:06	16:37:39	33.8	96.5	2	14.40	-	-	-	
Dec 29	07:32:20	16:38:24	18.7	55.6	2	13.30	2.5	5.2	13.30	0
Dec 30	07:32:31	16:39:12	51.5	178.6	2	11.00	8.7	37.0	10.20	40
Dec 31	07:32:40	16:40:01	59.3	319.2	12	12.30	15.1	37.8	12.30	0
Jan 1	07:32:47	16:40:52	70.4	321.2	12	12.30	-	-	-	
Jan 2	07:32:51	16:41:44	17.9	45.5	2	11.30	-	-	-	
Jan 3	07:32:53	16:42:39	70.6	242.0	12	12.30	-	-	-	
Jan 4	07:32:52	16:43:35	70.2	349.1	12	12.30	10.5	32.9	13.20	-50
Jan 5	07:32:49	16:44:32	75.8	352.7	12	12.30	28.2	50.1	12.00	30
Jan 6	07:32:44	16:45:32	45.8	141.9	2	10.50	16.2	36.3	10.50	0
Jan 7	07:32:36	16:46:32	36.8	165.6	2	10.20	14.0	49.5	10.20	0

Jan 8	07:32:26	16:47:34	37.4	145.8	2	14.10	11.8	34.2	14.10	0
Jan 9	07:32:14	16:48:37	20.1	98.4	2	9.20	3.9	30.0	9.20	0
Jan 10	07:31:59	16:49:42	33.4	121.5	12	11.40	7.7	27.7	11.40	0
Jan 11	07:31:42	16:50:48	21.9	123.8	12	12.30	3.4	26.7	12.30	0
Jan 12	07:31:22	16:51:55	15.4	87.4	2	14.20	-	-	-	
Jan 13	07:31:00	16:53:03	78.7	306.2	12	12.40	25.6	46.0	12.00	40
Jan 14	07:30:36	16:54:12	82.0	322.1	12	12.50	26.8	46.4	12.10	40
Jan 15	07:30:09	16:55:22	82.0	328.6	12	12.50	24.4	42.9	11.40	70
Jan 16	07:29:40	16:56:33	81.1	290.0	12	12.10	25.1	45.1	12.20	-10
Jan 17	07:29:09	16:57:44	77.9	295.5	12	12.10	21.0	41.1	12.20	-10
Jan 18	07:28:36	16:58:57	75.2	276.7	12	12.10	19.1	36.7	13.10	-60
Jan 19	07:28:00	17:00:10	83.0	306.9	12	12.10	19.5	35.5	12.40	-30

5.1 Illuminance Uniformity

The authors considered the parameter “Illuminance Uniformity” to verify the improvement of internal visual comfort compared to that obtained with the DLP.
According to the EN12464-1, it can be defined in two different ways, as shown respectively in equations 1 and 2:

$$U_0 = \frac{E_{min}}{E_{avg}} \tag{1}$$

$$U'_0 = \frac{E_{min}}{E_{max}} \tag{2}$$

Table 3, and Figures 11 and 12 show the calculated values of U_0 and U'_0 for all the test days at 10.00, 12.30 and 15.30.

Table 3. Calculated values of Illuminance uniformity.

	h 10.00		h 12.30		h 15.30	
	U_0	U'_0	U_0	U'_0	U_0	U'_0
Dec 22	0.69	0.43	0.71	0.50	0.66	0.40
Dec 23	0.79	0.58	0.71	0.38	0.75	0.53
Dec 24	0.82	0.62	0.70	0.34	0.70	0.47
Dec 25	0.09	0.06	0.55	0.36	0.48	0.29
Dec 26	0.23	0.14	0.63	0.41	0.13	0.08
Dec 27	0.60	0.39	0.71	0.51	0.32	0.19
Dec 28	0.61	0.41	0.71	0.51	0.71	0.49
Dec 29	0.26	0.16	0.63	0.43	0.43	0.26
Dec 30	0.81	0.61	0.77	0.50	0.63	0.40
Dec 31	0.83	0.63	0.68	0.29	0.61	0.39
Jan 01	0.72	0.50	0.68	0.29	0.82	0.60
Jan 02	0.60	0.39	0.65	0.44	0.00	0.00
Jan 03	0.78	0.58	0.70	0.35	0.61	0.40
Jan 04	0.82	0.63	0.67	0.27	0.73	0.50
Jan 05	0.76	0.63	0.40	0.27	0.74	0.61
Jan 06	0.70	0.50	0.73	0.48	0.51	0.31
Jan 07	0.78	0.58	0.70	0.50	0.45	0.26
Jan 08	0.56	0.36	0.71	0.51	0.81	0.60
Jan 09	0.69	0.46	0.68	0.47	0.00	0.00
Jan 10	0.71	0.50	0.70	0.49	0.48	0.30
Jan 11	0.60	0.41	0.72	0.46	0.63	0.41
Jan 12	0.00	0.00	0.54	0.34	0.13	0.07
Jan 13	0.81	0.62	0.67	0.35	0.82	0.59
Jan 14	0.80	0.62	0.67	0.35	0.83	0.60
Jan 15	0.80	0.62	0.66	0.34	0.82	0.59
Jan 16	0.81	0.62	0.67	0.37	0.82	0.58
Jan 17	0.80	0.60	0.65	0.34	0.81	0.57
Jan 18	0.79	0.60	0.69	0.39	0.79	0.60
Jan 19	0.79	0.61	0.65	0.33	0.83	0.60

From data reported in Table 3 and Figures 11 and 12 we can deduce that the illuminance uniformity is not ideal, because U_0’ is higher than 0.5 only in 38 % of cases, it is never higher than 0.8 and it is lower than 0.4 in 39 % of cases. Furthermore, U_0 is higher than 0.8 only in

18 % of cases and lower than 0.5 in 16 % of cases, while in 66 % of cases it ranges between 0.5 and 0.8 (31 % between 0.7 and 0.8 - 29 % between 0.6 and 0.7 - 5 % between 0.5 and 0.6).

On the other hand, some authors underline that these criteria seem to be too restrictive for environments illuminated with natural light where a lower degree of uniformity is tolerated by users if compared to similar situations but with the use of artificial light (Dubois 2001).

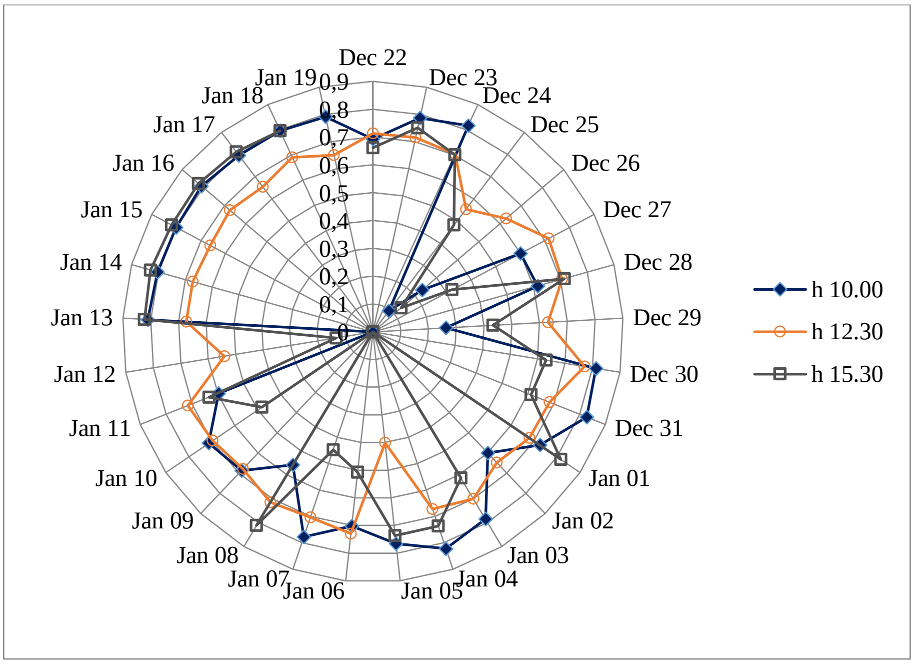

Figure 11. Illuminance uniformity U_0 on the work plane for all the test days, at 10.00, 12.30, and 15.30.

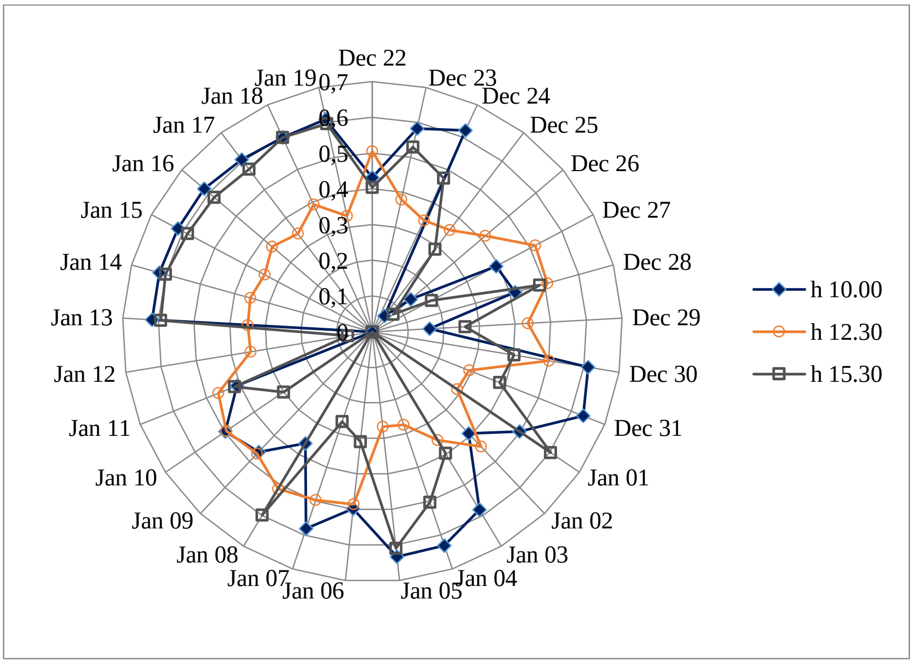

Figure 12. Illuminance uniformity U_0' on the work plane for all the test days, at 10.00, 12.30, and 15.30.

Table 3, and Figures 11 and 12 show that U_0 and U_0' have similar values for some days (i.e. 13-19 Jan). This trend is typical of sunny days with high external illuminance. In these cases, the illuminance uniformity is very similar at 10.00 and 15.30 and it is significantly lower at 12.30, probably due to the high value of solar elevation that causes less spatial penetrating reflections of solar radiation. Figure 13 shows the results on January the 16th as an example of a sunny day. Sensors in positions 2 and 12 have the maximum values all the time with high illuminance between 12.00 and 13.00, respectively 287 lx in position 12 at 12.20, and 242 lx in position 2 at 13.00. In the other measure positions, illuminance ranges between 100 and 160 lx. It is noteworthy that the maximum values of illuminance take place further away from the system, probably due to the reflections from the light shelf, so improving the light uniformity on the work plane.

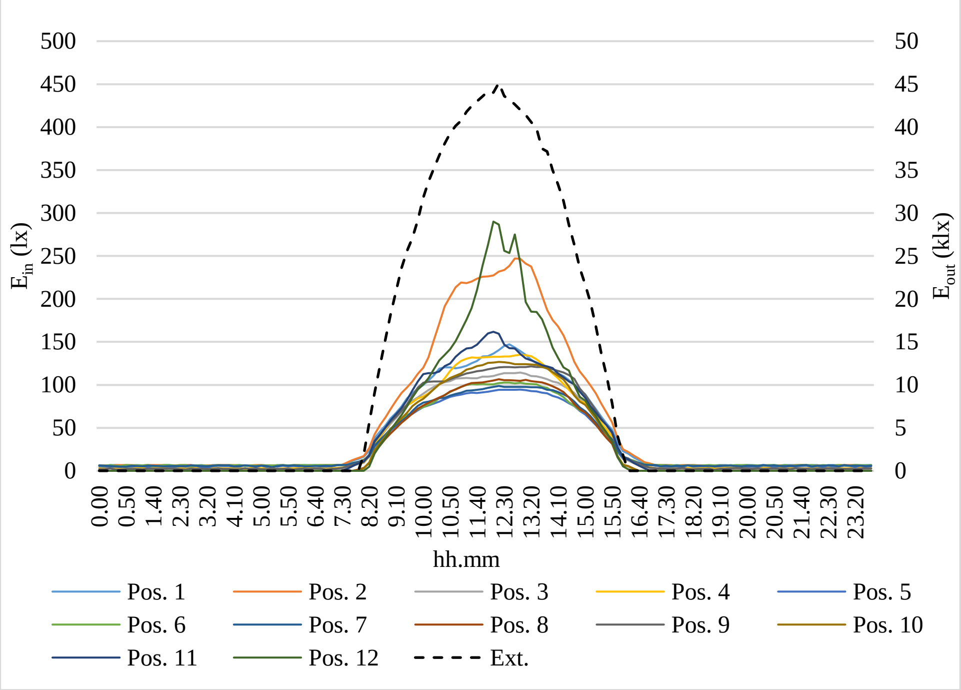

Figure 13. Illuminance data on January the 16th - External illuminance referred to the right axis

When direct solar radiation is quite absent and external illuminance is low, such as during cloudy days, the internal illuminance trend is very similar to the external one, without peak values. Figs. 14 and 15 show the results on December 25 and 26 as an example of this situation.

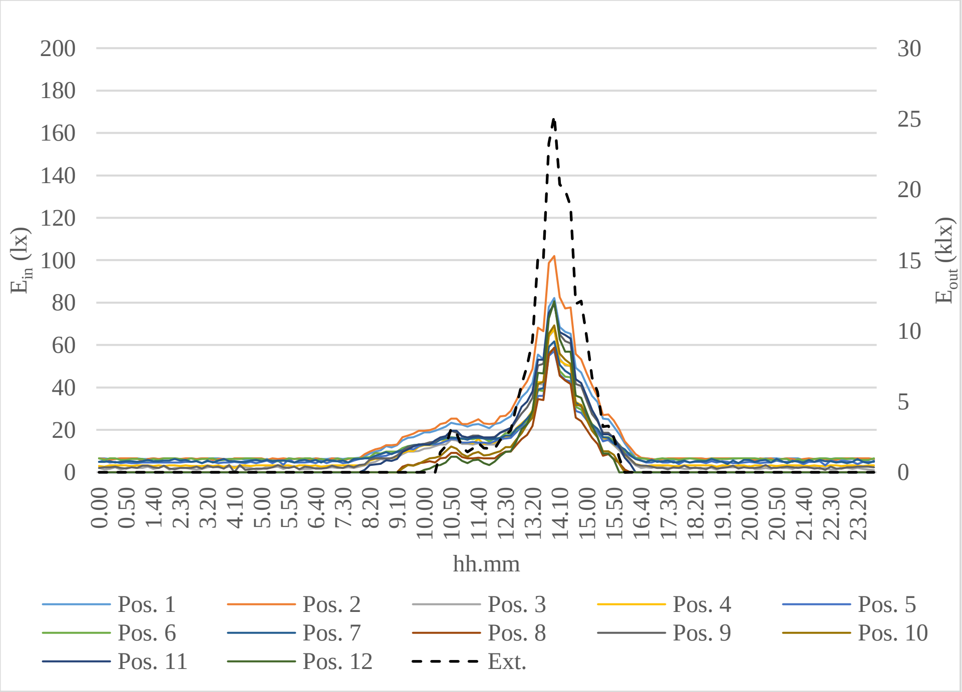

Figure 14. Illuminance data on December the 25th - External illuminance referred to the right axis

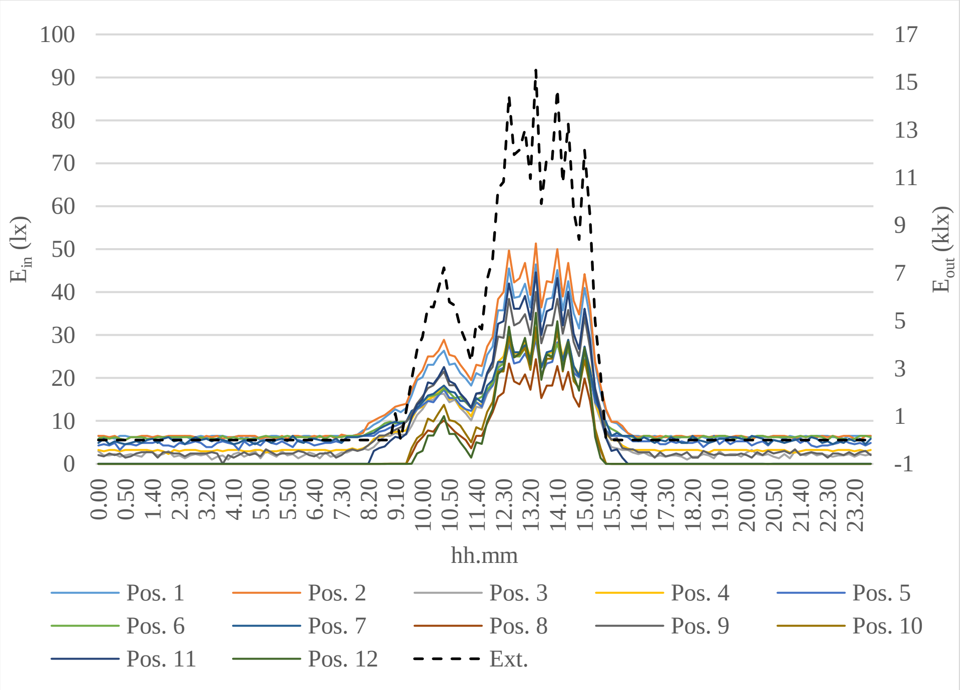

Figure 15. Illuminance data on December the 26th - External illuminance referred to the right axis

Note that also in these cases, the maximum values of internal illuminance take place in the corners of the room (position 1, 2, 11 or 12) as evidence of the fact that even in the absence of intense direct solar radiation, the light shelf effectively contributes to the diffusion of light in the environment.

6. Conclusions

In this paper the authors have described the results of a preliminary experimental activity carried out on a reduced scale model of the Modified Double Light Pipe (MDLP), an innovative daylighting system, set up to improve the performance of the Double Light Pipe (DLP) previously developed by the authors.

The experimental activity has been carried out in winter climatic conditions, between December 2021 and January 2022. The first results seem to be appreciable and encourage further investigation to better define the performance of the device.

Some problems of the DLP have been significantly attenuated: the cut of the lower part of the external tube decreases the overall dimensions of the system and the application of a light shelf on its upper portion reduces the risk of glare and improves the illuminance uniformity on the horizontal work plane.

Besides, taking into account that the tests have been carried out in winter climatic conditions, illuminance data on the work plane can be considered satisfactory for underground environments and they reach high values on sunny days.

Finally, the technological components of the system have been described in detail, as well as the installation procedure to a generic brick concrete roof slab.

The authors intend to continue the experimental activity on the scale model of the MDLP in order to collect a sufficient amount of data available to define the principal daylight dynamic parameters, as for example the Spatial Daylight Autonomy or the Useful Daylight Illuminance. In addition, they are going to carry out a parametric analysis of the performance of the MDLP through a numerical activity.

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