Effects of an Indoor Living Wall on Room Lighting Conditions: Comparison Between Measured and Simulated Data

Matteo Ghellere – ITC-CNR, Italy – ghellere@itc.cnr.it
Alice Bellazzi – ITC-CNR, Italy – bellazzi@itc.cnr.it
Anna Devitofrancesco – ITC-CNR, Italy – devitofrancesco@itc.cnr.it
Benedetta Barozzi – ITC-CNR, Italy – barozzi@itc.cnr.it

Abstract

In recent years, vertical greening systems have been progressively used not only on the external side of the building but also within indoor spaces. In parallel to other IEQ domains as thermal comfort, air and acoustic quality, an Indoor Living Wall (ILW) impacts lighting quality. In lighting design with specific simulation software, it is fundamental set the most appropriate colouration and reflectance coefficients (ϱ_s) of the surfaces. Otherwise, plants' reflectance coefficients are difficult to estimate since they do not have any of the following characteristics: planarity, colour and texture uniformity. In addition, each plant's essence is characterized by peculiar lighting and growing properties. These factors make the design process quite tricky because the unknown distance between simulated lighting conditions and real lighting performances is difficult to be evaluated in advance. This research describes a case study where a room containing an ILW is simulated with DialuxEVO and then compared and validated with in situ monitored data. An empirical procedure for estimating ϱ_s of the ILW in situ is used. The aim is to assess the level of precision of the previous procedure by comparing measured and simulated lighting data in order to carry out useful hints for ILW lighting simulations for designers.

1. Introduction

After the Coronavirus disease in 2019 (COVID-19), the design of a comfortable indoor space is even more urgent, considering also that people spent from 80 % to 90 % of their time indoors (Kaushik et al., 2020) and considering all the implications that the indoor environment has on productivity and physiological and psychological aspects (Li et al., 2022). The building design is becoming human-centred, oriented to satisfy, at the same time, resource savings optimizing human health, comfort, and productivity in a holistic approach (Lassen et al., 2021). There is a strong connection between Indoor Environmental Quality (IEQ), such as thermal comfort, acoustic comfort, air quality and visual comfort (Salamone et al., 2022; Mujan et al., 2021) and health and productivity, with a connection between perception and energy consumption (Pisello et al., 2021). In recent years, scientific research has been paying increasing attention to the positive effects produced by the presence of Vertical Greenery Solutions (VGS) in indoor environments in terms of users' satisfaction, control of air quality, temperature and relative humidity (Salamone et al., 2020). In literature, green walls are commonly divided into two categories: "green facades (GF)", ground-based, usually with climbing plants along the wall, and "living walls (LW)", which include planted technologies to be applied directly on the wall without connection to the ground and a uniform growth along the surface (Gunawardena & Steemers, 2019). In interior environments, living walls (ILW from now on) are the widely used solutions and their indoor application is becoming more frequent with benefits in relation to particles and VOC retention and CO_2 concentration (Torpy et al., 2017), temperature and humidity control (Fernández-Cañero et al., 2012) (Egea et al., 2014), acoustic (Scamoni et al., 2022) and well-being (Gunawardena & Steemers, 2019). Since VGS are living elements, their performances are influenced by their health/stress status: it has been demonstrated for years that the health level of these elements is related to chlorophyll activity and content (Gitelson & Merzlyak, 1996), but daylight is not sufficient for the correct growth of the ILW and the integration of an artificial lighting system may be necessary (Tan et al., 2017). Good lighting is by definition human-centric, as suggested by Houser et al. (2021), but the assessment of the visual environment through human perception is often complicated and

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needs, during the design phase, the maximum accuracy of the main parameters and indicators which influence the lighting environment (Bellazzi et al., 2022). Most used lighting indicators are related to illuminance level (EN 12464) and glare (UNI 11165), (EN 17037). The calculation of these indicators, especially in the design phase, needs a detailed knowledge of the building morphology, lighting facilities and of their optical properties. Among the factors, the reflection coefficient of surfaces (ϱ) is both one of the most influential (Makaremi et al., 2017) and difficult to estimate correctly, mainly in real environments (Peña-García & Salata, 2020). The assessment of these indicators is complex since indicators and variables often change dynamically but current models can analyse them in a predictable way. Another complex issue is the ILW modelling for lighting analysis. ILW, with respect to a usual indoor wall material, is not homogeneous in different aspects such as roughness, colour and placement/planarity of its leaves. In addition, light spectrum characteristics strongly affect plant growth leading to an unpredictable change of previous properties (Wu et al., 2019).

The paper aims to investigate ILW impacts on indoor lighting environments comparing monitoring campaign data of an ILW installed within a test cell and lit by a dedicated lighting system with the simulated data provided by the correspondent model made up with DialuxEVO 9.2 software (DIAL GmbH 2021). The most important lighting variables are evaluated: illuminance on the horizontal plane, vertical illuminance (on ILW, room wall surfaces and at eye level of the seated users), ILW and room walls surface luminance. Finally, a simplified and empirical estimation of the ILW reflectance coefficient is performed useful for lighting design purposes.

2. Methodology

The experimentation is conducted in a Test Room of the Construction Technologies Institute of the National Research Council of Italy (ITC-CNR, Milan) with no transparent openings with inner dimension of 4.95x2.8x2.8 meters (L x W x H). The ILW, installed on the room wall facing South (South wall), is lit by 4 spotlights with different light cones aperture of 38° and 60°. All lamps are LED based with the same colour temperature and power. The ILW is divided into 4 quadrants of 1x1 m, each characterized by a different planted essence as reported in Fig. 1 and fed throughout the test period by a dedicated irrigation system. Spotlights are aligned to quadrant centres: spotlights L1 and L4 lights (60° aperture angle) to upper quadrants UL and UD, spotlights L2 and L3 (38° aperture angle) to lower quadrants BL and BR. The experimentation is divided in two phases: T_0 and T_1, respectively before and after the ILW installation. During both phases, Illuminance and Luminance are measured on the same grid-points. Specifically, the following measurement points are considered: 25-points of a vertical grid on ILW (Fig. 2 b), 10-points of a vertical grid on the side walls (Fig. 2 c-d) and 15-points of a horizontal grid placed 0.80 meters above floor level (Fig. 2 a).

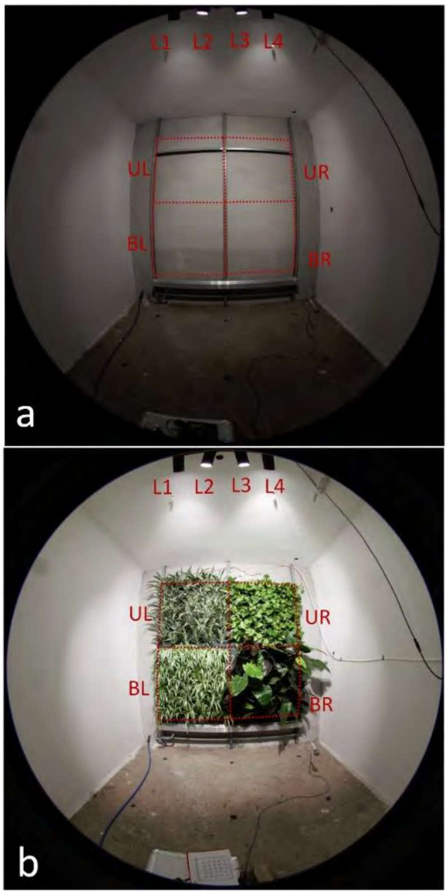

Fig. 1 – View of the ILW within the test cell in T0 (a) and T1 (b) through videophotometer

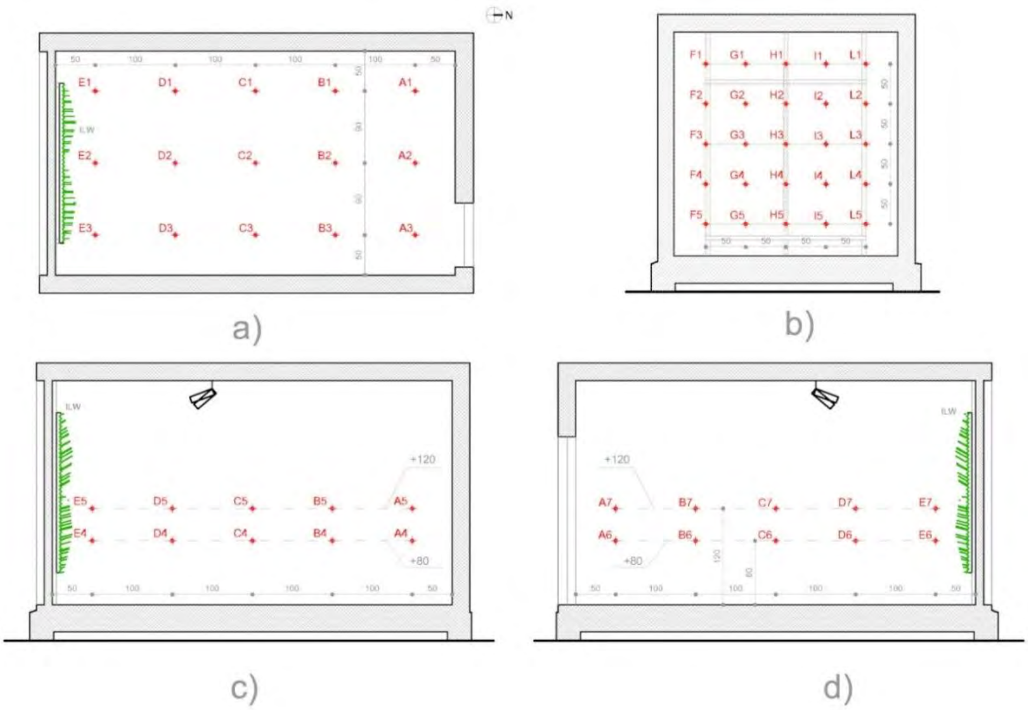

Fig. 2 – Position of the measurements points on horizontal plane (a), ILW surface (b), West side wall (c) and East side wall (d)

Vertical (E_v) and horizontal (E_h) Illuminance measurements are manually collected with a portable luxmeter (Konica Minolta T10) in order to avoid shadows on the receptor due to operator presence and waiting 30 seconds after luxmeter placement before recording the illuminance measure. The luxmeter is always placed on a fixed support so that it is always perpendicular to the surface to be measured and is not tilted: a support 80 cm high in the case of E_h and directly towards the wall at heights 80 and 120 in the case of E_v. Luminance measurements are collected only for vertical walls (L_s) through High Dynamic Range (HDR) images taken with a LMK videophotometer equipped with a 180° fisheye lens. Data measured in-situ during the phase T_0 were used to validate the geometric model of the Test Room in DialuxEVO with the following steps: a) calculation of ϱ_s values of the walls according to Lambert Cosine law using $L_{s,situ}$ and E_{vsitu} values; b) application of the previous reflectance values to the DialuxEVO model surfaces; c) calculation of the illuminance ($E_{v,calc}$) and luminance ($L_{s,calc}$) values over the same grid points; d) validation of the lighting conditions of the empty room. After ILW installation (T_1) reflection coefficients ϱ_s are estimated using in situ data of surface luminance and illuminance values. In order to test the feasibility of an on-field method of reflectance estimation, two methods are tested. The first (method I) uses both the in-situ data, surface luminance L_s and surface illuminance E_s, according to Lambert cosine law:

$$\rho_{s,ILW}=\frac{L_{s,situ}}{E_{s,situ}}\cdot\pi \quad (1)$$

In the second method (method II), ILW reflectance is retrieved only from in-situ surface luminance values starting from a known ϱ_s value (South wall in this case – $\rho_{s,south}$) and by adjusting it proportionally to the South wall / ILW luminance (L_s) ratio and considering also the variation of the distance between lights and surface centres of south wall (d_{south}) and ILW (d_{ILW}) using the inverse square law:

$$\rho_{s,ILW}=\frac{L_{s,situ,ILW}}{L_{s,situ,South}}\cdot\left(\frac{d_{ILW}}{d_{South}}\right)^2\cdot\rho_{s,South} \quad (2)$$

In both cases, ILW quadrants are assumed to be homogeneous and planar. Subsequently, ILW reflection values are transferred in the DialuxEVO model (Fig. 3) for the calculation of the Luminance and Illuminance values and their comparison with in situ measurements.

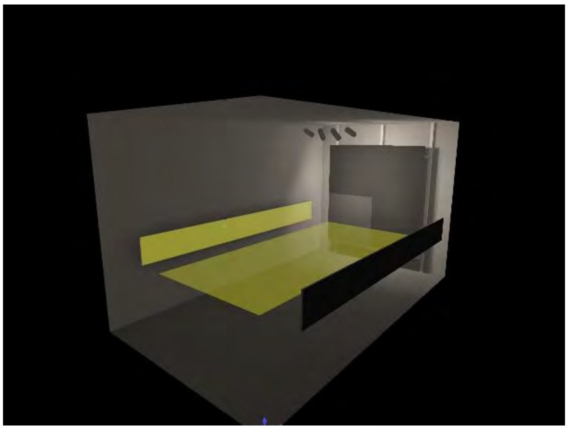

Fig. 3 — View of the DialuxEVO model of the test room

3. Results

In the first step, Luminance and Illuminance values are recorded in situ at T_0 in order to define ϱ_s values. Results are showed in Table 1, Table 2 and Table 3.

Table 1 – T_0 – test room – measured luminance, illuminance and reflectance values on West wall

Point	A4	A5	B4	B5	C4	C5	D4	D5	E4	E5
$L_{s,situ}$	21	24	31	34	45	48	73	81	131	168
$E_{v,situ}$	80	90	108	120	160	170	240	275	390	565
ϱ_s	0.82	0.84	0.89	0.88	0.89	0.89	0.95	0.93	1.05*	0.94

Table 2 –T_0 – test room – measured luminance, illuminance and reflectance values on East wall

Point	A6	A7	B6	B7	C6	C7	D6	D7	E6	E7
$L_{s,situ}$	25	27	29	32	45	49	80	90	151	186
$E_{v,situ}$	80	95	110	116	160	175	285	325	500	625
ϱ_s	0.96	0.88	0.83	0.86	0.87	0.88	0.88	0.87	0.95	0.93

Table 3 – T_0 – test room – measured luminance, illuminance and reflectance values on South/ILW wall

Point	G1	G2	G3	G4	G5	I1	I2	I3	I4	I5
$L_{s,situ}$	176	245	245	187	119	191	248	254	206	123
$E_{v,situ}$	1210	1723	1685	1310	895	1318	1755	1800	1400	860
ϱ_s	0.46	0.45	0.46	0.45	0.42	0.46	0.44	0.44	0.46	0.45

The followed approach allows, in absence of the ILW, to estimate the ϱ_s values of the south wall and side walls respectively to 0.45 and 0.89 with a correspondent standard deviation of 0.01 and 0.04. Within the calculation process, measurement points giving unrealistic reflectance values were discarded (i.e. E4) as well as for measurement points placed on ILW frame (points belonging to F, H and L columns). Previous ϱ_s values were used in DialuxEVO in order to calibrate the room model without the ILW installed (T_0). In this sense, Table 4 reported the main calculated values with DialuxEVO model and the comparison with the correspondent measured data.

Table 4 –T_0 – Comparison of measured/simulated data for East, West and South/ILW wall

Wall	$L_{s,max}$	$L_{s,min}$	E_v med	E_v Max	E_v min	$\Delta L_{s,m}$	$\Delta E_{v,m}$
West situ	168	21	220	565	80		
West calc	166	34	243	593	121	6	26
East situ	186	25	247	625	80		
East calc	156	34	240	583	117	14	33
South/ILW situ	248	119	1271	2180	645		
South/ILW calc	247	117	1261	2039	669	4	38

Observing the results, calculated mean Illuminance values differ from real ones by 3 % of the mean E_v on the south wall and up to 14 % of the East/West wall mean value. At the same time the comparison between Luminance values collected by HDR images and DialuxEVO model prediction shows a minimum difference ranging from 4 cd/m² on South-ILW wall to 14 cd/m² on West wall corresponding respectively to 2 % and 15 % of the mean measured value. Luminance maximum values are similar in ILW and the West wall, while lowest values are higher when simulated on DialuxEVO. Focusing on DialuxEVO side wall Luminance and Illuminance data, an overestimation of values on farthest points from ILW can be noted, receiving only reflected light. In relation to scenario T_1, the measured Illuminance values on ILW grid points are reported in Table 5.

Table 5 – T1 – test room – measured illuminance on ILW wall

Point/ $E_{v,situ}$	F	G	H	I	L
1	1240	1900	2470	2070	1230
2	1290	2160	2720	2270	1325
3	1265	2035	2210	2370	1230
4	1050	1290	1220	1000	750
5	540	630	620	670	510

ILW $L_{s,situ}$ values are determined for each quadrant by averaging the luminance values of the belonging pixels. Subsequently, the E_m value of each ILW quadrant is determined from belonging measurement points (one placed on the quadrant centre and eight on the quadrant edge) and, finally, the reflection coefficients are calculated according to method I (Table 6).

Table 6 – Method I – Summary of the calculation of reflection coefficient

Q	$E_{v,situ}$	$L_{s,situ}$	ρ_{ILW}
Q_{UL}	1921	37	0.06
Q_{UR}	1988	39	0.06
Q_{BL}	1206	43	0.11
Q_{BR}	1175	15	0.04

In order to apply method II, the measured distances between reference spotlight and correspondent ILW quadrant are 1.66 m for Q_{UL} and S_{UR} and 2.27 m for Q_{BL} and Q_{BR}. Since the ILW plane is 30 cm nearer to spotlights, the d_{ILW}/d_{South} factors are respectively 0.85 for S_{UL} and S_{UR} and 0.90 for Q_{BL} and Q_{BR}. Table 7 summarizes the calculation of ILW reflection coefficient according to method II.

Table 7 – Method II – summary of the calculation of the ILW reflection coefficient

	South wall		ILW		
Q	Ref. point	$L_{s,situ}$	$L_{s,situ}$	d_{ILW}/d_{South}	ϱ_{ILW}
Q_{UL}	G2	245	37	0.85	0.11
Q_{UR}	I2	248	39	0.85	0.11
Q_{BL}	G4	187	43	0.90	0.19
Q_{BR}	I4	206	15	0.90	0.06

By a quick comparison, method II leads to higher reflection coefficients for all the ILW quadrants. Previous reflectance values are then alternatively assigned to ILW within the DialuxEVO model and the obtained results are reported in Table 8.

Table 8 – T_1 - Summary of results obtained with DialuxEVO using method I and method II

Wall	L_s max	L_s min	E_v med	E_v max	E_v min	$\Delta L_{s,m}$	$\Delta E_{v,m}$
ILW situ	43	15	1443	2720	510		
ILW(I)	38	14	1252	2619	353	1	154
ILW(II)	69	22	1264	2632	365	10	154
East situ	131	12	151	460	35		
East (I)	100	15	123	375	48	13	62
East (II)	105	17	136	385	57	12	61
West situ	131	12	122	370	35		
West(I)	107	13	125	401	57	10	22
West (II)	111	17	137	410	57	10	18

The comparison of results carried out by method I and method II with real measurements shows, in most of cases, similar performances. Simulated maximum luminance values ($L_{s,max}$) are generally lower compared to those measured while $L_{s,min}$ are in line or slightly higher than measured. In this sense method II on ILW represents an exception with high luminance values up 50 % above measured. Focusing on illuminance analysis, calculated mean values were about 20 % lower than those measured, while $E_{v,max}$ tend to be similar and $E_{v,min}$ were significantly higher in the DialuxEVO model, especially on side walls with an overestimation of about 60 %. In order to validate the results obtained by applying the proposed methodology, the difference between simulated and measured values of luminance and illuminance are assessed and the correspondent standard deviation are calculated ($\Delta L_{s,m}$ and $\Delta E_{v,m}$ respectively). Calculated errors are similar for both methods. The main difference between the two methods regards ILW Luminance error because with method I the results are close to measured values (1) while method II calculation carries out a significant higher standard deviation value (10).

4. Discussion

The research described in the previous chapters shows significant differences between measured and simulated values of Luminance and Illuminance. In particular, it could be noted that values calculated with DialuxEVO tend to be closer to reality in direct lighting conditions while in diffuse or indirect lighting they deviate more with respect to measured data.

However, such data must be contextualized in relation to the visual well-being issue, by comparing specific indicators as the mean illuminance (E_m) and the illuminance uniformity ($U_{x/y}$), considered in technical standards (i.e. EN 12464-1 technical standard). Focusing on E_m indicator, calculated values with both methods are often lower than measured ones with a range of difference of 1 to 18 % according to the surface typology. For lighting design, the analysis over the horizontal plane is very important, where task illuminance and uniformity requirements must be satisfied (or achieved). Table 9 reports the comparison of results of all the considered scenario related to the horizontal plane.

Table 9 – Overview of the indoor lighting indicators values measured/calculated on the horizontal plane

	$E_{h,m}$	$E_{h,max}$	$E_{h,min}$	$U_{min/m}$	$U_{max/min}$
$T_{0,situ}$	440	1470	100	0.23	0.07
$T_{0,calc}$	392	1439	130	0.33	0.09
$T_{1,situ}$	298	980	50	0.17	0.05
$T_{1,I}$	268	1151	55	0.21	0.05
$T_{1,II}$	286	1195	65	0.22	0.05

The calculated $E_{h,m}$ values are lower (up to 11 %) with respect to the measured ones even on the horizontal plane. The overestimation of lower values in calculation influences the uniformity ratio $U_{min/m}$: the difference is lower when ILW is installed. On the contrary, the $U_{min/max}$ is substantially the same. Focusing on T_1 scenario, method I gives better uniformity results than method II.

Considering the implications of the previous results on lighting design, two aspects are to be pointed out. Firstly, the test room conditions are intentionally unusual (no openings, only directional lights towards ILW, no diffuse light) in order to emphasize the ILW contribution on the lighting environment. This fact implies that the results provided with the DialuxEVO model are very sensitive to the position of the grid of measurement, especially in points characterized by extreme lighting conditions (with very high or very low Illuminance). Secondly, despite the different E_m values, no subjective difference in lighting perception was expected. In fact, according to the EN 12464-1 standard, a 1.5 multiplication factor between subsequent levels of illuminance is the minimum threshold for the detection of changes in the lighting environment for a user. Both in T_0 and T_1, the E_m difference respects that threshold. And the fulfilment of the illuminance perception threshold reported by a previous standard has been verified in T_1 scenario, for 59/60 measurement points with method I, and for 57/60 measurement points with method II.

5. Conclusion

The experimentation demonstrated the differences of Illuminance and Luminance values in a room with an ILW, comparing measured data and simulation models outputs. However, the difference between measured and simulated data does not influence the overall lighting comfort and keeps the lighting design performance previsions valid. Both the proposed empirical assessments of the ϱ_s value represent a good compromise between the precision of results and the ease of assessment of the reflectance coefficient of ILW by spot measurements of surface Illuminance and Luminance with portable instruments like luxmeters and luminance meters. Investigating the results, method I, using both in-situ luminance and illuminance input data with the Lambert cosine law, ensures a slightly better precision than method II, that only uses in-situ luminance data, especially on luminance assessment. According to obtained results, the modelling of ILW elements could be reasonably simplified reducing the time and the effort of the design process. However, the presented results compare real data of a particular lighting scenario that is not common in current building rooms and spaces. Even if the absence of natural light allows for a better control of the internal parameters, in the next step a different lighting scenario will be considered. Another limit of this research is that the monitored data have been compared with a unique software. Despite its wide diffusion between professionals (DialuxEVO), the next step will be to compare monitored data with different software output. In this sense, future research activities could deepen the proposed methodology by a results comparison with other modelling software/engines such as Blender or Radiance and considering standard artificial lighting configurations that allows also a deep customization of surface lighting properties.

Nomenclature

Symbols

Δ	Deviation (measure units, -)
E	Illuminance (lux)
L	Luminance (cd/m^2)
Q	Quadrant (-)
ρ	Optical reflectance coefficient (-)
T	Moment of measurement (-)
U	Uniformity ratio (-)

Subscripts

0	Before the installation of the Indoor Living Wall
1	After the installation of the indoor living wall
B	Bottom
ILW	Indoor Living Wall
I	Method I
II	Method II
L	Left
h	Measured on horizontal plane
m	The mean value
max	The maximum value
min	The minimum value
R	Right
U	Up
v	Measured on vertical plane
VGS	Vertical Greenery Solutions
Calc	calculated with DialuxEVO software
Situ	Measured in test room

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