# Empirical and software verification of a simplified predictive model of luminous efficiency of light-pipes


**Bruna Luz, MSc**
*University of Sao Paulo*
*bluz@usp.br*

**Leonardo M. Monteiro, PhD**
*University of Sao Paulo*
*leo4mm@usp.br*

**Marcia P. Alucci, PhD**
*University of Sao Paulo*
*marcialu@usp.br*



## ABSTRACT

*This article presents the verification of a mathematical model for predicting the luminous efficiency of light-pipes, based on the principle of unit hemisphere and solid angles. For this, light-pipes were simulated in the software photopia and essayed under real sky conditions. The adopted method in this research is theoretical deductive, developing a luminous efficiency predictive model of light-pipes and its complementation by the lumens methods. In order to verify the results, an empirical inductive method was applied, considering physical models under real sky conditions. In addition to the empirical results, simulations were carried out in raytracing software Photopia. The first method calculates the value of the relationship (LPE) between the availability of light in the central point in the output section of the light-pipe and that in the horizontal plane of its entrance. The high correlation found between results from the measured data and results from the proposed luminous efficiency predictive model of light-pipes (LEPMLP) with the results obtained from the software Photopia, in terms of estimated values of light-pipes efficiency (LPE), showed that it is a reliable tool and is easily applicable for dimensioning this kind of system for taking advantage of daylighting in everyday architectural and building design practice, allowing to deliver daylight to rooms without direct contact with the external environment.*


## INTRODUCTION

The global scenario has been changing with the exigencies of the environment resources, which were used by past generations inconsequently. Currently, the concern for the planet and future generations puts emphasis on the use and development of efficient products that consume or use clean or renewable energy. In this context, light -pipe systems are developed to conduct the daylight to internal environments far from the envelope, as, for example, rooms without direct contact with the external environment or in undergrounds.

Consiering the advances in researches, new technological innovations have been developed to bring daylight to indoor environments. A variety of devices aimed at lighting were designed and researched to improve the quality of daylighting to increase user acceptance and provide tools for designers to specify and size these systems.

Kocifaj et al. (2008) observe that beginning research on products of light had interest in the innovative system, seeking to eliminate the deficits and gaps offered by conventional systems openings. In the beginning, installed systems have been researched and prototypes as a "black box" comparing the performance of the system as a whole with other systems. Within this group are works such as: Al-Marwaee & Carter (2006), Oaklley et al. (2000). In a second step the interest of the academic community becomes more specifically to the driver turning his scientific interests to the efficiency of those seeking to unravel the behavior of light to be conducted this phenomenon and propose predictive models resulting in the prediction of the efficiency of light transmission along the conductor and several theoretical predictive mathematical models and semi- empíricos.Esse in the case of papers presented by Swift & Smith (1995), Swift et al.(2008) and Luz et al (2010). Finally, recently, in the third stage of the research for the products of light, the interest is focused on the transport of light from the diffuser (commonly placed at the exit of the pipe-line) to the work plan or a point in this internal environment.

These searches are resulting predictive mathematical and computational models of the luminous efficiency by providing data on the luminous flux emitted by the environment in pipelines, and distributed illuminance on the working plane in lux. This allows the comparison of these systems with artificial lights and allows you to choose when you design with precise image scaling of the lighting system, allowing the association between daylighting and artificial lighting. The predictive models of light pipe efficiency have been developed by several researchers. S-DPF e E-DPF (Zhang, Muneer &Kubier, 2002), Universidade de Liverpool (Carter, 2002), Luxplots (Jenkins & Muneer, 2003), CIE Method (CIE 173, 2006). Dutton and Shao (2007) validate the software Photopia as a tool to predict the performance of pipelines, comparing this with six existing predictive methods (Wittwer, 1986; Swift & Smith, 1995; Edmonds, 1995 and Zhang et al, 2002, Jenkins & Muneer 2003, and Carters, 2002). This work presents the verification of a mathematical model for predicting the luminous efficiency of light-pipes (LEPMLP), in comparison with the results of raytracing simulation on Photopia software.

The LEPMLEP was based in the principle of projected solid angle or unit hemisphere. This principle is used by many graphic methods in order to obtain infor the sky component. Allowing the determination of its value even in situations in which the area of the luminous source is constituted by irregular forms (Hopkinson et al., 1975).

The objective of this paper is the use raytracing simulation (Photopia) to verify a mathematical simplified model that friendly estimates the light-pipe efficiency (LPE). For this, light -pipes were simulated in the software Photopia and tested under real sky conditions.

**PREDICTIVE MODEL OF LUMINOUS EFFICIENCY OF LIGHT-PIPES (LEPMLP)**

It was adopted the condition of uniform sky as source of daylight. The input section of the light-pipe is considered an emitter plane, which luminance is gathered in a horizontal unobstructed plan (considering a real situation).

The developed model predicts the value of the light-pipe efficiency (LPE), which is the ratio, in percentage, of illuminance in the output section and the available illuminance in the input section. The ratio is obtained through the sum of the illuminances in the output section of the light-pipe, arising from the luminance of the input section, as well as from the luminance of the reflected images in the mirrors, considering the successive losses due to absorption in the multiple reflections through the light-pipe.

The adopted procedure to consider the contribution of each image of the primary source (input section) is the projection of the images in the unit hemisphere considering the solid angle constituted by the input section and the centre point of the output section of the light-pipe. It's to say that luminance of the input section and its reflexions in the mirrors are delivered to the unit hemisphere.

The projected luminances in the unit hemisphere are in solid angles, constituting with the light-pipe vertical central axis angles (θi), which are the vertices of rectangles triangles, which base is the segment [(b.i)+b/2], where b is the input section length, and the height (h) is the length of the light-pipe. The value of the angle θi is determined by Equation 1.

$$\theta_i = atg\left[\left(i + \frac{1}{2}\right) \cdot \frac{b}{h}\right] \qquad (1)$$

where: i is the number of reflexions in the length of the pipe-light, or in other words, the number or images projected in the unit hemisphere; b is the input section length; h is the length of the light-pipe.

The projected luminances in the unit hemisphere produce circular sectors in the base of such hemisphere, which areas (Ai) (annulus) are defined by Equations 2 and 3.

$$a_i = \sin\theta_i \cdot r \qquad (2)$$

$$A_i = (a_i^2 - a_{i-1}^2) \cdot \pi \qquad (3)$$

where: Ai is the apparent area of the annulus; ai and ai-1 are the radius of the concentric circles determined by the projected luminances; r is the radius of the hemisphere (in this specific case, r=1).

Figure 1. Projected luminances in the unit hemisphere

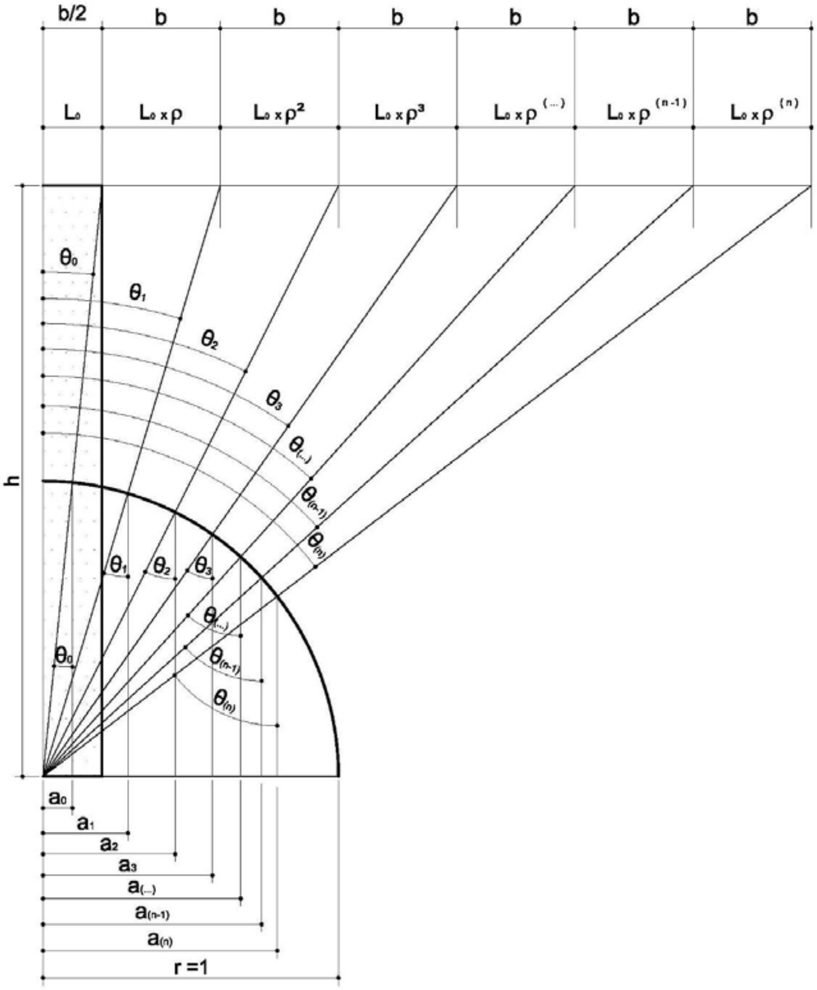
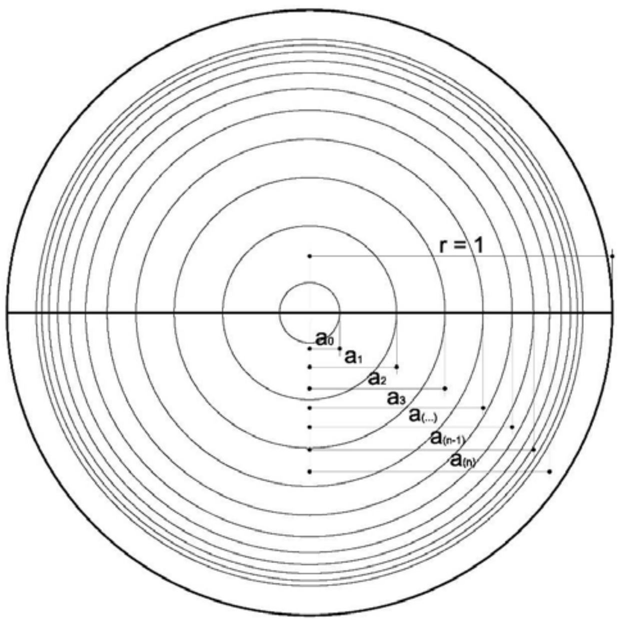



Figure 2. Annulus



The illuminance Ei is the contribution of each annulus. The sum of Ei for all annuli is the illuminance gathered in the central point of the output section, or it is to say, in the central point of the unit hemisphere. Ei is determined through Equation 4.

$$E_i = A_i \cdot L_0 \cdot \rho^i \qquad (4)$$

where: Ei is the illuminance of the annulus; Ai is the area of the annulus; L0 is the luminance in the light-pipe input section; ρ is the light-pipe internal reflectance. Considering the previous four equations, one may obtain the equation 5.

$$LPE = \frac{E_p}{E_{ext}} = \frac{\sum_{i=0}^{n} E_i}{\pi \cdot L_0} \qquad (5)$$

where: LPE is the light-pipe efficiency; Ep is the light-pipe output section illuminance; Eext is the available illuminance in the unobstructed horizontal plane; Ei is the annulus illuminance; L0 is the light-pipe input section illuminance; n is the number of the emitter plane reflections.

Mathematically, substituting equation 1 into 2, one obtains Equation 6.

$$a_i = \sin \cdot atg\left[\left(i + \tfrac{1}{2}\right) \cdot \tfrac{b}{h}\right] \qquad (6)$$

Substituting equation 6 into 3, one obtains Equation 7 and Equation 8.

When i = 0;

$$A_0 = \sin^2 \cdot atg\left(\tfrac{1}{2} \cdot \tfrac{b}{h}\right) \cdot \pi \qquad (7)$$

When i > 0;

$$A_i = \left\{\sin^2 \cdot atg\left[\left(i + \tfrac{1}{2}\right) \cdot \tfrac{b}{h}\right] - \sin^2 \cdot atg\left[\left(i - \tfrac{1}{2}\right) \cdot \tfrac{b}{h}\right]\right\} \cdot \pi \qquad (8)$$

Substituting equations 7 and 8 into 4, one obtains Equation 9 and Equation 10.

When i = 0;

$$E_0 = \sin^2 \cdot atg\left(\tfrac{1}{2} \cdot \tfrac{b}{h}\right) \cdot \pi \cdot L_0 \cdot \rho^0 \qquad (9)$$

When i > 0;

$$E_i = \left\{\sin^2 \cdot atg\left[\left(i + \tfrac{1}{2}\right) \cdot \tfrac{b}{h}\right] - \sin^2 \cdot atg\left[\left(i - \tfrac{1}{2}\right) \cdot \tfrac{b}{h}\right]\right\} \cdot \pi \cdot L_0 \cdot \rho^i \qquad (10)$$

Substituting equations 9 and 10 into 5, one obtains Equation 11, in order to predict the light-pipe efficiency (LPE).

$$LPE = \sin^2 \cdot atg\left(\tfrac{1}{2} \cdot \tfrac{b}{h}\right) + \sum_{i=1}^{n} \left\{\sin^2 \cdot atg\left[\left(i + \tfrac{1}{2}\right) \cdot \tfrac{b}{h}\right] - \sin^2 \cdot atg\left[\left(i - \tfrac{1}{2}\right) \cdot \tfrac{b}{h}\right]\right\} \cdot \rho^i \qquad (11)$$

The absolute values of LPE, obtained by equation 11, can be also considered in percentage values, as it is commonly used with the daylight factor (DF).

## SOFTWARE SIMULATION

Photopia is a general 3D luminaire design and analysis program specifically designed for non-imaging and illumination optical systems. Photopia's calculation basis is probabilistic raytracing, using real lamp geometries and measured intensity distributions, as well as measured directional reflectance and transmittance data for luminaire materials. User specified analysis settings allow for quick or detailed analyses of the luminaire design. In addition, all calculated output is available for viewing as calculations are in progress via a display update facility. In this way, a user can observe evolving output as a function of a specified percentage of the total analysis process.

Photopia includes "lamp" models for use in modeling daylight input into devices such as skylights, light pipes, solar collectors and room windows using daylight control systems. These source (lamp) models are based on the IESNA RP-21 daylight equations that model the absolute illuminance from the sun (solar disk) at various altitude angles and the sky for various sky conditions and solar altitude angles. The sky domes include variable luminance values across the hemisphere as described in RP-21. The sun models include a 0.53 deg. spread in their beam to model the actual angular size of the solar disk, averaged over its elliptical orbit. The combination of both the sun and sky dome models produces a total illuminance onto the daylighting device area that is intended to match real outdoor conditions. Keep in mind that real conditions can vary widely and the RP-21 equations represent average conditions. Such variability is what makes consistent physical measurement of daylight devices such a challenge and is one reason why daylight simulation is desirable.

Using the daylight source models is different than using the electric lamp models in Photopia's library since the daylight models illuminate the outside of a device to get light into it instead of illuminating a luminaire from within.

The default sky dome models are configured so that they uniformly illuminate about a 4' diameter area. Because of the way the light is emitted from the sky dome patches, light does spread beyond this 4' circle but it fades to a much lower level. In order to fully illuminate your device and also maximize the portion of sky dome rays that enter your device this model should also be scaled up or down depending on your device size relative to this 4' circular reference.

Since the sun and sky dome models will produce some rays that don't enter the daylight collection device, the complete model generally needs to include a shield so that the output of the device is isolated from the source models' stray light. The sky domes are relatively large in diameter since they need to generate a relatively even illuminance over an area large enough to accommodate the daylighting device. They concentrate most of their light toward the center of the hemisphere, but some light also strays away from the center. Only that light falling near the center of the hemisphere accurately models the way light is received from the sky dome.

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The efficiency (LOR) shown in the Photopia report will be the ratio of the lumens exiting the skylight divided by the total lumens produced by the sun and sky dome models. The total lumens produced by the sun and sky dome models is very large compared to the total number of lumens that are actually incident onto the daylight device. A more appropriate measure of the device efficiency is the ratio of the lumens exiting the device divided by the number of lumens incident onto it.

The studies presented by DUTTON & SHAO (2007) showed good results in using this software for predicting the performance of pipelines bright light compared to existing mathematical models. The simulations presented here, aimed to predict the transmittance of light through light pipes. For both pipe-lines were simulated with 36 input section ranging from 10cm, 20cm, 25cm, 30cm, 40cm and 50cm and lengths ranging from 1m, 1.5m, 2m, 3m, 4m and 5m.

## DATA TREATMENT

Photopia provides a photometric report in which the luminous flux emitted by the luminaire is given. This report also shows the efficiency of the light, but in the case of the pipeline. This efficiency is false because the Photopia calculates it based on total luminous flux produced by the light source, in which case the pipe-line is the celestial vault. Thus, the value of the efficiency of a lamp is always the ratio between the total fixture lumens coming out of the total lumens generated by the sources (lamps) . In the case of designs that use daylight, this result does not match the efficiency of the lamp itself, in order that the source light does not emanate from within the machine but from outside. Thus, as only a small fraction of this light is captured through the pipe-line, the calculated result is usually negligible.

Therefore, it is necessary to know the value of the luminous flux that actually enters the pipe-line so that one can calculate the correct efficiency. To calculate the luminous flux entering the pipe-line light is necessary to calculate the horizontal illuminance at the opening of the pipe-line ($lm/m^2$) and multiply it by the area of the opening.

Photopia provides an Excel spreadsheet for this calculation. This is the "Daylighting Calculator" option that is on the menu "Help". This tool provides two options for sky condition , with sun or no sun and two choices of units of measure to be chosen , the international system and the Imperial system for the simulations was chosen the international metric system , the units are in meters , lumens and lux . For these simulations we used the "Enter Altitude Solar" option because this option, simply enter the angular position of the sun and the area of the inlet opening of the collector, the spreadsheet calculates the luminous flux entering the pipe-line.

The Daylighting Calculator spreadsheet only requests diameter header pipe because it is assumed that the shape of the device is round. As the simulated pipe-lines were square in section, the area of the section was calculated and then multiplied by the value of the horizontal illuminance average daylight in the pipe-line. The average horizontal illuminance is calculated by the referred spreadsheet.

$$\phi_{in} = E_{média} \cdot A \qquad (12)$$

Where: φin is the total luminous fluz entering the pipeline; Emédia is the mean horizontal iluminance; A ia the entrance área of the pipeline.

Having obtained the luminous flux input, calculated by "Daylighting Calculator" (φin), the value of the total flux emitted by the product of light at the end of the simulation (φout) Photometric report and calculate the efficiency of the light pipe (in terms of percentage) by the following equation.

$$E = \frac{\phi_{out}}{\phi_{in}} \cdot 100 \qquad (13)$$

where: E is thelight-pipe efficiency (LPE); φout is the luminous flux from the light pipe.

**MEASUREMENTS**

For the empirical research nine light-pipes, made of wood coated by mirror (optimirror plus, reflectance ρ=0,86), with square sections of 10cm, 25cm and 40cm e lengths of 100cm, 150cm and 200cm were considered.

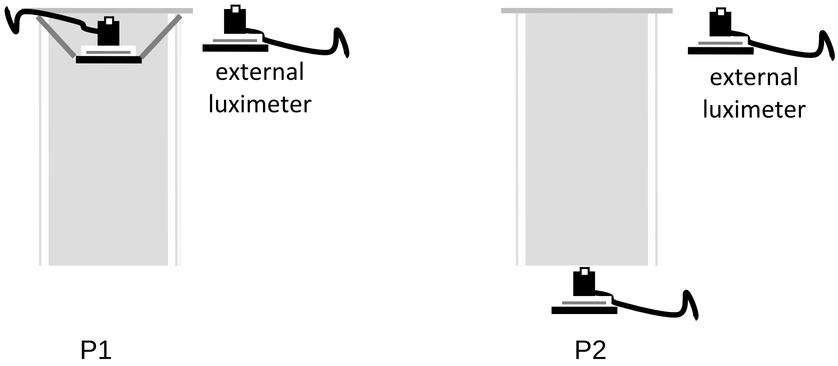
The mathematical model considers a theoretical uniform sky, thus in order to approximate the conditions of a real sky to the considered model, it was considered a real unobstructed overcast sky through the use of acrylic diffusers in the input section of the light-pipes.

The empirical field researches were done during 22/04/2009 and 06/05/2009.

Figure 3. Light-pipes of the empiric field research.

In order to log the data, digital luximeters HOMIS model 824 were used. They were set in the central spot of the input and output section of the light-pipes (respectively P1 and P2 in Figure 4). The data were collected in each point and each light-pipe one at a time, considering, as a reference, an external luximeter, measuring simultaneously the unobstructed horizontal plane.

Figure 4. Schematic illustration of luximeters positioning




## COMPARATIVE RESULTS

The results obtained in the simulations with 36 pipelines were compared with a real scale model under real sky condition (LUZ, 2009) and with results calculated using the luminous efficiency of light pipes predictive model (MPELD. These comparisons are presented in the following figures.

Figure 5. Correlation between predicted and measured LPE (light-pipe efficiency).

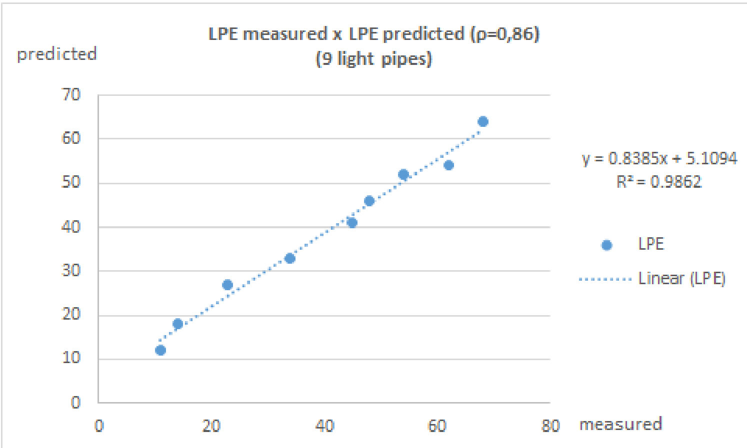



Figure 6. Correlation between predicted and simulated LPE (light-pipe efficiency).

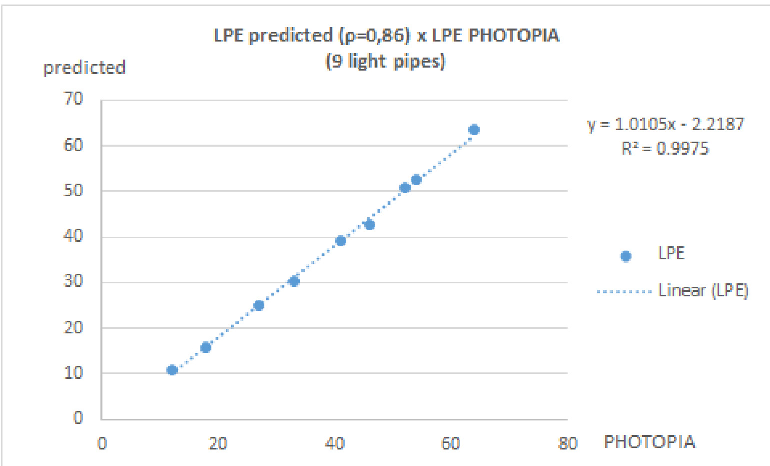
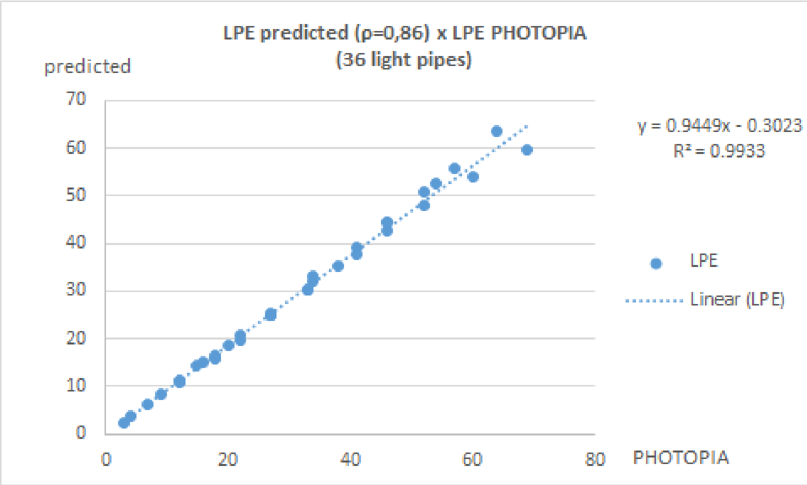


Figure 7. Correlation between predicted and simulated LPE (light-pipe efficiency).




## CONCLUSION

The high correlation found between results from the measured data and results from the proposed luminous efficiency predictive model of light-pipes (LEPMLP) with the results obtained from the software Photopia, in terms of estimated values of light-pipes efficiency (LPE), showed that the model is a reliable tool and is easily applicable for dimensioning light-pipes, taking advantage of daylighting in everyday architectural and building design practice, allowing to deliver daylight to rooms without direct contact with the external environment.

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## REFERENCES


ABNT – Associação Brasileira de Normas Técnicas. NBR 15215-4. Iluminação Natural – Parte 4 – Verificação Experimental das Condições de Iluminação Interna de Edificações – Método de Medição. Rio de Janeiro, 2005. 13 p.

Al-Marwaee, Mohammed & Carter, David. Tubular guidance systems for daylight: Achieved and predicted installation performances. Applied Energy 83, 2006. p. 774–788.

CARTER, D.J. The measured and predicted performance of passive solar light pipe systems. Lighting Research and Technology 34,1. 2002. p. 39-52.

CIE – Commission Internationale de L'Eclairage. Techinical Report. Tubular Daylight Guidance Systems.CIE 173, 2006.

Hopkinson, R.G; Petherbridge, P.& Longmore, J. Iluminação Natural. Lisboa, Fundação Kalouste Gulbenkian, 1975.

Jenkins, David & Muneer, Tariq. Light-pipe prediction methods. Applied Energy 79, 2004. p. 77–86.

KOCIFAJ, M., DARULA, S., KITTLER, R. HOLIGILM: Hollow light guide interior illumination method – An analytic calculation approach for cylindrical light-tubes. Solar Energy, 2008.

LUZ, B., ALUCCI, M. and MONTEIRO, L. M., (2010). A luminous efficiency predictive model of light-pipes. In 10th REHVA WORLD CONGRESS "Sustainable Energy Use in Buildings" (CLIMA-2010), Antalya, Turkey, May 09-12.

OAKLEY, G; RIFFAT, S.B. & SHAO, L. Daylight Performance of Lightpipes. Solar Energy. Vol. 69, N° 2, 2000. p. 89-98.

SWIFT, P.D; LAWLOR, R.; SMITH, G.B. & GENTLE, A. Retangular –section mirror light pipes. Solar Energy Materials & Solar Cells 92. 2008. p. 969-975.

SWIFT, P.D; SMITH, G.B., Cylindrical mirror light pipes. Solar Energy Materials & Solar Cells 36. 1995. p. 159-168.

ZHANG, X. MUNEER, T. and KUBIE, J. A design guide for performance assessment of solar light-pipes. Lighting Research and Technology 34. 2002.