School of Environmental Engineering
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Smart natural lighting systems.

Development & optimization of light pipes with integrated low energy consumption artificial lighting, managed by smart controls.

A Thesis submitted in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

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March 2021

To my precious Maya
and
my loving parents

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Acknowledgments

Writing a PhD thesis is a time-consuming and painful task, especially for students working and supporting a family. It has certainly been a long journey for me, with many ups and downs; changing subjects, setting up experiments, computers breaking down, a million things going wrong… On top of all of that, life happens!

However, I have been lucky to have had people supporting me to keep going. On that note, I would like to thank my supervisor, Prof. Denia Kolokotsa, for providing academic and emotional support and for her patience and persistence, during my PhD. She has been an inspirational female figure and mentor for me, and my daughter and we owe her a lot!

I would also like to thank Prof. Theocahris Tsoutsos and Prof. Agis Papadopoulos, as well as all the members of the PhD committee, for their guidance and feedback. The staff of EMBER lab has provided invaluable assistance. Dr Kostas Gobakis, Dr Nikos Kampelis and Dr Sotiris Papantoniou, I cannot thank you enough!

Part of the work described in this Thesis was initiated and funded from the European Commission, through the European Project: Holistic energy-efficient retrofitting of residential buildings (HERB), Grant agreement ID: 314283. HERB was the first large-scale project I participated in and I will always remember the rest of the participants with appreciation. I also owe a lot to the people that helped me write the relevant to this Thesis papers: Ioannis Kousis, Harris Asproulias and Ioannis Giannarakis.

My friends and family have always been supporting me, in whatever I have endeavoured. I would like to thank my partner, Matt, for his support; my friends, Elena Papagiannopoulou, Maria Saliari, Afroditi Synnefa, Theoni Karlessi, for being the siblings I never had; Ioulia, Christos and Dimitris Kontogiannis for being the family anyone could wish for, my Australian family: Dulama Richani, Kim Andersen, Kristina Xenos, Amara Zintgraff, Ciara Donnelly, Christina Goranitis, Mila Quinones, Kathy Adam, Mari Carmen Escribano, Alison Evernden, Jodie Wassner, Rachel Richardson, for taking care of me and my daughter; my colleagues Prof. C. Bridge, Vincent D’Cruz and Dr. Paola Favaro for their understanding and encouragement and Professor Helen Lochhead for believing in women and encouraging us to achieve our full potential.

This Thesis is dedicated to my mother, Efstathia, and my father, Kostas, for never doubting my choices, no matter how unorthodox they were, my giagia Ioulia, for being an incredible role model, and to my special, beautiful, loving, free-spirited and charismatic daughter Maya.

Περίληψη

Η διδακτορική αυτή διατριβή διερευνά τη φωτιστική και ενεργειακή απόδοση των φωτοσωλήνων. Οι φωτοσωλήνες αποτελούν καινοτόμα συστήματα φυσικού φωτισμού που μπορούν να μεταφέρουν το φως από την οροφή ή τις όψεις του κτιρίου, μέσω σωλήνων υψηλής ανακλαστικότητας, για μεγάλες αποστάσεις, και να προσφέρουν φυσικό φως σε χώρους που υπό άλλες συνθήκες δε θα είχαν πρόσβαση σε αυτό.

Βάσει της ανασκόπησης της υπάρχουσας βιβλιογραφίας και των κενών που εντοπίστηκαν, η παρούσα διατριβή έχει σα στόχο να συνεισφέρει στη γνώση τη σχετική με την τεχνολογία των φωτοσωλήνων, μέσω πειραματικής εξέτασης της απόδοσής τους στο περιβάλλον της Ελλάδας, να μελετήσει τις υπάρχουσες θεωρητικές μεθοδολογίες και τα προσομοιωτικά εργαλεία υπολογισμού της απόδοσης των φωτοσωλήνων και την ακρίβειά τους να προβλέψουν την απόδοση στις συγκεκριμένες συνθήκες, να αναπτύξει μεθοδολογίες για την ακριβή πρόβλεψη της απόδοσης των φωτοσωλήνων, να διερευνήσει πώς θα μπορούσαν οι φωτοσωλήνες να συνδυαστούν με συστήματα τεχνητού φωτισμού και να υπολογίσει τη δυνητική εξοικονόμηση ενέργειας από τη χρήση τους.

Αρχικά, δύο θεωρητικές μεθοδολογίες, οι μέθοδοι Luxplot και TTE αλλά και προσομοιώσεις εφαρμόστηκαν, αναλύθηκαν και τα αποτελέσματά τους συγκρίθηκαν. Η σύγκριση έδειξε ότι τα αποτελέσματα μπορούν να διαφέρουν σημαντικά. Για όλες τις εξεταζόμενες μεθοδολογίες, αναπτύχθηκαν σχέσεις που παρέχουν πιο άμεσα τη μέση Φωτεινότητα από ένα φωτοσωλήνα σε ορθογώνιου σχήματος χώρους.

Παράλληλα, ένας φωτοσωλήνας εγκαταστάθηκε σε πειραματικό περιβάλλον ώστε να μελετηθεί η απόδοσή του στις συνθήκες της Αθήνας. Το σύστημα συμπεριλάμβανε το φωτοσωλήνα, λαμπτήρες LED, και αισθητήρα που αντιλαμβάνεται το φυσικό φως και ελέγχει τη φωτεινή ροή των λαμπτήρων. Ο πειραματικός χώρος βρίσκεται στην Πανεπιστημιούπολη του Πανεπιστημίου Αθηνών. Οι παράμετροι που καταγράφηκαν ήταν η εσωτερική και εξωτερική Φωτεινότητα. Η πειραματική περίοδος διήρκεσε από τις 28 Νοεμβρίου 2014 ως τις αρχές Αυγούστου 2015, με διακοπή κατά τη διάρκεια του Ιανουαρίου.

Τα πειραματικά δεδομένα που συλλέχθηκαν δείχνουν ότι η μέση Φωτεινότητα από το φωτοσωλήνα κατά τη διάρκεια του πειράματος ήταν 100 lux, ενώ ο μέσος παράγοντας φυσικού φωτός λόγω του φωτοσωλήνα (Daylight Penetration Factor) είναι 0.15%, περίπου. Η μέγιστη τιμή Φωτεινότητας καταγράφηκε στο επίπεδο αναφοράς στις 26/04/2015, 12:15μμ με εξωτερική Φωτεινότητα περίπου 120 klux και ήταν 8.4 klux. Η ελάχιστη τιμή κατά την ίδια χρονική στιγμή ήταν 38 lux και η μέση Φωτεινότητα ήταν 1.043 lux. Οι περιοχές πολύ υψηλής Φωτεινότητας που παρατηρούνται στο επίπεδο εργασίας κατά τη διάρκεια ημερών με καθαρό ουρανό και ηλιοφάνεια, μειώνουν την ομοιογένεια, η οποία κατά μέσο όρο ήταν 0,26. Η ομοιογένεια βελτιώνεται σημαντικά για χαμηλότερες εξωτερικές Φωτεινότητες και όταν το επίπεδο εργασίας περιορίζεται σε χώρο μικρότερου εμβαδού.

Οι τιμές εσωτερικής Φωτεινότητας που καταγράφηκαν παρουσιάζουν μεγάλη χρονική και χωρική μεταβλητότητα. Η ανάλυση που πραγματοποιήθηκε δείχνει ότι η μέση εσωτερική Φωτεινότητα μεταβάλλεται σε σχέση με την καθαρότητα του ουρανού και την εξωτερική Φωτεινότητα. Σημαντική μείωση των εσωτερικών επιπέδων φωτισμού παρατηρείται για υψηλές τιμές του παράγοντα K_d, (Δείκτης Αιθριότητας της Διάχυτης Ακτινοβολίας), δηλ. για πιο συννεφιασμένο ουρανό. Υπολογίστηκε πως σε συνθήκες καθαρού ουρανού, η μέση

εσωτερική Φωτεινότητα μπορεί να είναι ως 5 φορές μεγαλύτερη από τη Φωτεινότητα σε συνθήκες νεφοσκεπούς ουρανού. Παρατηρήθηκε επίσης ότι η σχέση μεταξύ της εσωτερικής και εξωτερικής Φωτεινότητας είναι σχεδόν εκθετική.

Χρησιμοποιώντας τα πειραματικά δεδομένα, αναπτύχθηκαν σχέσεις που επιτρέπουν τον υπολογισμό της μέσης εσωτερικής Φωτεινότητας από το φωτοσωλήνα στο επίπεδο αναφοράς, με ανεξάρτητη μεταβλητή την εξωτερική Φωτεινότητα. Ο Δείκτης Αιθριότητας της Διάχυτης Ακτινοβολίας επίσης ελήφθη υπόψη, αφού αναπτύχθηκαν 10 εξισώσεις, για 10 ομάδες τιμών K_d. Το R^2 για τις σχέσεις που αναπτύχθηκαν κυμαίνεται μεταξύ 0.90 και 0.99.

Κατόπιν, τα πειραματικά δεδομένα συγκρίθηκαν με τα αποτελέσματα που προσφέρουν οι σχέσεις που αναπτύχθηκαν με τη χρήση θεωρητικών μοντέλων και προσομοιώσεων. Η μέθοδος TTE αποδείχθηκε πως παράγει αποτελέσματα που διαφέρουν σημαντικά με τις πραγματικές τιμές. Τα αποτελέσματα από τη χρήση της μεθόδου Luxplot, καθώς και από τη χρήση των προσομοιώσεων παρουσιάζουν μεγαλύτερη ακρίβεια, με λάθος που κυμαίνεται μεταξύ 38 και 43%. Το λάθος των τριών αυτών μεθοδολογιών δε διαφέρει σημαντικά σα συνάρτηση των εξωτερικών συνθηκών φωτισμού.

Η χρήση πειραματικών δεδομένων για την αξιολόγηση του τεχνητού φωτισμού που είχε εγκατασταθεί στο πείραμα δεν κατέστη δυνατή λόγω τεχνικών προβλημάτων. Έτσι, πραγματοποιήθηκαν προσομοιώσεις και με στατιστικές μεθόδους υπολογίστηκε η εκτιμώμενη χρησιμοποιούμενη ισχύς για τεχνητό φωτισμό, σε ένα χώρο όμοιο με αυτό του πειράματος και με την ύπαρξη του ίδιου φωτοσωλήνα. Τα συστήματα φωτισμού που χρησιμοποιήθηκαν ήταν δύο: το ένα αναπαρήγαγε τη διάταξη του πειράματος, με λαμπτήρες γύρω από το φωτοσωλήνα, ενώ το δεύτερο περιελάβανε φωτιστικά LED, τοποθετημένα σε ορθό-κανονική διάταξη. Όλα τα συστήματα που χρησιμοποιήθηκαν ελέγχονταν από αισθητήρες φωτός.

Από τα δεδομένα των προσομοιώσεων αναπτύχθηκαν σχέσεις που παρέχουν τη χρησιμοποιούμενη ισχύ του συστήματος τεχνητού φωτισμού, για το σύνολο της πειραματικής περιόδου και επί μέρους για κάθε μήνα. Οι ανεξάρτητες μεταβλητές σε αυτή την περίπτωση ήταν η εξωτερική Φωτεινότητα, η θέση του ήλιου (αζιμούθιο και γωνία ύψους) και ο δείκτης αιθριότητας της διάχυτης ακτινοβολίας. Τα τέσσερα συστήματα που δοκιμάστηκαν βρέθηκε να καταναλώνουν από 10 ως 38% λιγότερη ενέργεια, σε σχέση με το ίδιο σύστημα τεχνητού φωτισμού χωρίς την ύπαρξη φωτοσωλήνα και αισθητήρα φωτός. Σε σχέση με τις δυο διατάξεις τεχνητού φωτισμού, βρέθηκε πως στις διατάξεις όπου τα φωτιστικά σώματα είναι κατανεμημένα στο χώρο και όχι γύρω από το φωτοσωλήνα, παρέχουν μεγαλύτερη εξοικονόμηση και πιο ομοιογενή επίπεδα φωτισμού.

Τα αποτελέσματα και οι προτεινόμενες σχέσεις που παρουσιάζονται σε αυτή τη διατριβή ισχύουν για το συγκεκριμένο περιβάλλον και τα φωτιστικά συστήματα. Ο στόχος ήταν να αναπτυχθούν μεθοδολογίες και όχι σχέσεις για γενικευμένη χρήση.

Abstract

The present Thesis examines the lighting and energy performance of light pipes. Light pipes are innovative daylight systems that can guide daylight and sunlight from the roof or the facades of buildings, for long distances, through very reflective tubes and provide natural light to spaces that would not otherwise have access to it.

Based on the existing literature and the identified gaps, the present Thesis aimed to contribute to the knowledge on the technology of light pipes by experimentally investigating their performance in the Mediterranean - Greek environment and sky conditions; study the already available theoretical tools and/or simulation methods and whether they are able to predict the light pipe performance in the Greek environment and sky conditions; develop methodology/ies for the prediction of the light pipe lighting performance in the specific context; explore how light pipes can be efficiently combined with artificial lighting and controls and what is the magnitude of the energy savings achieved.

Initially, two theoretical methodologies, the Luxplot method and the TTE method and simulations were analysed, tested, and compared. The results from the three methodologies may differ significantly. Equations providing the average illuminance from one light pipe in a rectangular space were developed for all the tested methodologies, for easier and faster application.

Meanwhile, an experiment was set up to test the performance of a light pipe in the weather/sky conditions of Athens, Greece. A lighting system, consisting of a light pipe, LED lamps and daylight linked controls was designed and constructed in a test cell, located at the campus of the Kapodistrian University of Athens, Greece. The parameters initially monitored were the exterior and interior illuminance. The testing period lasted for approximately 7 months, from November 28th, 2014 until the beginning of August 2015 (no data was recorded in January 2015).

The data acquired from the experiment show that the light pipe installed in the test cell offers 100 lux of interior illuminance on average, while the average Daylight Penetration Factor is around 0.15%. The maximum indoor illuminance recorded by a sensor throughout the testing period was 8.4 klux, on 26/04/2015, 12:15 pm. At the same moment, the minimum illuminance was 38 lux, the average illuminance in the space was 1,043 lux, while the exterior illuminance 120 klux. The bright patches of light on the reference plane during clear sky days, decrease the uniformity, which on average is 0.26. Uniformity is higher when the sky is relatively clear and when the reference plane is limited to the area under the light pipe diffuser.

The indoor illuminance values were found to present a strong temporal and spatial variability. The analysis showed that the average indoor illuminance varies strongly as a function of the sky clearness and of the exterior illuminance levels. A significant reduction of the average indoor illuminance is observed for increasing K_d values, i.e., for cloudy skies. As measured, under clear sky conditions ($0.07 < K_d < 0.14$), the average indoor illuminance was about five times higher than during the almost fully cloudy period ($0.84 < Kd < 0.93$). It was also found that the relation between the average indoor and outdoor illuminance is almost exponential.

The illuminance delivered by the light pipe on the reference plane was expressed as formulae, with the independent variable being the exterior illuminance. The sky clearness

was also considered, as each of the 10 developed formulae corresponds to one of 10 Kd clusters. The R-squared for the developed equations ranges between 0.90 and 0.99.

The experimental interior illuminance data was compared to the results calculated and simulated with the equations developed from the theoretical methodologies and the simulations. The TTE method was found to give results that are considerably different than the experimental data. On the other hand, the equations developed from the Luxplot method and the simulations emulating the light pipe as a luminaire of cosine luminous intensity, as well as the forward ray tracing simulations, provide comparable results with an error between 38 and 43%. The error for each methodology does not change significantly based on the exterior illumination.

Since it was not possible to use experimental data for the lighting or energy consumption of the artificial lights installed in the test cell, simulations were used for estimating the used power for artificial lighting systems used in conjunction with light pipes. The artificial lighting systems that were simulated were two: a system like the one installed in the test cell and an "office system", i.e., LED lamps, commonly used in office spaces, installed in an ortho-canonical grid, while the room modelled had the characteristics of the test cell (size, reflectance values). All the systems were dimmed according to the available daylight levels in the space.

Equations for the calculation of the used power of the artificial lighting systems considered were developed, for the whole experimental period and for each month within that period, with independent variables being the exterior illuminance (Eex), the sun azimuth (α) and altitude (γ) and the sky diffuse coefficient (Kd). The four tested systems were found to consume 10 to 38% less energy than if the respective artificial lighting system was the only light source in the space. Arranging the luminaires in an ortho-canonical grid provides greater energy savings and better uniformity levels and should be preferred for environments with increased lighting quality requirements.

The results presented in this Thesis apply to the specific environment and lighting systems used and simulated and are intended to showcase methodologies, rather than provide formulas for universal use.

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Nomenclature

Acronyms

CFS	Complex Fenestration Systems
CIE	Commission International de l' Eclairage
TDGS	Tubular Daylight Guidance Systems
DF	Daylight Factor
DPF	Daylight Penetration Factor
TTE	Tube Transmission Efficiency
LED	Light Emitting Diode
CFD	Computational Fluid Dynamics
MF	maintenance factor
EG	overall guide efficiency
UF	Utilization Factor

Symbols

I	Intensity of light (cd)
α	sun elevation angle (altitude) (degrees)
R	light pipe radius (m)
d	light pipe diameter (m)
L	light pipe length (m)
ρ	reflectance of the interior of the tube
ρ_{surv}	reflectance of the interior of room
m	Air mass ratio
T_{atm}	Transmission of the atmosphere
I_0	extra-terrestrial intensity (cd)
K_t	sky clearness index
K_d	diffuse solar radiation clearness index
k	atmospheric absorption coefficient
A	light guide area (m^2)
A_w	area of a window (m^2)
A_p	aspect ratio of light pipe (length/diameter)
H	vertical distance between the diffuser and the working plane (m)
D	distance between the light pipe diffuser and a specific point on the working plane (m)
θ	the angle between the line from the diffuser to the point of measurement and the normal to the diffuser centre (degrees)
θi	the angle of incidence of light in the tube (degrees)
ϕ	luminous flux (lm)
Φi	flux emerging from the diffuser (lm)
Φe	total flux entering the light guide (lm)
τ	light transmission of the light pipe
τ_c	combined transmittance of the clear collecting dome and of the diffuser
τ_{dome}	transmittance of the clear collecting dome
τ_{dif}	transmittance of the diffuser
E	illuminance (lux)
E_{ex}	exterior illuminance (lux)
E_{pipe}	interior illuminance due to a light pipe (lux)
g	asymmetry parameter
l	room length (m)

w	room width (m)
h	room height (m)
σ	standard deviation

Chapter 1: Introduction

1.1 Synopsis

Light is one of the most important parameters of architectural design. Even though living beings, as we know them, would not exist without light, it is interesting to try to imagine architecture without lighting. Space would be experienced in completely different ways. The appearance of buildings would not matter. Visual cues, for example signs, colours, patterns, etc, would have no significance. Openings would be used only for ventilation and the use of transparent materials would have no meaning. The roles of texture, sound and even smell would be upgraded, and alternative types and abilities of space perception would be developed.

The first chapter of this thesis is a summary of the main properties and characteristics of light and lighting. The basic photometric quantities used in this thesis are explained and the importance of light and lighting on the human health, wellbeing, vision, and on architecture and energy conservation are analysed. The properties of daylight and of the main types of artificial light sources are briefly discussed, as they will be extensively used in this thesis.

1.2 Early theories for the nature of light

The importance of light in humans' lives was recognized by many ancient civilizations which, depending on external influences and the time in history, conceived theories about its nature and its sacred character. For example, solar deities associated with the sun and/or light but also with heat, haling, love, prosperity, craftsmanship, arts, and fertility are present in almost every ancient civilization. In some cases, sun was linked to deities with negative characteristics. For example, Sopdu, was the Egyptian god of war and of the extreme summer heat (*Ancient Egypt Online*, no date).

Ancient philosophers and astronomers tried to give a more scientific explanation to light's nature. The Greek philosophers Euclid, Aristotle, Plato and Empedocles, believed that the human eyes emit rays of light, gather information and bring it back to the eyes (Oas, 2019). Democritos developed a theory of perception, saying that macroscopic objects contain numerous replicas (eidola). These replicas travel in the form of atoms in the air, towards the eyes of each viewer. Ibn al-Haytham (965-1040) was one of the most important scientists that studied the ways light is reflected and refracted. In contrary to the philosophers of the ancient era, Ibn al-Haytham based his work not only on observations, but also on mathematic models and experiments (*Photon Terrace*, no date). Sir Isaac Newton (1643-1727) was the first to understand that light comprises of coloured rays, by passing light through a prism and blending the resulting coloured light rays with the help of another prism (*The College of Optometrists*, no date). Newton also believed that light is in the form of particles, which as a whole, behave like waves (Oas, 2019). Christian Huygens (1629-1695) developed the theory that light is a wave. James Clerk Maxwell's electromagnetic theory of light propagation was a major scientific achievement. Maxwell's theory, built on Huygens research, argued that an electric field, a magnetic field and light could all be explained using a single theory (The Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy, 2014). Finally, in 1905, Albert Einstein introduced the particle theory of light. These particles were named photons in 1926. Einstein's theory explained all the properties of the photoelectric effect, and for that he was awarded the Nobel Prize in 1922 (Oas, 2019).

However, Maxwell's theory is not invalid. The two versions, i.e., light as a flow of particles and light as a wave, remained as alternative theories for the nature of light, until the 19th century. Light has a dual nature: some of its properties can be described by one of the two natures, while others can be explained by the combination of the wave and the particle nature. When light interacts with matter, it behaves like a particle, while, at the same time it acts like a wave (Walmsley, 2015).

1.3 The nature of light

Light is usually described as the part of the electromagnetic spectrum that the human eye can perceive. The whole electromagnetic spectrum ranges from x rays to microwaves and radio waves and light takes up only a small part of it, ranging from approximately 380nm to 750nm, between the ultraviolet (with shorter wavelengths) and the infrared (with longer wavelengths). At the short wavelengths (x-rays and shorter), electromagnetic radiation behaves like a flow of particles, whereas long wavelengths behave more like a wave. Light, which lays in the middle, exhibits wave and particle behaviours, as previously mentioned (Ryer, 1998).

The basic photometric quantities, that can describe the phenomena related to lighting in the built environment are its Intensity, Flux, Illuminance and Luminance.

Table 1. Basic photometric quantities

Flux (Φ): The total flow of light from a source. Unit: Lumens (lm)
Luminous Intensity (I): The visible power in a given direction. Unit: Candelas (cd) It is calculated from the number of lumens (Flux) divided by the angular size of the beam, measured in steradians. 1 candela= 1 lumen/steradian
Illuminance (E): The amount of light (Flux) per unit area. Unit: Lux (lx) 1 Lux= 1 lumen/ square meter
Luminance (L): the intensity of light emitted from a surface per unit area in a given direction. Unit: cd/m^2

Other lighting parameters that help us understand light’s nature and the way it interacts with the material world are Glare, Colour temperature and Colour rendering.

Table 2. Properties of light

Colour temperature: Describes the colour appearance of the light source. The exact colour of the (white) light is identified by comparing it to the colour of a black body radiator (Correlated Colour Temperature).
Colour Rendering Index (CRI): CRI is a measure of the ability of a light source to render the colours of the objects it lights, realistically, compared to a reference source, with known colour rendering characteristics.
Glare: The discomfort and/or loss of visual ability and performance caused by luminances significantly higher than the luminance to which adaptation has occurred.

1.4 The effects of light on humans

Sight is probably the sense that most people would rate as the most important, as it enables us to see and perceive the world around us. Light is the medium that activates this process. Apart from this basic function, light affects humans in several other, not that obvious, but still direct, ways.

1.4.1 Vision

The human eye works as a collector and transmitter of images from the environment to the brain. What the human brain perceives as an image of the world depends on the ability of the visual system of every person but also on this person's knowledge and experiences (Tregenza and Loe, 2014).

The processing of the images starts from the eye and specifically the retina. The images formed on the retina are transformed from the photoreceptor cells, known as rods and cones, into light signals. The optic nerve receives these signals and transmits them to the human brain. Each of the two types of photoreceptors have a different function. Cones work under photopic conditions (illuminances that are met during the daytime or in relatively bright interior spaces) and are responsible for colour vision. Rods work under scotopic conditions, i.e., when the ambient illumination is low, and cannot perceive colours. That means that in low lighting conditions, the human vision perceives the objects as being grey, even though, sometimes, our experiences and knowledge do not let us realise this fact.

An interesting fact about cones and rods is that they do not have the same spectral sensitivity. Because of that, in dark environments the light that is perceived as brighter is bluer than the light perceived as brighter in photopic conditions, which is more yellow. The maximum visual acuity during scotopic conditions is at approximately 505nm, while in photopic conditions the maximum spectral sensitivity to spectral colour is presented at 555nm (Tsangrassoulis, A. Kenny *et al.*, no date).

The spectral sensitivity under photopic, mesopic or scotopic conditions, refers to the adapted eye. The human eye and more specifically the retina, adapts to the luminous environment to achieve optimum sensitivity. Areas or objects with luminances that are much lower than the average luminance of the environment appear as black shadows, while objects with much greater luminances cause glare (Tregenza and Loe, 2014).

1.4.2 Non-visual effects of light

The ability to see our surroundings is the most obvious and well-understood effect of light to humans. However, other important body functions also depend on or are affected by light. A more recently discovered photoreceptor in the eye, the intrinsically photosensitive retinal ganglion cells (ipRGCs), are found to provide the main input to the circadian system (Lucas *et al.*, 2014).

One of the most important effects of the day-night (or light-dark) cycle is the secretion of melatonin from the pineal gland. High levels of melatonin are produced during dark periods of the day. Melatonin regulates the circadian rhythms of the human biological clock, like the sleep-wake cycle, the secretion of hormones, bowel movements, etc (Webb, 2006). Changes in the usual day-night pattern may cause changes in the body's functions. For example, high lighting levels are used in working environments where workers do nightshifts, to increase alertness. However, studies show that the provision of artificial light for extended periods during the night might increase the risk for breast cancer and may have negative effects on the psychological, cardiovascular and/or metabolic functions. Research has shown that shorter wavelengths of light, even of low intensities, are more effective in supressing melatonin secretion and cause circadian phase shifts (Cho *et al.*, 2015).

Other impacts of light on humans include the increase of heart rate, body temperature as well as alertness (Butler, 2017). Light also impacts human emotions, in many cases significantly. One of the best documented phenomena is the Seasonal Affective Disorder (SAD). Annual changing of the melatonin cycle caused by the long periods of night or day in northern countries of the northern hemisphere, can be the cause of SAD, a type of depression. Exposure of people suffering from SAD to bright light has led to improvement of the symptoms of the disorder (Webb, 2006).

UV radiation from the sun has other effects on humans, like erythema, photoaging of the skin, DNA damage and eye damage, or Vitamin D production. However, since UV radiation is not visible, these effects are not analysed in this study.

1.5 Light in the built environment

1.5.1 Light and Space

Light, and more specifically natural light is one of the basic parameters determining the appearance of a space. Its availability depends on the geographic location, the characteristics of the neighbouring obstacles (buildings, structures, vegetation, etc), the building orientation, size and shape, the interior materials, the characteristics of the openings and their shading systems, etc. A report by Veitch and Galasiu (2012) reviewing the relevant literature argues that people prefer spaces with windows and natural lighting, even though the use of the space, the environment around the building (determining the view as well as the privacy), and cultural parameters affect the preferences on the size and type of openings. Also people believe that natural lighting and outdoor views in working environments increase productivity (Leslie, 2003). That belief is verified in various studies, investigating the effects of daylight on reading speed and comprehension (Heydarian *et al.*, 2016), office worker satisfaction and wellbeing (Wineman, 1982; Aries, Veitch and Newsham, 2010), student attendance and academic performance (Edwards and Torcellini, 2002) and the wellbeing of patients and staff in hospitals and assisted-living facilities (Edwards and Torcellini, 2002).

The right to natural light in buildings is protected by local regulations in many countries around the world. National Construction Codes of every country include provisions about the number, size, and positioning of openings on the building skin, for various building types. Probably the first time the availability of natural light in buildings is regulated as a necessary element by the Greek National Construction Code (Γενικός Οικοδομικός Κανονισμός-ΓΟΚ) was in 1955. Section 32 of the Code stated that every “habitable” room of residential buildings, as well as spaces where people work, should receive direct daylight, from openings facing outdoor spaces (communal or public spaces, courtyards, etc).

Another important provision in building regulations, is that of *easements* (δουλείες) for daylight provision. An easement is a section of land registered on someone’s property title, that can be used by someone who is not the landowner, for a specific purpose. Easements for the provision of daylight are spaces in someone’s land that should be kept open and not built-in order for natural light to reach the openings of a neighbouring property. Easements were regulated by the Greek Construction Code until recently. In UK, the easements related to the preservation of the lighting levels in buildings are more widely referred to as “Right to light”.

Other types of regulations determine the urban layout, the height and volume of buildings and occasionally the quality (materials) of the building skin, for the streets and the buildings around them to benefit from daylight and sunlight, as well as fresh air.

1.5.2 Energy efficiency in lighting

Buildings contribute significantly to the global energy consumption, with the building construction and operation sector accounting for 36% of the total energy use, in 2017. Even when the energy use for the transport of building materials is excluded, the building sector remains the greatest energy consumer, followed by industry (32% of the global energy consumption) and transport (28% of the global energy consumption) (International Energy Agency, 2018). Energy consumption for artificial lighting of buildings and public spaces accounts for about 15% of the global power consumption and for 5% of the global greenhouse gas emissions. In residential buildings, consumption for lighting has a significant share, ranging between 9 and 12% of the total building consumption (11% in US, 9% in China and 12% in Europe). For commercial buildings the numbers are similar, reaching 37% in US (lighting and other), 8% in China and 14% in Europe (von Weizsacker *et al.*, 2009). Despite the wide range of energy efficient lighting technologies, it is expected that within the next two decades, consumption for lighting will increase by 50% compared to current consumption levels, if countries do not implement the necessary policies and regulations (United Nations Environment Programme, 2017).

According to UNEP, if by 2030 all countries adopted energy efficient lighting technologies in all sectors (residential, commercial/industrial and outdoor), the electricity demand for lighting would be reduced by approximately 32%, while CO2 emissions would be reduced by 3.5 Gt (United Nations Environment Programme, 2014). The main solutions and techniques that can contribute to energy efficiency in lighting, are:

- Appropriate building design. Buildings that are designed to provide high daylight availability in all the spaces that are occupied during daylight hours have much lower needs for artificial lighting. The quality of the entering daylight, controlled by the position and size of openings and the properties of the transmissive materials, is also important, as it determines the user acceptability.
- Use of energy efficient lighting sources (lamps and luminaires). It is assumed that, the replacement of older lighting technologies (incandescent, halogen and old fluorescent lamps) to LEDs in all building sectors, would result in 52% less global electricity consumption for lighting (United Nations Environment Programme, 2014).
- Use of lighting controls. The use of appropriate controls would maximise the use of daylight and minimise the energy consumption for artificial lighting, providing stimulating lighting environments.

The following paragraphs include a short analysis of the above techniques for energy savings for lighting.

1.6 Lighting sources

There are two types of light sources: artificial light sources, a category including all the different electric lamps, luminaires and associated systems, and the sun, which is the only natural light source.

1.6.1 Artificial lighting

Artificial lighting is produced by one or a combination of the following elements/systems.

Lamps

There are many different types of lamps available nowadays, that can suit any application, interior or exterior. The choice of lamp depends on many parameters, such as:

- The required luminous efficacy (lm/W);
- The desired distribution of light;
- The useful life of the lamp;
- The cost of the lamp and of its operation and the frequency of maintenance required;
- The colour properties of the lamp (CCT and CRI);
- The available luminaires that can support/operate with a specific lamp type, etc.

Table 3 summarizes the basic properties of the most common types of lamps, used in the built environment.

Table 3. Main lamp type properties

Lamp Type	Luminous Efficacy (lm/w)	Luminous Output (lumens)	Wattage	CCT (typical/dominant wavelength)	CRI	Lifetime
LED lamp (neutral)	146	2,000	13.7	4,000	>=80	60,000
LED lamp (warm)	88	3,000	34.1	3,000	>=90	60,000
HID (high pressure sodium)	112	28,000	250	2,000	-	12,000-24,000
Linear fluorescent lamp system (t5)	89	3,320	35	4,000	>=80	45,000
HID (metal halide)	115	8,400	70	warm white (930 WDL), neutral white (942 NDL)	>=90	20,000
CFL	-	1,600	23	4,000	>=80	10,000-20,000
Halogen	-	260	25	2,700	100	2,000
Incadescent (oven lamps)	-	400	40	2,700	100	1,000

(Source: OSRAM products overview https://www.osram.com/ds/index.jsp)

Luminaires

Apart from the lamp type, luminaires also affect the amount of the emitted light, its colour and distribution. Luminaires support and protect the lamps and they also provide the energy (electricity) required. However, they also perform the very important function of (re)directing the light emitted from the lamp. With the use of reflectors, refractors and diffusers, luminaires enable the flow of light in the desired directions or create complicated light patterns.

Artificial lighting has the advantage over daylighting that is available upon request, any time of the day, in the desired intensity and distribution. The range of the commonly used lamps and luminaires can offer different properties and characteristics, providing the desired luminous environment for any application. However, artificial lighting sources are not capable to compete with daylight in efficiency, intensity, and quality of light.

Controls

Lighting controls, for either artificial or natural lighting, is a term referring to elements and systems used to regulate the amount, distribution or even colour (CCT) of the light emitted by a source. The main purpose of the controls is to create a pleasant, comfortable, and productive visual environment. However, they are usually associated to energy efficiency and reduced energy consumption, as they can provide significant savings when their role is to minimise the use of artificial lighting when natural light is available. The level of sophistication and complexity of the available control systems is vast, and it can range from a simple dimmer to elaborate smart software for controlling groups of luminaires, shading devices and even equipment other than lighting. The strategies than can be used are numerous and depend on the result that needs to be achieved.

1.6.2 Daylight

Daylight is the light reaching the objects and living creatures on the surface of the earth and is emitted by the sun. Often, a distinction is made between the direct natural light reaching a surface, called sunlight and the diffuse light from the sun after passing through the clouds and other particles in the atmosphere, or reflected from surfaces of the environment, which is called daylight.

The perceived colour of daylight and of the sun itself depends on the time of day and the position of the sun in the sky, the climatic and sky conditions, the air pollution, etc. For example, when the sun is in a low position, the greater the distance from the viewer and thus the greater the distance the light needs to travel in the atmosphere. In this case, the sun appears to have warmer colours (i.e., orange, and red). This is because short wavelength light (blueish light) is scattered more in the atmosphere. The sun's CCT ranges between 2,000 (Sunrise or sunset) and 5,800 K (direct midsummer sunlight), while diffuse skylight ranges from approximately 6,000 (Overcast sky) to over 9,500 K (Summer skylight) (Mardaljevic, 2016).

The advantages of the availability of natural lighting in buildings are numerous and quite important. Daylight provides the necessary light for various functions in any type of space. Depending on the geographical location of a building, but also its positioning in relation to other buildings, trees, obstructions, etc, the sky and prevailing weather conditions, the architectural design, the interior and exterior construction materials and other parameters, daylight could provide all or part of the necessary lighting for the tasks performed in an interior. This incoming light, if it is reflected on neutral-coloured surfaces, has the best colour rendering properties of the known light sources. The amount and the quality (mainly the distribution and the absence of glare) of the incoming daylight define the energy savings for artificial lighting that daylight can offer in specific applications.

The following chapter analyses the main natural lighting systems and examines the available literature on the development, performance and energy savings potential of the technology investigated later in this thesis, the light pipes.

Chapter 2: Natural lighting systems

2.1 Synopsis

Ideally, daylight should be present in every space where people spend even a short period of time each day, as it can contribute to their physical and emotional well-being, as explained in the introduction of this thesis. *Natural lighting elements and systems* are considered all the systems that enable daylight to reach an interior space and that affect and control its intensity and distribution. These systems can be architectural elements or more sophisticated systems and technologies that provide daylight to spaces that would not otherwise have access to it.

Simple architectural elements, like windows and clerestory windows, atria, skylights, lightwells, simple shading elements, such as awnings, blinds, etc, can be found in any building. They enable the daylight to pass through the building skin -exterior walls and roof- and reach the interior spaces adjacent to it. Simple architectural elements and structures can be very efficient and may cover the total lighting needs of a space, under specific conditions: when the size of the opening is appropriate for the size of the respective room, the distribution of the daylighting elements in the space is balanced, the interior and exterior environments enable the light to be emitted and/or reflected towards the deeper parts, when the sky and weather characteristics of the specific location are favourable, etc.

Architectural lighting elements can be combined with systems that provide shading or protection from glare. Louvres, blinds, and lamellas can be used to block sunlight and reduce glare. Moreover, shading can considerably reduce the energy consumption for cooling in warm climates (Tzempelikos and Athienitis, 2007; Palmero-Marrero and Oliveira, 2010; Mandalaki *et al.*, 2012; Bellia, De Falco and Minichiello, 2013), while reducing glare and improving lighting quality (Appelfeld and Svendsen, 2013; Hoffmann *et al.*, 2016; Konstantzos and Tzempelikos, 2017; Uribe, Bustamante and Vera, 2017). Complex Fenestration Systems (CFS) are conventional openings with complex glazing, such as translucent insulating materials, films for solar control, louvres between two glass panes, etc, that aim to provide some daylight in a space with better thermal characteristics than conventional windows (Laouadi and Parekh, 2007). While CFS have generally better energy performance than windows, user satisfaction is quite low, as they prevent view to the exterior environment, and they increase luminance and glare occurrences.

The usual daylighting systems cannot always provide enough daylight. For example, in deep plan rooms, the core areas and/or areas far away from the windows are usually underlit and require electric lighting, sometimes throughout the day. Moreover, spaces that are not on the top floor of buildings cannot be lit by skylights. More complex and sophisticated technologies and systems, often referred to as *innovative daylighting systems* in scientific studies and reports, can provide natural lighting or increase the daylight levels in such spaces. The main characteristics and properties of the most common innovative lighting systems are described in the following paragraphs. Light pipes' properties as well as a review of the research studies that have been conducted on their development and performance, are also described.

2.2 Innovative daylighting systems

Innovative daylight systems can be grouped in many ways, depending on their function, materials, or performance. The systems described in the following paragraphs are included in two main categories: the systems that are installed on the side walls and/or windows and provide daylight to areas close to the perimeter of the building and those that provide daylight to the core of deep buildings or to spaces that have no windows or skylights. Other sub-categories are created within these main two categories.

2.2.1 Daylight systems for the building perimeter

Light shelves

Light shelves are horizontal or inclined, flat or curved, passive or active elements, placed internally, externally or on both sides of a window (Antonis Kontadakis *et al.*, 2017). They can be made of many materials, such us metal, plastic, or wood, if their top surface, where light is reflected from, is highly reflective. They are used to guide the daylight to the deeper parts of the room and shade the areas close to the opening (Littlefair, 1995). They also lead to reduced energy consumption for lighting and often for mechanical cooling, due to their shading capabilities.

Light shelves use multiple reflections of light, to provide diffuse sunlight or daylight to the deepest parts of an interior. Littlefair (1995), tested the performance of flat light shelves, mainly with the use of a computer software but also with measurements in a scale model. He found that the distribution of the daylight levels on the working plane is improved (uniformity is increased) not because the illuminance on the rear part of the space is increased, but because the high illuminances close to the windows are reduced. According to the same study, external shelves can provide good shading to the areas close to the windows and internal ones can provide shading to the areas slightly deeper into the room, when the sun is high (high solar altitude). Generally, core daylight illuminances are not substantially increased due to light shelves, unless there is a large external obstruction that reduces the daylight availability of the room significantly. The fact that uniformity is improved with the use of light shelves is suggested by many studies (Carlos and Soler, 2001; Joarder *et al.*, 2009; Lim and Ahmad, 2015; Meresi, 2016; Moazzeni and Ghiabaklou, 2016; Lee, Jeon, *et al.*, 2017; Berardi and Anaraki, 2018).

Studies on the performance of tilted light shelves show that for south oriented façades for buildings on the northern hemisphere, and depending on the latitude of the site, tilted light shelves can increase uniformity of lighting levels for clear sky conditions (Meresi, 2016). The effect of curving the reflective surface of light shelves, as well as the use of multiple reflectors, were tested by Beltran et al. (Beltrán, Lee and Selkowitz, 1997). These forms of light shelves enable the maximisation of the amount of daylight captured and redirected towards the ceiling.

Alternative systems, aiming to solve issues related to performance or environmental parameters have also been designed and tested. Lee et al (2017), studied the performance of an external perforated shelf and compared it to an opening without light shelf and to an opening with a solid (without perforations) light shelf. The light shelves could also be rotated around their long axes and the width could be altered. The perforation was introduced to avoid system destructions due to high wind pressures in high-rise buildings. They concluded that even a shelf with over 35% of its surface perforated can increase the illuminance levels in a space and reduce the energy consumption for lighting significantly, compared to the same window without a light shelf.

Another system, which may not be a light shelf, but works according to the same principles, is analysed by Edmonds and Greenup (Edmonds and Greenup, 2002). The system reduces the incoming sunlight and the solar gains and glare, by utilising a parabolic reflector and a light guiding shade. Sunlight is entering the system through a small aperture covered by diffusing glass and is then reflected from the parabolic reflector. The light that enters the room is diffuse and provides more even distribution on the ceiling and the working plane.

Active systems, that track the sun position and adjust the light shelves' rotation have also been studied. It was found that the lighting performance of active systems is better than that of static systems, however, the thermal gains are also increased (A Kontadakis *et al.*, 2017). Dogan and Stec (2018) studied the performance of a light shelf fitted with an array of mirrors which could rotate in two axes, mounted on the internal side of a window. It was found that the proposed system significantly increased the lighting levels in the deeper parts of the space during morning and evening hours and it also improved the Continuous Daylight Autonomy up to 20%. The electricity savings for artificial lighting reached 35%. However, the bright patterns on the ceiling that mirrors create are considered a potential glare source, depending on the interior surfaces' properties and the position of the viewers-users of the space.

Regarding the properties of the shelf, Littlefair's research (1995) showed that this needs to be as reflective as possible. The depth of an internal shelf should roughly be equal to the height of the head of the clerestory window above the shelf. The depth of an external shelf should be approximately equal to the height of the shelf above the working plane.

Slats / Blinds

Simple blinds systems, that use slats to redirect the sunlight, are quite common as they can be installed close (internally, externally or between two glass panes) to the glass pane of the window, with minimum effect on the building appearance. They can also be installed on roof daylight systems (skylights) to redirect skylight or even on the window sill (Littlefair, 1990). The more efficient systems incorporate slats with highly reflective upper surfaces and profiles that can selectively reflect sunlight depending on the location and the season.

Some sophisticated systems are analysed by Tsangrassoulis (2016). The Retrolux and the Okasolar-W systems present seasonal selectivity to the radiation and enable redirection of natural light.

Greenup and Edmonds (Greenup and Edmonds, 2004) developed a sophisticated shading and daylight redirecting panel, comprised of numerous elements. Each "group" of these elements includes a diffusing input aperture and two specially shaped reflectors, which are essentially two collimators. Testing of the system showed that rooms can benefit from greater illuminance levels, but glare issues can develop.

Transparent Insulation Materials (TIMs)

Recent research studies investigate the use of Transparent Insulation Materials (TIMs) for covering the building openings, providing energy savings both for lighting and heating and/or cooling (Bianco *et al.*, 2017; Vlachokostas and Madamopoulos, 2017). Aerogel is one of the materials the performance of which has been investigated widely (Reim *et al.*, 2005; Buratti and Moretti, 2012; Cotana *et al.*, 2014). More recently, Vlachokostas and Madamopoulos (2017) simulated the lighting and thermal performance of a liquid (water) filled prismatic louver façade (LFPL) system, mounted inside the room, flush against the window glazing. The system proved to increase daylight availability, reduce glare and cooling needs, when compared to an ordinary double-glazed window.

Prisms and Holographic optical elements

Prismatic panels are acrylic elements or laser-cut panels with prisms (sawtooth devices) used to redirect or refract light. They are usually installed between two glass panes, in vertical or roof windows, to make maintenance easier. Prismatic panels need detailed design and arrangement (positioning and tilting), depending on application, in order to avoid dispersion of light or redirection of sunlight at angles where they can cause glare (IEA, 2000). Their redistributing performance and the increase in lighting levels in spaces has been found to be significant in clear sky conditions with sun and important when the sky is overcast (Edmonds, 1993, 2005; Ruck, Christoffersen and Julian, 1999). Thin films can achieve similar results with prismatic panels. A clear film with prisms was tested by Thanachareonkit et al. (2014) in a clerestory window of a full scale test cell and was found to redirect sunlight and increase the illuminance levels at the rear of the room significantly, compared to a clear window with interior blinds. To face the glare issues that were created by the prismatic film, the researchers had to add a diffusing film.

Anidolic systems

Anidolic systems may be included in both envelope and core lighting categories, depending on the characteristics of the specific application. Through detailed design of the entry aperture, skylight is redirected towards the upper/deeper parts of a room. Scartezzini and Courret (2002) summarized the characteristics and performances of the three main anidolic systems: the anidolic ceiling, an integrated anidolic system and the anidolic solar blinds. Higher daylight availability was found in the cases of the anidolic ceiling and of the integrated system while the anidolic solar blinds were found to enhance the daylight levels in the rear of the room. Usually, the lighting conditions created with help of anidolic systems do not have significant glare issues.

2.2.2 Daylight systems for core lighting

Optical Fibres

Fibre optics are elements used to transmit data or light in long distances. They are made of three layers: 1. the core which is made of glass or plastic and is the light transmitting element, 2. the cladding which is also made of glass or plastic but of a different refraction index than the core, causing total internal reflection to occur and 3. The external coating, used to protect the fibre from the environment. The optical fibres used for daylight are usually acrylic, due to their good transmission and heat resistance properties (Tsangrassoulis, 2016). The Himawari and Parans systems are the best-known commercial daylight systems that utilise optical fibres. In both systems, sunlight is tracked and collected through Fresnel lenses, then transmitted with the use of optical fibres and delivered into the spaces with the use of special devices (luminaires) (Mayhoub, 2014).

Heliostats

Heliostats are systems that use two or more mirrors to transfer sunlight to spaces in the core of buildings. However, these systems also employ active tracking of the sun’s position for achieving maximum performance (Tsangrassoulis, 2008; Kim and Kim, 2010). Many real applications of heliostat systems have been constructed and operate throughout the world, like the Stuttgart Airport in Germany and the One Central Park project in Sydney Australia. The performance of heliostats depends on the distance from the first mirror-collector to the emitter in the space and the design of the system (Tsangrassoulis, 2016).

2.3 Tubular Daylight Guidance Systems

According to the CIE Technical Report 173:2006, Tubular Daylight Guidance Systems (TDGS) are “linear devices that channel daylight into the core of a building” (CIE, 2006). During the last few years scientists that carry out reviews of the types and performance of daylight systems have made a distinction between light pipes and sun pipes, with light pipes being the horizontal and sun pipes the vertical systems. In the present document, the terms light pipes and sun pipes are considered interchangeable.

Light pipes can belong to one of the following categories of natural lighting systems:

1. Light pipes with horizontal tubes designed to fit within the ceiling plenum, with the light receiving element being part of a vertical or tilted façade of the building. Light emitting elements (diffusers) can be placed anywhere under the transport element, over the space. A reflector system is usually needed to collect (collimate) incoming sunlight and to maximize the efficiency of the system (Beltrán, Lee and Selkowitz, 1997; Chirarattananon, Chedsiri and Renshen, 2000). Beltran et al (1997), tested the lighting performance of different geometries of horizontal light pipes against the performance of light shelves. They found that both systems can provide adequate daylight for office tasks, in a 4.60-9.10 m zone of a deep space. Light pipes were found to provide more daylight for longer periods compared to light shelves.
2. The most common type of light pipe, however, is the passive zenithal tubular one. It consists of three basic elements: 1. the light collector, 2. the tube and 3. an element which distributes daylight and/or sunlight into the space.
   a) The light collector is usually a glass or polycarbonate dome of high light-transmittance. The dome of the light pipe can either be hemispherical or have a diamond shape. The latter is used to maximise the penetration of sunlight through the flat prisms and to capture the early morning and late afternoon sun. The light transmittance of the material is usually over 80%.
   b) Sunlight entering the dome is transported towards the space through a pipe, with very high reflectance. The Technical Report 173:2012 reports tube reflectance values for commercial light pipes between 92 and 99.5% (CIE, 2012). The tube of the light pipe is usually made of aluminium. The interior surface is coated with substances (PVD) and films that enhance reflectance and UV durability and provide good colour rendition. The tube is provided by manufacturers in pieces which are put together during installation. These pieces may be straight or bended.
   c) After multiple reflections in the tube, sunlight reaches the lower end and is transmitted in the space through an output component. This component can be clear, opal or prismatic. More often, the diffuser is made of acrylic glass. The use of the diffuser is very important as it distributes daylight into a space more evenly and it covers the interior of the tube from view, reducing any glare issues that might occur. The light transmittance of the various types of diffusers varies significantly; a clear cover admits more daylight but will cause glare, especially during sunny days; the opal diffuser is very good at dispersing light rays and at providing a uniform environment but has low transmittance; the prismatic diffusers offer even distribution and greater transmittances.
   d) An optional feature of commercial light pipes is the shutter, which covers (shades) the tube whenever black-out conditions are required. The shutter is a

disk, with diameter equal to that of the tube, which rotates, permitting or blocking daylight from reaching the lower part of the tube.

2.3.1 Light Pipe Performance

The knowledge of the performance or efficiency of light pipes is useful to manufacturers as well as to lighting designers and consumers wanting to install such a technology. Ideally, the performance of each combination of light pipe elements (i.e., tube diameter, tube length, type of diffuser, etc) would be given in the form of photometric data, as it happens for artificial lighting sources. However, the measurement of the photometry of these systems would be a very difficult, time-consuming, and expensive task. The performance of the light pipe systems is as dynamic as the parameters that affect it, such as sun elevation, sky clarity, exterior lighting levels, etc (Zhang, Muneer and Kubie, 2002). Thus, not only the systems that would need to be tested are numerous, but the instruments and facilities needed are not widely available (CIE, 2006). Therefore, most of the tools for the performance prediction of light pipes have resulted from analytical methods; less studies have used simulations and experimental testing of systems. Even though the characteristics of the light pipes can vary significantly, the results are occasionally comparable. The main body of literature on the properties and performance of light pipes is reviewed in the following paragraphs.

Literature on performance prediction

One of the first studies investigating the performance of light pipes, was performed by Zastrow and Wittwer (1987) and presented in the 30th Annual Technical Symposium in US. The authors produced formulae for the calculation of the system light transmission efficiency, for light pipes of circular as well as of triangular cross-sections. The formulae required the knowledge of the length and diameter of the pipe and the angle between an incoming light ray and the pipe's axis.

A few years later, the calculation principles for the transmission of light pipes were provided by Edmonds et al. (1995). The input power on a light pipe is:

$$I\pi R^2 sin\alpha \qquad (1)$$

where I is the intensity of sunlight, α is the sun elevation angle (altitude) and R is the radius of the light pipe. In projected view, light coming into a light pipe at a distance x from the axis, falls on the interior of the tube at an angle i, with:

$$i=sin\text{-}1(x/R) \qquad (2)$$

The horizontal distance covered by light after each reflection is:

$$d=2R\ cosi \qquad (3)$$

while the vertical distance (descent) is:

$$d\ tan\ \alpha=2R\ cosi\ tan\alpha \qquad (4)$$

If L is the length of the light pipe, the number of reflections needed for the light to reach the diffuser is:

$$N=L/2R\ cosi\ tan\alpha \qquad (5)$$

If the reflectance of the interior of the tube is ρ, the transmission of a ray is ρ^N. The energy entering the light pipe dome in an interval between x and Δx is proportional to $\Delta x(R^2\text{-}x^2)^{1/2}$. So, the transmission T(α) of the light pipe is given by:

$$T(\alpha) = 4\int_0^R W\rho^N dx/\pi R^2 \tag{6}$$

Where W is a weighting factor equal to $(R^2-x^2)^{1/2}/R$.

The illumination prediction would require considering the sunlight intensity, depending on the atmospheric absorption coefficient k and the air mass ratio m, and the sun elevation α. The power transmitted through the light pipe is given by:

$$P=I_0\,T_{atm}\,\pi R^2 sin\alpha\,T(\alpha) \tag{7}$$

Where T_{atm} is the transmission of the atmosphere and I_0 is the extra-terrestrial intensity. Edmonds et al. (1995) found that the performance of light pipes falls significantly when the sun elevation is low and proposed the use of a low-angle deflecting panels that increase transmission.

More recent studies, based on experimental findings, have attempted to provide more easily applied formulae. Zhang and Muneer (2000) performed measurements in a nursery in Currie, UK, where a light pipe was installed. They introduced the term Daylight Penetration Factor (DPF), which expresses the light output of a light pipe. DPF is an equivalent to the Daylight Factor (DF), and is equal to the Illuminance at a point in a room lit by a light pipe to the total external illuminance, expressed as a percentage. A model for the calculation of DPF is proposed, including the distance from the diffuser to a point in the space, the sky clearness index, and the solar altitude. The model was however applicable only for straight light pipes. In a more recent study, Zhang et al. (2002) investigated a generalisation of the DPF formula to include straight light pipes of various lengths and diameters and a separate formula for light pipes with bends. This was one of the first studies that recorded the performance of light pipes in a controlled environment and compared the findings with a mathematical model. The DPF model that resulted is:

$$DPF_{(x,y,z)}(\alpha_o+\alpha_1 k_t+\alpha_2\alpha_s)\rho^{(\alpha_3+\alpha_4 A_p+\alpha_5 cot\alpha_s+\alpha_6 A_p cot\alpha_s)}R^2(\frac{H}{D})^m/D^2 \tag{8}$$

Where α_s is the sun elevation, a_o-a_6 are coefficients provided by the authors, k_t is the sky clearness index, ρ is the reflectance of the interior surface of the tube, A_p is the aspect ratio of the light pipe (length/diameter), R is the light pipe radius, H is the height of the diffuser above working plane, D is the distance of the light pipe diffuser to a specific point on the working plane and m a parameter with a value of 1.3. Data calculated with eq. (8) above were in good agreement with recorded data retrieved from the test site. The relation is valid for light pipes with opal diffusers and it was proven that the errors were low under clear sky conditions and greater under overcast or low lighting external conditions.

The above methodology has also been used by Su et al. (2012) as a basis for a performance prediction model of light pipes with bends.

Jenkins, Muneer and Kubie (2005), developed another noteworthy and widely recognized method of light pipe performance prediction, based on previous research findings by Jenkins and Muneer (2003).

The authors used a theoretical method to calculate the illuminance on a specific point on the reference plane and validated it with experimental data. The theoretical model uses the inverse square law of illuminance combined with the relationship giving the luminous intensity of an area source. The final formula for the illuminance from a light pipe, at a point on the reference plane is given by:

$$E_i = 0.494 \frac{\varphi_{SP}}{H^2} cos^4\theta \quad (9)$$

Where θ is the angle between the line from the diffuser to the point of measurement and the line normal to diffuser centre, H is the vertical distance between the diffuser and the reference plane or point and 0.494 is a factor resulting from the experimental data. ϕ_{SP} is the luminous flux emitted by the light pipe diffuser, given by:

$$\varphi_{SP} = \tau\, E_{ex}\, \pi\, R^2 \quad (10)$$

where τ is the light transmission of the light pipe, E_{ex} is the external illuminance and R the pipe radius.

Equation (9) was validated, and the results showed validity for straight light pipes of various diameters and lengths and is more accurate for overcast skies, even though it should also be reliable for light pipes with medium and long lengths under clear sky conditions. It also needs to be noted that the dome was considered to have a transmittance of 88% and that the diffuser had a stippled surface.

Jenkins, Zhang and Muneer (2005) combined equations (9) and (10) with the definition of the Daylight Penetration Factor (DPF) and provided the following equation:

$$DPF_{(x,y,z)} = (0.406) \frac{e^{-0.11A}}{V^2} \pi R^2 cos^4\theta \quad (11)$$

The above methodology has been used and customised by a number of scientists to evaluate the performance of light pipes in other parts of the world (Yun, G.Y., Hwang, T., Kim, 2010; Ju Young Shin, Yun and Kim, 2011). The Jenkins and Muneer method previously mentioned is going to be further described and used in the next chapter, where the main calculation methods are tested.

Oakley et al. (2000) tested a number of light pipes installed in residential, workshop and office environments. They found that, under the conditions in which the measurements took place, every bend reduced the performance of the system by approximately 14%. The study also highlighted the importance of the aspect ratio of the light pipe, but also of the space size and layout on the final performance of the daylight system. The Daylight Factors (or Daylight Penetration Factors) achieved were in the range of 0.18 to 0.48%, depending on the above-mentioned parameters.

Carter (2002) had a different approach than the previous research teams. He treated the light pipe as a "luminaire", using an apparatus to measure luminous intensity and a photometric integrator to measure the luminous flux of the light pipe. Nadir and exterior illuminances were also recorded. The measured intensity values for the γ plane for overcast and cloudy conditions were averaged and plotted on the same scale. The curve is valid for pipe diameter of 0.33m, lengths of 0.61 and 1.22 m, with an opal diffuser and for two C-planes, namely, 0° and 30°. Light pipes of the same lengths and diameter gave a very similar polar curve for clear sky conditions.

The luminous flux and the nadir illuminance were measured for other light pipes and the nadir luminous intensity and the total luminous flux output were calculated from these parameters. The measured and calculated values were in good agreement, showing that nadir illuminance can be used for the determination of luminous flux output.

In this important study, Carter (2002) describes a procedure for calculating the distribution of light from a light pipe on a reference plane, using manual calculations or software, with the use of the intensity distribution and the luminous flux obtained with the previously described procedure (measurements and calculations).

Carter, also performed measurements for light pipes without a diffuser, under clear sky conditions and found that the light distribution was skewed, depending on sun position.

Kocifaj et al. (2008) developed a model based on basic physics laws and analytical mathematical calculations named HOLIGILM. HOLIGILM can calculate the illuminance on a reference plane in a space, as well as the luminance distribution on the diffuser of vertical cylindrical light pipes, for the identification of hotspots. A later study by Kocifaj (2009a) confirmed that HOLIGILM can also be used for other types of diffusers or light pipe elements with acceptable accuracy. The use of HOLIGILM to simulate the performance of various light pipes under overcast and clear sky conditions showed that light pipes may have better efficiencies under overcast sky but the performance is worse, due to low exterior daylight availability (Darula, Kocifaj and Mohelníková, 2013). The theoretical model developed by Kocifaj (2009a) was tested by Darula et al. (2010) for light pipes with bends. The three studies mentioned highlighted the issues of using clear ceiling covers. Even though the average illuminance on the working plane is increased compared to light pipes with diffusers, the hotspots created inside the tube are reflected on the reference plane, creating high contrasts and possible glare issues.

Kocifaj (2009b) attempted to reduce the issue of hotspots with the use of a diffuser where only the central part was diffusing while the exterior ring was made of clear glass. That way, the performance of the light pipe remained good, while the hotspots were eliminated, in the case of relatively long light pipes. In a later study, the same team (Kocifaj and Kundracik, 2011) focused on the characterization of the light pipes with clear ceiling elements (diffusers) by means of luminous intensity solid and asymmetry parameter. The directional behaviour of the luminous intensity solids, depending on the position of the sun and the type of sky, was quantified by the average cosine, otherwise called asymmetry parameter g. It was found that the luminous intensity solid can have peaks that change during sunny days. Even if the sky is homogeneous the luminous intensity solid can have peaks due to imperfections in the interior surface of the tube, for example after accumulation of dirt. HOLIGILM has been used in a number of other studies (Petržala, Kocifaj and Kómar, 2018; Tsang *et al.*, 2018)

Chirarattananon et al. (2010) also developed a model that calculates the transmittance of a light pipe, with or without bends, depending on the type of sky.

CIE Technical Committee TC3-38, in Technical Report 173:2012 (CIE, 2012), describes another performance prediction methodology, based on tube-transmission efficiency (TTE), which gives reliable results for overcast sky conditions and an angle, representing the portion of the zenithal sky from which daylight enters the tube, equal with $Z=30^{o}$ (Al-Marwaee and Carter, 2006). The methodology is going to be described in detail in the following chapter, as it is one of the tested prediction procedures.

Laouadi et al. (Laouadi, Arsenault, *et al.*, 2013; Laouadi, Galasiu, *et al.*, 2013), proposed an analytical methodology for calculating the optical characteristics (transmittance, reflectance and absorptance of each light pipe glazing element) based on the (analytical) raytracing technique. They also developed metrics for the optical, lighting, and thermal performance of light pipes for product rating purposes.

Malet-Damour et al. (2016) used experimental data to improve existing algorithms developed in the past.

Literature on site measurement of light pipe performance

Shao et al. (1998) measured the performance of light pipes of various diameters (0.33m and 0.53m), lengths (0.60 to 12 m), aspect ratios (2 to over 30), and number of bends (0 to 4) in real applications in UK. They found that for the case studies they investigated, internal to external illuminance ratios were from 1 to 0.1%, with the lower performances attributed to systems with small aspect ratios and/or great amount of bends.

Al-Marwaee and Carter (2006) performed measurements in 13 buildings in UK during winter days, where a number of light pipes were installed in working spaces, to provide daylight along with the electric lighting system. It was found that daylight contribution was between 25% and 50% of total illuminance in the spaces, depending on the number of the systems installed.

The study by Paroncini et al. (2007) showed the clear impact of the sun's position in the sky to the distribution of the daylight on the reference plane by a regular light pipe. The maximum average internal to external illuminance ratio on the working-plane was found to be 0.4% during winter and reached 0.6% during summer. The system tested also incorporated a lens below the dome, used to collimate the rays from low-angle sunlight. It was found that the lens increased the light pipe performance for short periods of time during the morning while reduced the interior illuminance in the middle of the daylight hours.

Mohelnikova (2009) tested the performance of a light pipe with varying diameters and a single length (5.00m) and measured the luminance of the diffuser (1,000 cd m^{-2} for overcast sky conditions, 4000 cd m^{-2} for partly cloudy sky conditions and 12,000 cd m^{-2} for clear sky conditions) and the illuminance distribution on the reference plane of a real application.

Robertson et al. (2010), performed a detailed study on the effect of different light pipe physical parameters (bends, type of diffuser, type of roof element, diameter, length) on the transmission and performance of the system. The study also showed that the transmission efficiency of the light pipes was higher under diffuse ambient lighting conditions.

Li et al. (2010) performed measurements in a commercial building in Hong Kong, where light pipes were installed in a top floor corridor. They found that the transmittance (τ) varied between 0.16 and 0.26, according to the external illuminance. The energy consumption for lighting was calculated to be reduced by up to 54%, with the use of on-off and dimming controls, compared to no lighting controls.

Literature on software use for performance prediction

Ellis et al (2004) report satisfactory results for the simulation of the daylighting effects, solar gains and conductive/ convective heat transfer of light pipes using the software EnergyPlus. Also, Zazzini et al. (2006) tested the accuracy of the software tools ECOTECT and EnergyPlus in predicting the performance of light pipes. It was found that EnergyPlus underrated the illuminances close to the pipes and overrated the lighting levels further away from them, while Ecotect underestimated the light pipe's performance. The comparison was made with a 1:5 scale model tested under an artificial sky.

Paroncini et al. (2008) compared experimental data to data acquired by simulations using Radiance and the results were in very good agreement. However, the authors do not mention whether backward or forward tracing techniques were used. Farrell et al. (Farrell, Norton and Kennedy, 2004) also tested Radiance and concluded that the forward ray tracer (PMAP) produced a more accurate prediction of the illumination levels of spaces lit by light pipes than the backward ray tracer (Desktop Radiance), using a luminance ratio multiplier.

Photopia was used by Dutton and Shao (2007) to predict light pipe transmission and the results were comparable to the experimental data gathered by Swift and Smith (1995).

Lo Verso et al. (2011) carried out simulations in the software SkyVision as well as measurements in an artificial sky setting, in order to determine the global efficiency of tubular daylight guidance systems as the product of the efficiency of the collector, pipe and diffuser.

Ciugudeanu and Beu (2016) used Dialux software to compare the simulated performance of a light pipe with a bend with data from an application in a residential room. In Dialux, the light pipe was simulated as a skylight with a total transmittance like that of the actual system and it was found that the mean error was around 8.6% for overcast sky conditions.

Literature on the performance of specially modified light pipes or light pipes with additional/optional elements

An optional element of the light pipe system is the sun tracker, which uses movable or stable heliostatic mirrors, which capture sunlight and redirect it into the tube, minimizing reflection losses. Sun trackers usually cause loss of performance of the light pipe during cloudy or overcast sky conditions. Garcia Hansen et al. (2009) studied the performance of passive versus active laser cut panels (LCPs) for the collection of sunlight and the improvement of the performance of large scale light pipes. The passive system comprised LCPs in pyramid form, whereas the active system used a tilted LCP, rotating 360° in 24 hours. It was found that the active system caused the interior light levels to be increased for low sun elevations and that the distribution of light was more even, especially during the winter period. The passive LCP system (which consisted of LCPs in a pyramid form) increased the performance of the regular light pipe for low elevation angles and reduced performance for high elevation angles. Garcia Hansen and Edmonds (2003) had tested a similar system utilizing LCPs and large scale light pipes with extraction apertures at each floor of a multi-storey building in an earlier study with good performance results. Active collection of daylight has also been successfully combined with fibre optics. The Himawari and Parans systems can transport light many metres away from the collection point with very good efficiencies. The high cost of these systems makes them useful for only few specialised applications (Mayhoub and Carter, 2010).

Swift et al. (2006) studied the hotspots created at the exit aperture (diffuser) of the light pipe and suggested a way to avoid them. They found that by placing a diffuse material at the entrance aperture the irradiance pattern can be made almost uniform without significant reduction in the pipe transmittance.

Appropriate modifications to a conventional light pipe could provide natural ventilation to a space. Elmualim et al. (1999) studied the performance of an integrated natural ventilation and daylighting system, with the form of concentric light pipe and ventilation stack. The use of dichroic materials in the tube caused the infrared part of the solar radiation to be transmitted to the stack thus enhancing the natural ventilation flow by approximately 14%.

Prismatic Fresnel lens or laser-cut panels may be placed at the pipe's entrance to enhance performance and/or extra diffusers can be added to the entrance/exit to enhance light diffusion (Laouadi, Galasiu, *et al.*, 2013).

Garcia Hansen and Edmonds (2015) investigated the methods to distribute equal amounts of light at each level of a multi-story building from a single light pipe. The researchers designed a natural lighting system with tracked collector and extractors that provided very good performance. Kennedy and O'Rourke (2015) gave another option, by designing a light pipe where the lowest floor is lit by a diffuser, as in regular light pipes, while the intermediate floors receive daylight by apertures on the sidewalls.

The project ARTHELIO included the study of the integration of daylight and artificial light into a new type of lighting system that incorporated a light pipe. More specifically, the lighting system consisted of a daylight collecting device (heliostat), a light guiding pipe, sulphur lamps to supplement daylight when needed and clear hollow tubes containing the prismatic film that transport light placed horizontally (below the ceiling) or vertically (to light a staircase). The system showed good performance and considerable energy savings for lighting (Rosemann and Kaase, 2005).

Baroncini et al. (2010) also studied the performance of a new type of light pipe. This system had a larger dome and a transparent tube, concentric to the reflective tube of the light pipe, positioned externally of the tube. This layout provided not only light to the room where the diffuser was placed but also to the intermediate spaces through which the tube passes. The system was found to be useful in providing daylight to spaces without windows or other openings, but glare issues were noticed in the spaces lit by the vertical transparent tube.

Sharma et al. (2018) studied the transmission performance of various modifications to a classic light pipe design and found a layout with a wider lower part that presented good performance.

Sikula et al. (2014) investigated the thermal properties of light pipes, as they can cause thermal bridging and condensation problems, especially in buildings with highly thermally insulated roofs. The authors performed CFD thermal analysis that showed that an additional double or triple glass unit installed in the light pipes can reduce the air movement and temperature distribution in the light. However, the additional glass can reduce the transmittance of the system from 10 to 30% approximately, depending on the thickness (triple, double or single unit).

2.3.2 User perceptions on light pipe performance

A review of the relative literature shows that people prefer to work in spaces with access to daylight (Roche, Dewey and Littlefair, 2000; Galasiu and Veitch, 2006; Aries, Veitch and Newsham, 2010; Garcia Hansen, Isoardi and Miller, 2010). However, people's response to the visual environment depends on several physical, psychological, and social parameters. Daylight may provide all or part of the required light to perform a specific task, but windows also provide connection to the external environment, view out and time hints. The fact that light pipes provide daylight but not direct view outside makes users' acceptance differ from that of windows.

Al Marwaee and Carter (2006) studied the performance of light pipes in 14 commercial buildings in UK (commercial, healthcare or academic functions) and the views of the people working in these buildings on the quality of the visual environment and the contribution of light pipes. Their study showed that people associate daylight with windows, even though both windows and light pipes provided hints of temporal variation due to the lack of daylight linked controls for the artificial lighting. In spaces where light pipes were the only daylight system, 70% of the users were dissatisfied by not being able to have view and detect changes in the exterior environment. A later study by the same team (Carter and Al Marwaee, 2009) provided results supporting those of the aforementioned study, however, user satisfaction with some aspects, such as the perception of the amount of daylight, the assessment of colour, evenness of the lighting and detection of weather changes, improved with increased DPF. An interesting finding was that one quarter of users of windowless rooms could detect diurnal variations by changes in brightness of the light pipe diffuser.

A similar study by Garcia Hansen et al. (2010) investigating the user views on the performance of light pipes in two buildings in Australia, showed that user acceptance was higher when light pipes were part of a “designed” lighting system, integrated with windows and with the artificial lights. Also, it was found that glare can have a great impact on people’s perception and acceptance of light pipes.

2.3.3 Energy saving potential and cost-effectiveness of light pipes.

Shin et al. (2011) calculated the reduction in energy consumption that can be achieved for lighting when light pipes are used. The light pipe performance was based on an analytical model and the artificial lighting control scenario were on/off, two-phase, and continuous dimming. Dimming of artificial lights depending on the daylight availability was found to be the most efficient control method, especially under partly overcast sky conditions in the environment of Korea. Li et al. (2010), as previously mentioned, found that the energy consumption for lighting can be reduced by up to 54%, with the use of on-off and dimming controls, compared to no lighting controls.

Gorgulu and Ekren (2013) tested the performance of a fuzzy logic controller that dimmed fluorescent lights depending on the daylight emitted by a light pipe, installed in an office in Turkey. They found that the system was able to maintain stable lighting conditions and that during the winter months, the energy consumption for lighting was reduced by approximately 30% compared to a room without light pipe. This percentage matches the anticipated energy savings reported in relevant Technical Notes (National Institute of Building Sciences, 2010).

Carter (2008) performed a cost and value analysis of the use of light pipes in offices in UK, with very interesting results. The analysis took into consideration the equipment (artificial lighting and light pipe combined with dimmable electric ballasts and controllers) capital cost, the cost of the installations of all systems, the running costs (maintenance and the cost of electricity) as well as the activities carried out in each space and the illuminance levels that the systems needed to achieve. The results showed that the increase in light pipe length increased the cost significantly, as opposed to the impact of the diameter which was small. So, the “simple payback” period for the capital cost of light pipes with rather small lengths (approximately 2.00m) was 34 years whereas the period for light pipes that run through 2 or 3 storeys is of the order of 100 years.

The average capital cost of the systems with light pipes and daylight linked controls was 62% higher than that of systems with electric lighting only. However, the power costs for electric-only systems were 50% higher than the capital cost, while the power costs of systems with light pipes and daylight linking was half the capital cost. Thus, daylight linking was found to be crucial in achieving a cost-effective system. Finally, the average annual CO_2 emission due to lighting across the studied spaces was 2.4 tonnes when the lighting system comprised only electric lights, 1.6 tonnes when daylight was available and 0.6 tonnes when light pipes achieved a DPF of 2%.

Another study comparing the costs and benefits of different daylight delivery systems concluded that light pipes are more economical than more sophisticated systems with higher capital costs (Mayhoub and Carter, 2011).

2.4 Research questions and objectives

The literature review in this chapter revealed that light pipes are daylighting systems which have been studied for a few years, however, information that would make this technology useful, accessible, and practical is still missing.

Since most of the studies investigating the performance of light pipes and which have developed algorithms for its calculation have used data from northern Europe and more specifically from UK (see Zhang and Muneer, 2000, Oakley, Riffat and Shao, 2000, Carter, 2002, etc.), it is interesting to compare their results with data of the performance of light pipes in other climates and sky conditions and work out whether the theoretical algorithms are valid for environments other than those for which they were developed.

The available literature is also poor in providing data about the properties and characteristics of artificial lighting systems that would result in improved visual environments and reduced energy consumption when combined with light pipes.

Based on the review of the relevant literature, the research questions that arise are:

1. What is the performance of light pipes in the Mediterranean - Greek environment and sky conditions?
2. Are already available theoretical tools and/or simulation methods able to predict the light pipe performance in the Greek environment and sky conditions?
3. Can methodology/ies for the prediction of the light pipe lighting performance in the specific context be developed?
4. Can light pipes be efficiently combined with artificial lighting and controls and what is the magnitude of the energy savings achieved?

To reply these questions, this Thesis provides an extensive application and testing methodology of the main theoretical and simulation tools available. Functions for the application of these methods, using simple independent variables are also produced.

To provide information about the performance of light pipes in the Greek environment, a light pipe is installed, and its performance is recorded and analysed. Statistical methods are employed to condition the experimental data acquired over a 7-month period. The data is then correlated with independent environmental parameters, such as the exterior illuminance, the position of the sun and the sky clearness and compared to the existing calculation tools (theoretical algorithms and simulations). The methodology for calculating the light performance of light pipes under the specific weather/sky conditions is showcased.

Finally, the combination of the light pipe with artificial lighting systems is investigated. The lighting levels and the energy savings achieved are studied and methodologies for the estimation of the power used from the electric lighting is developed and provided.

2.5 Thesis outline

Following the introduction in Chapter 1 and the Literature Review in Chapter 2, the main existing tools for the calculation of the light pipe performance are presented, analysed and applied in Chapter 3. The tools used are the Guide Transmission Efficiency (or Transmission Tube Efficiency) method, as presented in CIE Technical Report 173.2012 with data from the Solar Project SRL (CIE, 2012), the Luxplot method, developed by Jenkins, Muneer and Kubie (2005), realistic modelling of the light pipe and also the modelling of the system with a number of assumptions about the dimensions and the element transmittances, and modelling of the light pipe as a luminaire of cosine luminous intensity distribution. The above tools were applied for several room dimensions and light pipe characteristics and equations providing the average interior illuminance from a light pipe are developed and presented. The results from the use of all the theoretical tools are compared and discussed. Part of Chapter 3 was published in the International Journal of Sustainable Energy (Vasilakopoulou *et al.*, 2016).

Chapter 4 of the Thesis describes the experimental layout and the lighting system that was constructed and tested. In brief, the system consists of a light pipe and LEDs controlled by a daylight sensor, providing relatively stable interior lighting levels and energy savings for lighting, compared to more conventional daylight components and systems that do not exploit daylight. The test cell was located at the University of Athens campus (Zografou, Athens, Greece) and data was collected over a 7-month period, from late November 2014 until early August 2015.

Chapter 5 includes the analysis of the lighting performance of the experimental lighting system. More specifically, the illuminance data acquired by the experiment was initially cleaned; the outliers and the errors, mainly due to instrument inaccuracy, were specified and removed from the sample. Following an initial analysis of all the recorded values, the data set was split into 10 clusters, and the performance of the light pipe in terms of lighting levels on the horizontal reference plane for each of these clusters was studied. Part of Chapter 5 was published in the journal Energy and Buildings (Vasilakopoulou *et al.*, 2017).

The experimental data is then compared to the theoretical methods previously analysed, in Chapter 6. The relevance and appropriateness of the use of methods developed by other scientific teams for light pipes installed in Greek buildings is investigated. Additionally, this chapter includes results from modelling the test cell and the experimental lighting system and simulating the lighting conditions using a forward ray tracing tool.

Chapter 7 provides methodologies for estimating the used power for artificial lighting systems used in conjunction with light pipes. The used power can lead to an estimate of energy consumption and savings when combined with the time of use. Four tasks, with different electric lighting layouts and/or lighting goals were studied. The methodologies developed provided equations for the calculation of the used power of the artificial lighting systems, for the whole experimental period and for each month within that period, with independent variables being the exterior illuminance (E_{ex}), the sun azimuth (α) and altitude (γ) and the sky diffuse coefficient (K_d).

Chapter 8 includes the conclusions of the Thesis.

Chapter 3: Application, assessment, and comparison of existing performance prediction methodologies.

3.1 Synopsis

Passive zenithal light guides, or more commonly light pipes, are a type of Tubular Daylight Guidance System, which are systems that can channel daylight to the core of buildings. To assess the performance of light pipes, to calculate the number of light pipes needed in a space and the amount of additional artificial lighting required to reach specific interior illuminance levels scientists and designers need prediction methods that can give the daylight availability, due to one light pipe. Some of the existing prediction methods were mentioned in the previous chapter of this Thesis.

The objective of this chapter is:

- to analytically present the main existing prediction methodologies of light pipe performance;
- to test these methodologies, using different light pipe and room parameters and identify their main parameters;
- to develop theoretical (analytical) methods for the calculation of the interior illuminance on the reference plane due to a light pipe, for each of the main methodologies;
- to compare the light pipe performances calculated with the main methodologies.

The theoretical methods tested, are:

1. The Guide Transmission Efficiency (or Transmission Tube Efficiency) method (CIE, 2012), and
2. the Luxplot method, developed by Jenkins, Muneer and Kubie (2005).

Simulations were also carried out, using the IES VE pro software and include:

1. Realistic modelling of the light pipe and the modelling of the system with several assumptions about the dimensions and the element transmittances, and
2. Modelling of the light pipe as a luminaire of cosine luminous intensity distribution.

Simulations using forward raytracing algorithms became more easily applicable after the completion of this chapter and have been included in Chapter 6:.

3.2 Algorithms for the calculation of the light pipe performance

There are several formulae and algorithms resulting from analytical methods as well as from laboratory testing of the performance of light pipes and only a few software packages that can be used to calculate/simulate their performance. The most popular algorithms and tools were analysed in Chapter 2: of this thesis.

To assess the performance of light pipes, two of the theoretical/mathematical prediction methodologies for light pipes have been described in detail and applied in this Chapter. These methodologies are the Guide Transmission Efficiency method, which is the most detailed of the methodologies described in the CIE Technical Report 173:2012 (CIE, 2012), and the prediction method developed by Jenkins et al. as described in (Jenkins and Muneer, 2004) and (Jenkins, Muneer and Kubie, 2005), referred to as Luxplot method. The calculations were performed for external conditions that are of low daylight availability, i.e., for an overcast sky of E_{ex}=5,000 lux, to find the minimum output of a light pipe, regardless of the geographical site.

3.2.1 Guide transmission efficiency method

The Guide Transmission Efficiency or Transmission Tube Efficiency (called TTE method for simplicity in this study) is an analytical methodology described in the CIE Technical Report 173:2012 (CIE, 2012). It gives the luminous flux emerging from a light pipe diffuser and then the Daylight Penetration Factor in a room. The method is based on the Transmission Tube Efficiency (TTE), which represents the losses due to the tube in the basic relation calculating the flux. The method is limited to overcast sky conditions.

TTE calculation formula incorporates the length, diameter, and reflectance of the guide, and can be approximated by the following relation:

$$\boldsymbol{TTE} = \frac{\boldsymbol{e^{\frac{L}{d}tan\theta\ ln\rho}}}{(\boldsymbol{1 - A_p\ tan\theta_i\ ln\rho})^{\boldsymbol{0.5}}} \qquad (12)$$

where:

ρ=specular reflectance of tube material,

L=equivalent optical length (m),

d=diameter (m)

A_p=aspect ratio (L/D) of pipe and

θ_i= the angle of incidence of light in the tube.

However, the CIE Technical Report 173:2012 (CIE, 2012), also provides TTE values for different pipe diameters, lengths and reflectances, in a tabulated form for a more straightforward application.

To calculate the flux Φ_i emerging from the diffuser of a light pipe, the following equation is applied:

$$\Phi_i = \Phi_e\ EG \qquad (13)$$

Where:

$$\Phi_e = E_{ex}\ A \qquad (14)$$

is the total flux entering the guide and EG is the overall guide efficiency given by:

$$EG = TTE\ \tau_c\ MF \quad (15)$$

In the previous relations E_{ex} is the external global illuminance (lux), A is the guide area (m^2), TTE is the transmission tube efficiency, calculated by eq. (12) or derived by the tables of the CIE technical report, τ_c is the combined transmittance of the clear collecting dome and of the diffuser and MF is a maintenance factor related to the light tube. Values of maintenance factors, depending on the use of the space and on the environmental pollution levels, are also given in the technical report (CIE, 2012).

To calculate the Daylight Penetration Factor (DPF), the following equation is applied:

$$DPF = (N\ \Phi_i\ UF) / (A\ E_{ex})\ \% \quad (16)$$

where:

N= number of light pipes in a space,

Φ_i= total flux emerging from the output device (lm),

UF= Utilization Factor for the output device (CIE, 2012),

A= light pipe area.

Theoretically, since DPF is the ratio of the illuminance at a point on the reference plane due to a light pipe to the total external illuminance, the average illuminance in a certain space can be calculated, by multiplying DPF with the external illuminance E_{ex} and dividing the product with 100.

This method can also consider pipe bends. The CIE Technical Report provides tables of Aspect Ratios that correspond to various bend angles. These Aspect Ratios are added to the Aspect Ratios of the straight sections, resulting in a total system Aspect Ratio. Depending on the light pipe diameter and the total Aspect Ratio, a TTE value is read from the tables given by the CIE Technical Report 173:2012, which is then used to calculate the flux output (eq.(13), (14) and (15)), and the light availability in the space (eq.(16)).

3.2.2 Application of the TTE method for straight light pipes

The TTE method was tested in eight rooms of varying sizes (Table 4). The reflectance values of the interior surfaces were walls: 50%, ceiling: 70%, floor/reference plane: 30%. The working plane on which the illuminance levels were calculated or simulated was 0.85 m above the room floor and 0.50 m offset from the walls. The external conditions were assumed to be of an overcast sky with illuminance of 5,000 lux.

Table 4. The rooms that were used for the calculations

	Length (m)	Width (m)	Height (m)	Room Index
ROOM 1	4	4	3	0.67
ROOM 2	4	4	5	0.40
ROOM 3	6	4	3	0.80
ROOM 4	7	4	3	0.85
ROOM 5	5	5	4	0.63
ROOM 6	6	6	2,5	1.20
ROOM 7	4	3	3	0.57
ROOM 8	5	4	3	0.74

For the above-mentioned rooms, light pipes of two reflectance values (0.95 and 0.98), six diameters and seventeen lengths (Table 5) were used and calculations were performed. The transmission of both the clear dome and the diffuser was 0.82. In total, 1,728 scenarios were calculated.

Table 5. The light pipe diameters and lengths used for the calculations

Light Pipe Diametres (m)																	
0.25			0.35			0.375			0.53			0.65			0.90		
Light Pipe Lengths (m)																	
0.25	0.50	0.75	1	2	3	4	5	6	8	10	12	14	15	16	18	20	25

For the light pipe characteristics described in Table 5, the TTE values were taken from table 2 (pg 19) of the CIE technical report (CIE, 2012). For any length that is not included in the CIE technical report, the TTE value of the light pipes with diameters included in Table 5 and of tube reflectances 0.92, 0.95, 0.98 or 0.995, can be derived from Table 6. These relations resulted from regression analysis, estimating the relationships between the length (L), the diameter (d) and the reflectance (ρ) of the tube.

Table 6. Relationships for the calculation of the TTE values

		Reflectance			
		0.92	**0.95**	**0.98**	**0.995**
Diameter	**0.25**	$-0.235\ln(L) + 0.678$	$0.9268e^{-0.144L}$	$0.9817e^{-0.063L}$	$0.9985e^{-0.017L}$
	0.35	$0.9007e^{-0.164L}$	$0.9504e^{-0.12L}$	$0.9901e^{-0.046L}$	$0.999e^{-0.012L}$
	0.375	$0.9315e^{-0.159L}$	$0.957e^{-0.107L}$	$0.9913e^{-0.043L}$	$0.9986e^{-0.011L}$
	0.53	$0.9502e^{-0.114L}$	$0.9768e^{-0.074L}$	$0.9949e^{-0.031L}$	$1.0004e^{-0.008L}$
	0.65	$0.9679e^{-0.096L}$	$0.9795e^{-0.073L}$	$0.9958e^{-0.025L}$	$e^{-0.007L}$
	0.90	$0.9767e^{-0.071L}$	$0.9875e^{-0.045L}$	$0.9985e^{-0.019L}$	$1.0009e^{-0.005L}$

A Maintenance Factor of 0.9 was chosen as a value that expresses an intermediate situation between the most common roof and dome placement layouts (horizontal, inclined, vertical glazing) and pollution conditions.

From eq. (15) the overall guide efficiency EG was calculated for each pipe length and diameter. From eq. (13) and (14) the total flux emerging from the diffuser (Φ_i), was calculated.

The Daylight Penetration Factor (DPF) and the interior illuminance in each room were calculated according to eq. (16). The sky was considered to be overcast so the sun's position and sky clearance index were considered to have insignificant impact (Zhang and Muneer, 2000). The results of the calculations are given in Appendix I. The application of the TTE method for light pipes with bends is included in Appendix II.

3.2.3 The Luxplot method

The Luxplot method was developed by Jenkins et al (Jenkins and Muneer, 2004; Jenkins, Muneer and Kubie, 2005). Technical Report 173:2012 (CIE, 2012) includes the method as a tool validated by the authors.

The calculation method first introduces an equation for the flux emerging from the diffuser. If the flux at the top of the pipe Φ_e is given by:

$$\Phi_e = E_{ex} \pi R^2 \quad (17)$$

the flux emerging from the diffuser of the pipe Φ_i is given by:

$$\Phi_i = \tau E_{ex} \pi R^2 \quad (18)$$

In the previous equations E_{ex} is the external illuminance (lux), R= the light pipe radius (m) and τ= the transmittance of the pipe/system.

Using experimental data for light pipes of diameter 0.30 m, 95% reflectance and with lengths ranging from 0.60-5.40m, the authors found the transmittance of the system, which is approximately:

$$\tau = 0.82\, e^{-0.11Ap} \quad (19)$$

where A_p= the aspect ratio (L/D) of the light pipe.

In eq. (19) the term 0.82 represents the transmittance of the light pipe dome and diffuser, while $e^{-0.11}$ gives the transmittance of the tube material per unit aspect ratio.

To calculate the illuminance at a point (P) on the reference plane, the authors have derived the following relation:

$$E_p = 0.494 \frac{\Phi_i}{V^2} cos^4\theta \quad (20)$$

where P, θ and V are shown in Figure 1. The term 0.494 is an empirical term, derived by measurements carried out by the authors in UK, for specific light pipe sizes and optical properties. However, eq. (20) is considered reliable for use with every straight light pipe.

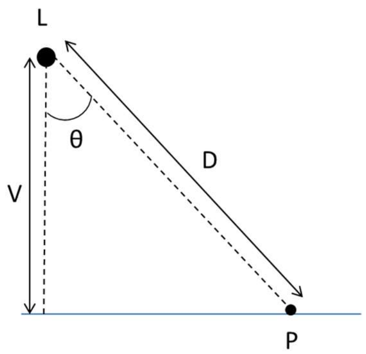

Figure 1. Eq. (20) gives the illuminance on point P, which receives light from a light pipe with an output device (L)

3.2.4 Application of the Luxplot method

The Luxplot method was applied for the same room sizes and the same light pipe characteristics as was the TTE method (Table 4, Table 5). The optical properties of the room surfaces and of the light pipe materials were also the same. The transmittance of the system was initially calculated according to eq. (19) and then the flux emerging from the light pipe diffuser was calculated with eq. (18).

The results for all the possible combinations of input parameters are given in Appendix III.

By comparing the results of the flux calculation derived by the application of the Luxplot and the TTE methods (Table 7Table 7 and Appendix III), it is observed that they are comparable for light pipe lengths 1-2m. The difference in the results is due to the difference between the system transmittance τ, calculated with eq. (19) and the TTE values calculated with eq.(12) or derived from the equations in Table 6. Since the transmittance of the dome and the diffuser in both cases is 0.82, it is the losses in the tube that are causing the deviation in the results.

Since the TTE method is the main method recommended by CIE Technical Report 173:2012 (CIE, 2012), the flux values derived with the TTE method were used for the illuminance calculation with eq. (20). The illuminance was calculated on the working plane, of the rooms described in Table 4, for light pipe diameters given in Table 5, light pipe lengths 0.25, 0.5, 1, 3, 6, 12 m and tube reflectance equal to 0.98. The reference plane of each room (which is located 0.85m above the room floor and 0.50m offset from the walls) was divided in a 0.5 by 0.5 m grid, and the point illuminance was calculated on the grid points. All the parameters (MF, TTE, τ_{dome} τ_{dif}, E_{ex}) were the same as for the TTE method calculations. The results of the calculations are given in Appendix IV.

Table 7. Flux (lm) emitted by one light pipe, calculated with the Luxplot and the TTE methods

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ calculated using eq. (19)	TTE	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.38	0.19	0.25	0.67	0.76	0.98	420.60	399.48
		0.50	1.33	0.71	0.97	390.86	395.21
		0.75	2.00	0.66	0.96	363.22	390.98
		1.00	2.67	0.61	0.95	337.54	386.80
		2.00	5.33	0.46	0.91	251.73	370.52
		3.00	8.00	0.34	0.87	187.73	354.93
		4.00	10.67	0.25	0.83	140.01	339.99
		5.00	13.33	0.19	0.80	104.41	325.68
		6.00	16.00	0.14	0.77	77.87	311.97
		8.00	21.33	0.08	0.70	43.31	286.26
		10.00	26.67	0.04	0.64	24.09	262.67
		12.00	32.00	0.02	0.59	13.40	241.03
		14.00	37.33	0.01	0.54	7.45	221.17
		15.00	40.00	0.01	0.52	5.56	211.86
		16.00	42.67	0.01	0.50	4.14	202.94
		18.00	48.00	0.00	0.46	2.30	186.22
		20.00	53.33	0.00	0.42	1.28	170.87
		25.00	66.67	0.00	0.34	0.30	137.82

3.3 Computer simulations

Except from the mathematical algorithms, simulations with the IES VE pro software were performed, to compare the simulated to the calculated results. Both analytical methodologies and simulations were applied for the same room and light pipe characteristics.

Two sets of simulations were performed. The first set was performed to explore the possibility of getting reliable results from modelling the light pipe in a realistic way, i.e., with the actual dimensions, reflectance values, etc. The other set of simulations was performed with the same software but by replacing the light pipe with a luminaire of cosine luminous intensity distribution.

3.3.1 Simulations with "realistic" modelling of the light pipe

As previously mentioned, the simulations were performed with the IES VE pro software which can perform lighting analysis, for daylight and artificial lighting and it can also perform lumen and glare calculations as it incorporates the Radiance algorithm.

At the beginning of the study, the 3-dimensional models that were made included a realistic and detailed reproduction of the actual light pipes. For example, a pipe with a length of 3.00 meters and a diameter of 0.27m, was modelled as a tube with exactly 0.27m diameter and height of 3.00 m, made of a material with 98% reflectance (stainless steel), with a diffusing surface at the bottom and a clear dome on the top. The external conditions were set to be those of an overcast sky with illuminance of 5,000 lux.

Soon, it was clear that Radiance through IES VE pro was not the appropriate tool for the simulations, as the illuminance values that resulted were, for almost every light pipe layout, equal to zero. The backward raytracing algorithm makes the tracing of the light source from the room through a small opening surrounded by a long tube almost impossible. The same 3D models, run with the radiosity algorithm gave more realistic results, however illuminance was becoming extremely low when the light pipe exceeded 2,00m in length.

The next scenario that was simulated was the modelling of a light pipe with 0.25m length, with a tube of 0.98 reflectance and with the combined transmittance of the dome and the diffuser equal to the product of TTE x τ_{dome} x τ_{dif}. This type of model, run with the radiosity algorithm, gave the most realistic illuminance values on the reference plane which, however, significantly exceeded the illuminance values calculated with the Luxplot and the TTE methods. The same 3D models run in Radiance gave rather low illuminance values, that were not changing with light pipe length, as much as expected. Indicative results of the various simulation scenarios are given in Table 8.

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Table 8. Illuminance values that resulted from simulations, using various 3D models of light pipes in different simulation algorithms.

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	FLUX (lm) calculated with the TTE method	ILLUMINANCE (lux) calculated with the Luxplot method	ILLUMINANCE (lux) simulated with realistic modelling of the light pipe (radiosity algorithm)	ILLUMINANCE (lux) simulated with pipe length of 0.25m and total transmittance=TTE x τdome x τdif (radiosity algorithm)	ILLUMINANCE (lux) simulated with pipe length of 0.25m and total transmittance=TTE x τdome x τdif (raytracing algorithm)
4.00	4.00	3.00	0.25	0.25	136.31	8.53	14.00	14.00	0.48
4.00	4.00	3.00	0.25	0.50	132.31	8.42	4.52	13.30	0.48
4.00	4.00	3.00	0.25	0.75	130.25	8.31	0.00	13.12	0.45
4.00	4.00	3.00	0.53	0.25	617.15	41.18	86.80	85.74	12.92
4.00	4.00	3.00	0.53	0.50	612.38	40.95	51.00	84.72	12.80
4.00	4.00	3.00	0.53	1.00	602.96	40.47	20.90	83.70	12.50
4.00	4.00	3.00	0.53	2.00	584.56	39.55	0.00	80.60	12.43
4.00	4.00	3.00	0.90	0.25	1791.40	122.74	141.43	189.70	56.95
4.00	4.00	3.00	0.90	4.00	1668.21	116.58	10.85	177.70	53.00
4.00	4.00	3.00	0.90	18.00	1278.58	97.08	0.00	136.00	44.75

The next alternative for the modelling of the light pipe was a suggestion of a light pipe manufacturer. The proposed model incorporates a cylinder of a fixed height equal to 0.10m, a flat transparent cover instead of a dome and a flat diffuser. The diameter of the cylinder is 15% larger than that of the real light pipe and the reflectance of the cylinder side walls is 98% (the reflectance of the actual tube used by the manufacturer). The transmittance of the top roof light and of the diffuser is approximately 72%, for a light pipe about 3,00m long.

The simulations that were made included the assumptions mentioned above, except for the transmittances, as the length of the pipe was 1,00 m. The transmittance of the system (dome, diffuser, and tube losses) was assumed to be 72%. The set of simulations was carried out for the rooms described in Table 1 and for the external conditions that were used for the analytical methods and the simulations previously described. The light pipe diameters that were modelled were: 0.27, 0.30, 0.35, 0.47, 0.50 and 0.70 m. Appendix V includes results of the simulations.

The same set of simulations was performed also for an external illuminance of 10,000 lux. As expected, the results showed that an increase in external illumination causes a proportional increase in interior lighting conditions, when all other parameters remain the same.

As the results of the "realistic" straight light pipe simulations did not prove to be credible, simulations for light pipes with bends were not performed.

3.3.2 Simulations modelling the light pipe as a luminaire with cosine luminous intensity distribution

If the diffuser of the light pipe is considered to emit completely diffused light, the flux (Φ_i) for a specific exterior global illuminance, calculated with the TTE or any other reliable method, can be used as the lumen output of a luminaire with cosine luminous intensity distribution, with almost any lighting software. The Utilization Factors for output devices are given by the CIE Technical Report 173:2012 (CIE, 2012), depending on the room index and reflectances of the interior surfaces.

The procedure mainly consists of the following steps:

- Finding or designing a circular luminaire, with cosine luminous intensity distribution;
- Setting the diameter of the luminaire to be the same as the light pipe diameter;
- Replacing the lumen output of the original luminaire with the flux derived from the TTE method, for a given external illuminance;
- Replacing the luminaire Utilization Factor with the light pipe Utilization Factor.

The above-described simulations give an approximation of the average illuminance on the reference plane of a room, provided by one or more light pipes.

Simulations were performed for the rooms described in Table 4, for tube reflectance equal to 0.98 and of dimensions given in Table 5 (except from diameter 0.375). The rest of the parameters were set as previously (MF=0.9, E_{ex}=5,000lux, τ_{dome} x τ_{dif}=0.82, etc). The results of the simulations are given in Appendix VI.

3.4 Comparison of the performance calculation methods

The four performance calculation methodologies that were analysed in the previous sections differ in several ways. The two analytical methods (TTE and Luxplot) require the same parameters as inputs for the calculation of the flux emerging from the diffuser: the light pipe dimensions (length, radius), the properties of the light pipe elements (transmittance of the dome and of the diffuser and reflectance of the pipe material) and the external illuminance. In addition, a maintenance factor for the light pipe is used in the case of the TTE method.

For the flux calculation, TTE and Luxplot methods mainly differ in the way the efficiency or transmittance of the tube is calculated. The comparison of the equations (12) **Error! Reference source not found.**and (19) reveals that difference. The Jenkins-Munner (Luxplot) methodology uses the term $e^{-0.11}$, which accounts for the light loss per unit aspect ratio. The term is valid for a pipe of specific reflectance (0.95) and even though it can be altered for pipes with other characteristics, this is only possible when measurements are available. So, for a tube of specific reflectance, the transmittance of the tube is described by eq. (19). Instead, the TTE method uses eq. (12), in which tube reflectance ρ can take any value.

Except from the input parameters required for the flux calculation, for the average illuminance calculation in a specific room, the TTE method suggests the use of eq. (16) to calculate the Daylight Penetration Factor (DPF) due to a light pipe. The space characteristics (dimensions, reflectances) are required for the choice of the Utilisation Factor of the room, which can be obtained by the CIE Technical report (CIE, 2012), or in (Jenkins, Muneer and Kubie, 2005). The Luxplot method, on the contrary, proposes eq. (20) for the calculation of point illuminance, considering the exact distance of the reference point from the diffuser, but not the optical properties of the room surface materials.

Another difference between the studied methodologies is relative to the external conditions for which they can be applied. Eq. (16) giving the DPF for the various light pipe configurations, using the TTE formula, is limited to Overcast sky conditions, assuming that only light within a cone subtending an angle of 30° from zenith enters the guide. On the contrary, the Luxplot methodology and the realistic modelling simulation apply to any sky conditions. However, the authors of the Luxplot methodology claim that the performance of the model will be more satisfactory when compared to data from overcast skies.

Considering the results of the application of the three studied methods, their comparison reveals great differences and low level of consistency of the data obtained.

When the Luxplot method is compared to the TTE method, the obtained Flux (Φ_i) results for light pipe lengths over 2.00m start to diverge significantly. The Luxplot method gives much smaller flux values as the length of the pipe increases, which is due to the way the tube efficiency is calculated. Figure 2 to Figure 6 give the tube efficiency as a function of the pipe length for the TTE and the Luxplot methods. In both methodologies the efficiency of the tube is reduced exponentially to the pipe length, however, in the case of the Luxplot method the flux is reduced much more rapidly than in the TTE method for increasing lengths of the pipe (Appendix III).

Table 9. Comparison of the Flux calculated with the Luxplot and the TTE methods, for a light pipe diameter of 0.375m and reflectance 0.98

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.375	0.1875	0.25	0.67	420.60	399.48
		0.50	1.33	390.86	395.21
		0.75	2.00	363.22	390.98
		1.00	2.67	337.54	386.80
		2.00	5.33	251.73	370.52
		3.00	8.00	187.73	354.93
		4.00	10.67	140.01	339.99
		5.00	13.33	104.41	325.68
		6.00	16.00	77.87	311.97
		8.00	21.33	43.31	286.26
		10.00	26.67	24.09	262.67
		12.00	32.00	13.40	241.03
		14.00	37.33	7.45	221.17
		15.00	40.00	5.56	211.86
		16.00	42.67	4.14	202.94
		18.00	48.00	2.30	186.22
		20.00	53.33	1.28	170.87
		25.00	66.67	0.30	137.82

Figure 2. The “transparency” or “efficiency” of the tube (D=0,25m, R=0.95) related to the length of the pipe, for the TTE and the Luxplot methods

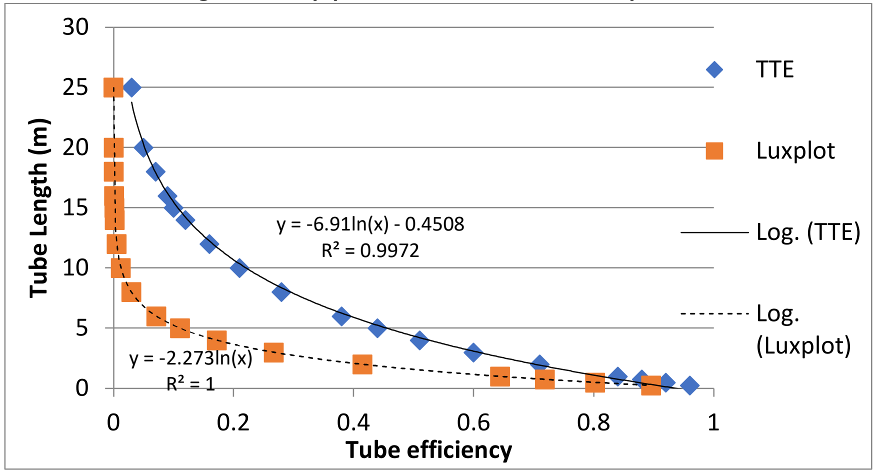


Figure 3. The “transparency” or “efficiency” of the tube (D=0,35m, R=0.95) related to the length of the pipe, for the TTE and the Luxplot methods

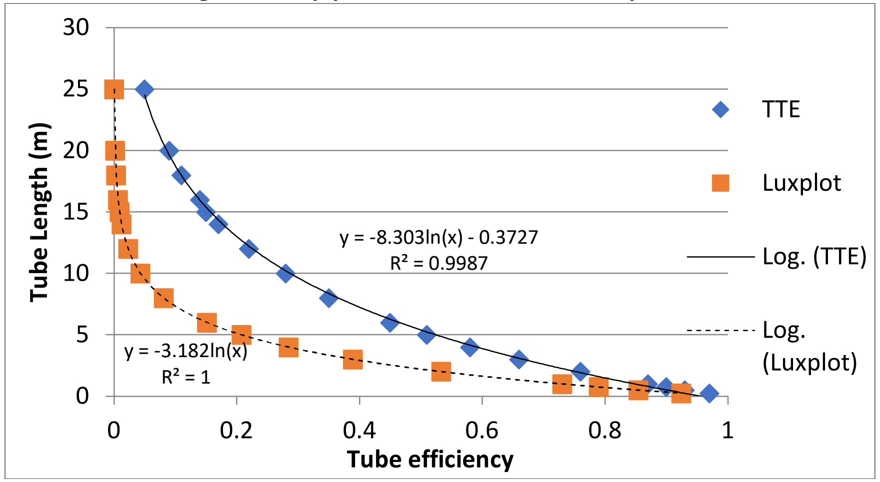


Figure 4. The “transparency” or “efficiency” of the tube (D=0,53m, R=0.95) related to the length of the pipe, for the TTE and the Luxplot methods

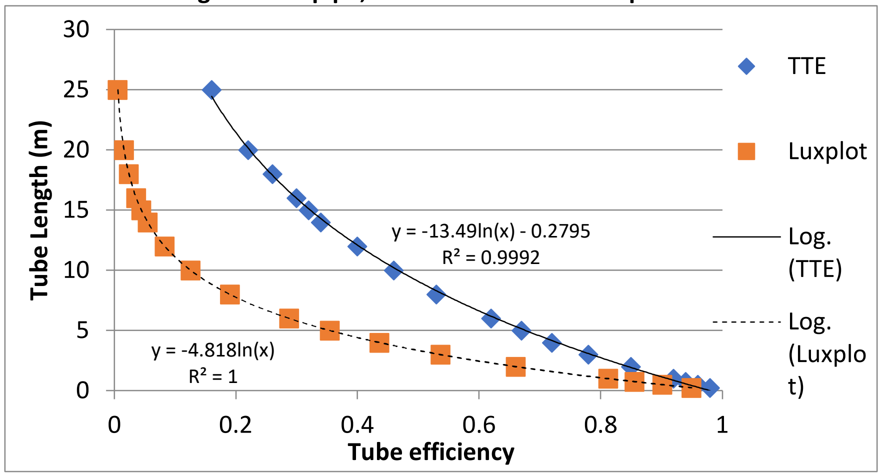


Figure 5. The “transparency” or “efficiency” of the tube (D=0,65m, R=0.95) related to the length of the pipe, for the TTE and the Luxplot methods

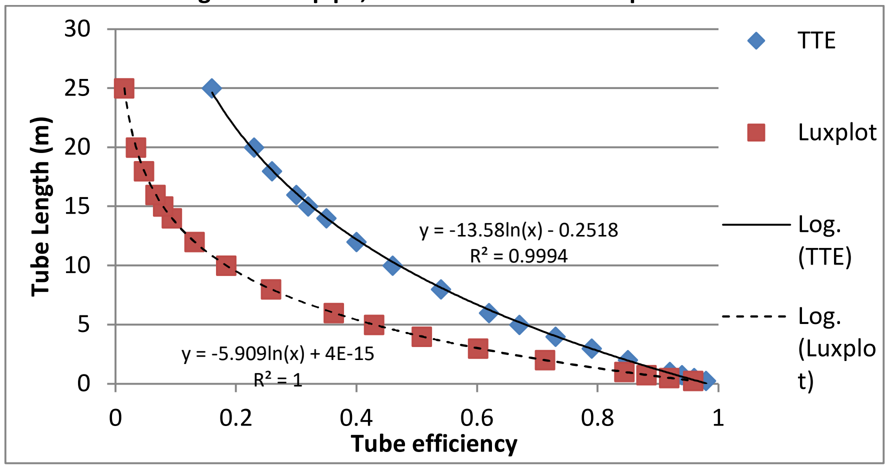
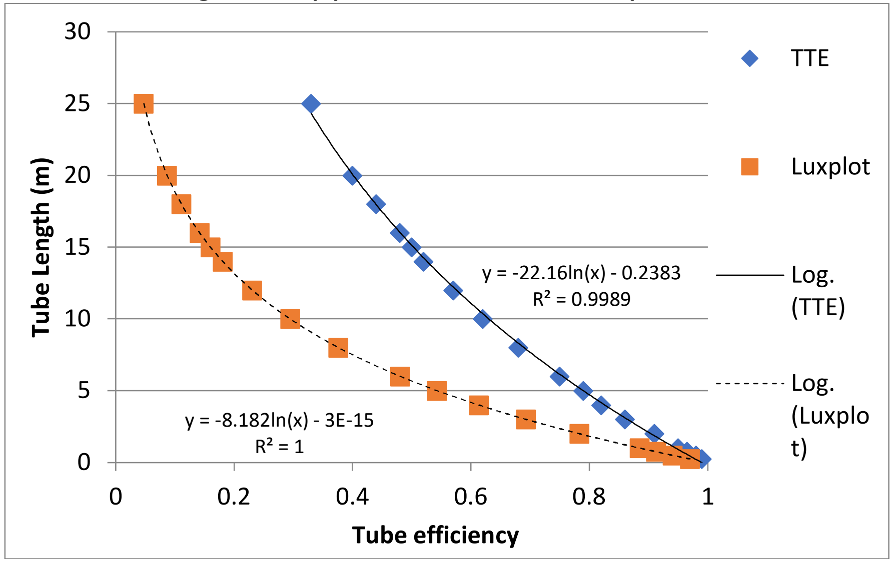


Figure 6. The "transparency" or "efficiency" of the tube (D=0,90m, R=0.95) related to the length of the pipe, for the TTE and the Luxplot methods



In the case of the application of the TTE method for the illuminance calculation, the relationship giving the DPF can be altered to give the average illuminance on the reference plane. However, the results of the application of this method showed that the average interior illuminance remains almost the same for any pipe diameter (Table 10).

Table 10. Comparison of the illuminance values derived by eq. (16) for various light pipe diameters.

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	FLUX (lm)	ILLUMINANCE (lux) calculated with TTE method
4.00	4.00	3.00	0.25	0.25	0.98	177.42	19.07
4.00	4.00	3.00	0.35	0.25	0.98	347.31	19.05
4.00	4.00	3.00	0.38	0.25	0.98	399.48	19.09
4.00	4.00	3.00	0.53	0.25	0.99	803.27	19.21
4.00	4.00	3.00	0.65	0.25	0.99	1211.10	19.26
4.00	4.00	3.00	0.90	0.25	0.99	2331.67	19.34

The illuminance was also calculated with eq. (20) of the Luxplot methodology, using the flux values derived with the TTE method. The procedure is much more time consuming, as the angle from the normal to the light pipe with the point where the illuminance is to be calculated, must be defined. Also, the larger the room, the greater the number of the reference points where illuminance needs to be calculated for more accurate results is. The results of the Luxplot methodology appear to be much more reasonable than these of the TTE method (Appendix VII), as they differ as the light pipe characteristics change.

Using a computer program to simulate the lighting conditions in a space with a light pipe modelled accurately, showed that backward raytracing is not able to simulate this type of daylight system. For tube lengths greater than 0.5m the software would fail to give any light distribution in the interior. On the contrary, data resulting from simulations of realistic reproduction of the light pipes with radiosity, gave much greater values. However, there was inconsistency of the results.

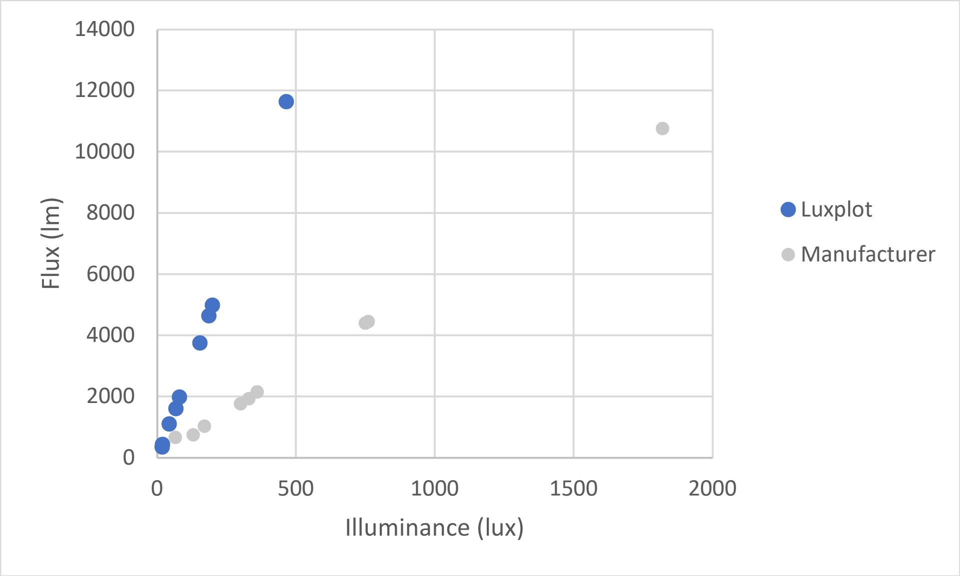
Instead of creating a realistic reproduction of the light pipe layout, it was decided that the 3D model suggested by a light pipe manufacturer would be used, as it was one of the set of assumptions that gave results closer to the data given by the manufacturer. However, when the manufacturer’s data or those resulting from the simulations are compared to that of the mathematical methods (TTE and Luxplot), great differences are observed. It is interesting that the flux resulting from the calculations with the TTE method has very different relation to the illuminance on the working plane (1.5m below the diffuser) than the values given by the manufacturer (Figure 7). These differences may occur because the manufacturer’s data were obtained through measurements. The sky in real conditions can never be as uniform as in simulations or mathematical calculations assuming a uniform and stable external illuminance. Also, the diffusers used in real applications are never perfectly diffusing, as this would cause great light losses.

Table 11. Comparison of the flux and the illuminance calculated with the Luxplot method, with flux and illuminance provided by a light pipe manufacturer, for rooms of areas 7.5, 14 and 22 m^2, for light pipe diameters of 0.27, 0.3 and 0.475 m, tube reflectance 0.98 and external illuminances 105, 45 and 10 klux.

						LUXPLOT		MANUFACTURER DATA*	
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	Exterior ILLUMINANCE (lux)	FLUX (lm)	ILLUMINANCE (lux)	FLUX (lm)	ILLUMINANCE (lux)
3	2.5	1.5	0.27	0.25	105000	3762.705	154.04	2160	360
3	2.5	1.5	0.27	0.25	45000	1612.588	68.04	1045	170
3	2.5	1.5	0.27	0.25	10000	358.3528	17.87	670	65
4	3.5	1.5	0.3	0.25	105000	4645.315	186.94	4460	760
4	3.5	1.5	0.3	0.25	45000	1990.849	80.76	1940	330
4	3.5	1.5	0.3	0.25	10000	442.4109	18.82	760	130
5.5	4	1.5	0.475	0.25	105000	11645.55	465.15	10770	1820
5.5	4	1.5	0.475	0.25	45000	4990.948	198.97	4410	750
5.5	4	1.5	0.475	0.25	10000	1109.1	43.69	1768	300

**Source: Personal communication with manufacturer. The pipe length was picked to provide comparable results with those provided by the manufacturer.*

Figure 7. Illuminance as a function of Flux for the Luxplot method and from manufacturer's data



Modelling the light pipe as a luminaire of cosine luminous intensity distribution, seems to be the most reliable method for predicting the light pipe performance, using a computer software. The flux of the TTE method is used for the luminaire lumen output and the illuminance results have a consistent sequence. Generally, the use of a computer software has many advantages, which are:

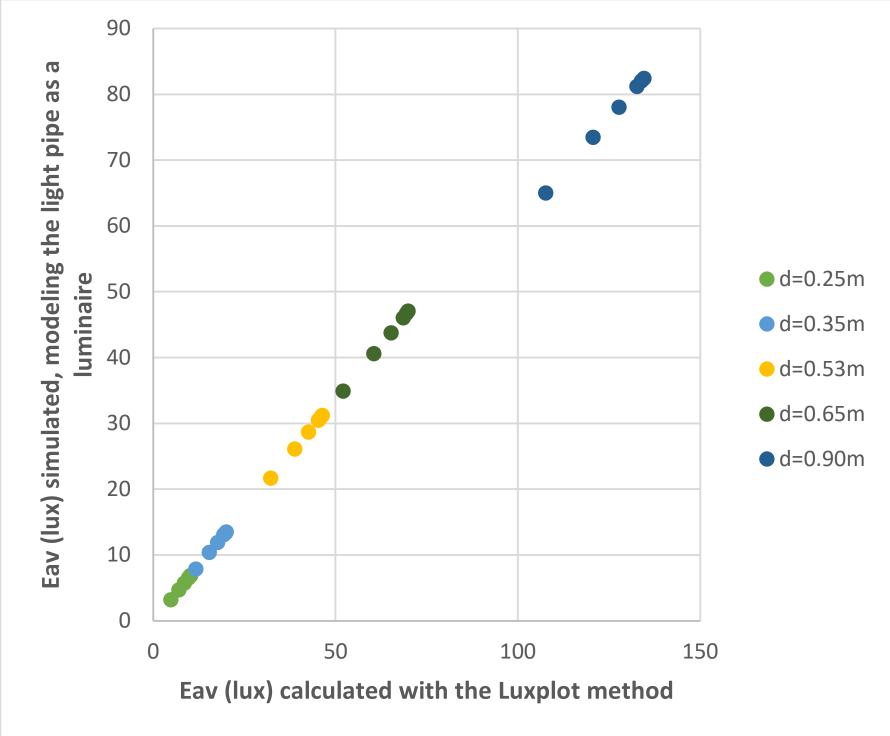
- it is able to illustrate the interior lighting conditions, by giving the illuminance at every point of the reference plane;
- it can give not only average, but also minimum and maximum values of illuminance on the reference plane;
- it can give results for any room geometry;
- it can easily combine various different natural light sources in the same room;
- depending on the software used, it can provide other information, such as energy savings, life-cycle analysis, etc.

However, this inconsistency between the results of all the analysed methods, creates a great problem of reference data, with which the simulation results can be validated, for a reliable prediction tool or method to be produced. This obstacle can only be overcome with real measurements under lab conditions.

Table 12. Comparison of the illuminance values that resulted from the application of the TTE method, of the Luxplot method (with the flux taken from the TTE method) and from simulations, in which the light pipe emulated a luminaire with cosine luminous intensity distribution. (E_{ex}=5,000 lux, ρ=0.98, τ_{dome} τ_{dif}=0.82, Room surface reflectances (ρ_{sur}): Walls/Ceiling/Reference plane=50/70/30, MF=0.9, Reference plane at 0.85m above floor and 0.50m offset from walls).

Room Dimensions (length/ width/ height, m)	Light Pipe Diameter (m)	Light Pipe Length (m)	ILLUMINANCE (lux) - TTE Method	ILLUMINANCE (lux) - LUXPLOT Method	ILLUMINANCE (lux) - Light Pipe modeled as a luminaire
4/4/3	0.25	0.25	18.81	10.24	6.93
		0.5	18.51	10.13	6.89
		1	17.94	9.63	6.53
		3	15.82	8.49	5.75
		6	13.09	7.03	4.77
		12	8.97	4.82	3.25
	0.35	0.25	19.05	20.04	13.56
		0.5	18.83	19.81	13.42
		1	18.4	19.36	13.11
		3	16.79	17.66	11.96
		6	14.62	15.38	10.43
		12	11.1	11.67	7.89
	0.53	0.25	19.21	46.35	31.23
		0.5	19.07	45.99	31
		1	18.77	45.29	30.53
		3	17.64	42.56	28.7
		6	16.08	38.78	26.14
		12	13.35	32.2	21.7
	0.65	0.25	19.26	69.89	47.09
		0.5	19.14	69.45	46.78
		1	18.9	68.59	46.1
		3	17.98	65.24	43.8
		6	16.68	60.53	40.62
		12	14.36	52.1	34.97
	0.9	0.25	19.34	134.55	82.46
		0.5	19.25	133.91	82.07
		1	19.07	132.64	81.23
		3	18.36	127.7	78.1
		6	17.34	120.62	73.51
		12	15.47	107.63	65.03

Figure 8. The relation between average illuminance (lux) calculated with the Luxplot method and simulated, modelling the light pipe as a luminaire. The calculation parameters are given in Table 12.



3.5 Development of data driven calculation formulas

3.5.1 Equation derived from the TTE method

An equation was developed using the TTE method, derived by the calculations presented in paragraph 3.2.2. More specifically, the calculations were performed for the rooms described in Table 4 and for the light pipe characteristics presented in Table 5. The tube reflectance value that was used is 0.98 and the combined transmittance of the diffuser and the dome is 0.82. The UF and MF values were derived by CIE Technical Report 173:2012 (CIE, 2012) with MF taking the value of 0.9. The TTE values were either taken from the CIE technical report (CIE, 2012), or were calculated using the relations included in Table 6.

The external conditions were assumed to be of an overcast sky with 5,000 lux illuminance. The results of the calculations are given in Appendix I.

The correlation of the room dimensions and the TTE with the calculated illuminance values, led to the following equation:

$$E_{pipe} = -1.04 + 0.67\, l + 1.46\, w - 2.62\, h + 19.97\, TTE \quad (21)$$

where l is the room length (the largest dimension of the room) (m), w is the room width (m), h is the room height (m) and TTE is the transmission tube efficiency.

The most important parameter for the determination of the E_{pipe} value is the efficiency of the light pipe, a parameter dependent on the light pipe size (diameter and length) and reflection.

The relation is valid for specific conditions (E_{ex}=5,000 lux, τ_c=0.82, etc), however it can be easily altered to consider different exterior and interior conditions and light pipe characteristics.

$$E_{pipe} = (-1.04 + 0.67\, l + 1.46\, w - 2.62\, h + 19.97\, TTE)\,(E_{ex}/5{,}000)\,(\tau_{dom}\, \tau_{dif}/0.82)\,(MF/0.9) \quad (22)$$

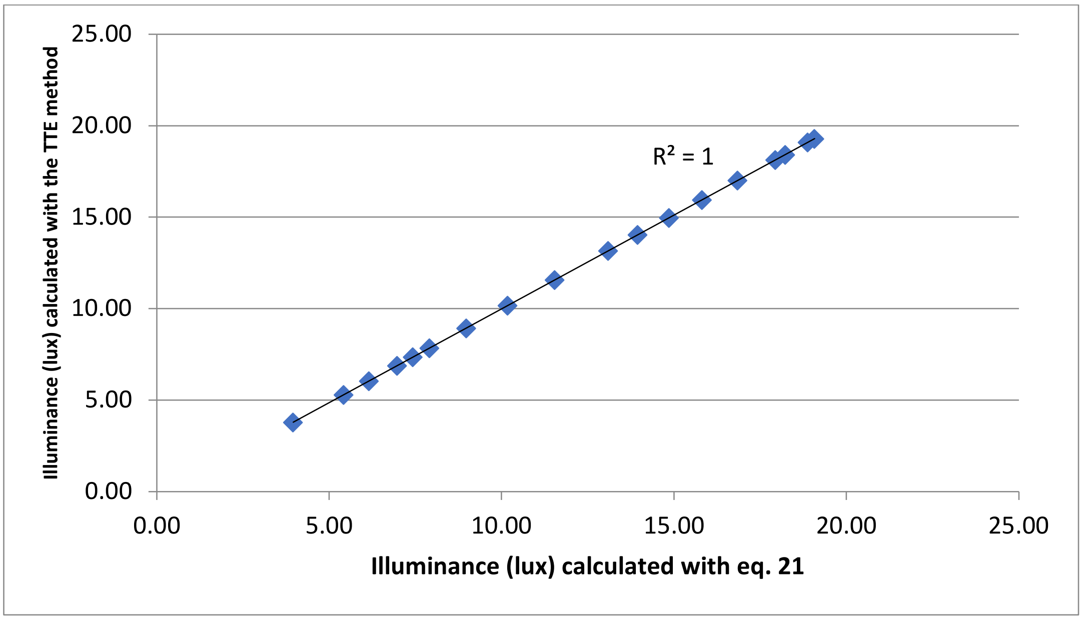
The comparison of the illuminance values calculated with the analytical form of the TTE method and with the equation that resulted from the correlation of the various parameters (eq. (21)**) shows great consistency (Table 13,**

Figure 9).

Table 13. Comparison of the illuminance calculated with the TTE method and with eq. (21), for a room with dimensions (l, w, h)=(4, 4, 3) and a light pipe diameter of 0.25m and reflectance 0.98

Light Pipe Radius (m)	Light Pipe Length (m)	TTE	FLUX (lm)	DPF (%)	ILLUMINANCE (lux) calculated with the TTE method	ILLUMINANCE (lux) calculated with eq.(21)
0.13	0.25	0.98	177.42	0.38	19.07	19.30
0.13	0.50	0.97	175.61	0.38	18.88	19.10
0.13	0.75	0.94	169.53	0.36	18.22	18.42
0.13	1.00	0.92	166.88	0.36	17.94	18.13
0.13	2.00	0.87	156.69	0.34	16.84	17.01
0.13	3.00	0.81	147.12	0.32	15.82	15.95
0.13	4.00	0.76	138.14	0.30	14.85	14.96
0.13	5.00	0.72	129.70	0.28	13.94	14.03
0.13	6.00	0.67	121.78	0.26	13.09	13.16
0.13	8.00	0.59	107.37	0.23	11.54	11.57
0.13	10.00	0.52	94.66	0.20	10.18	10.17
0.13	12.00	0.46	83.45	0.18	8.97	8.93
0.13	14.00	0.41	73.57	0.16	7.91	7.84
0.13	15.00	0.38	69.08	0.15	7.43	7.35
0.13	16.00	0.36	64.86	0.14	6.97	6.88
0.13	18.00	0.32	57.18	0.12	6.15	6.03
0.13	20.00	0.28	50.41	0.11	5.42	5.29
0.13	25.00	0.20	36.79	0.08	3.96	3.78

Figure 9. Correlation of the illuminance calculated with eq. (21) and with the TTE methodology. The calculation parameters are given in Table 13.



3.5.2 Equation derived from the Luxplot method

The equation that was developed using the Luxplot method was derived by the algorithm presented in paragraph 3.2.4. However, since the flux Φ_i calculated with eq. (18) was significantly lower than the flux calculated with the method proposed by CIE for light pipe lengths greater than 2.00 m, the flux calculated with the TTE method was used for the illuminance calculation.

The calculations were performed for the rooms described in Table 4 and for the light pipe characteristics presented in Table 5. The tube reflectance value that was used is 0.98 and the combined transmittance of the diffuser and the dome is 0.82. The TTE values were either taken from the CIE technical report or were calculated by the equations included in Table 6.

The external conditions were assumed to be of an overcast sky of illuminance 5,000 lux.

The results of the calculations are given in Appendix IV.

The correlation of the illuminance values, calculated with the Luxplot method, with the room dimensions and the TTE, led to the following equations (Table 14), depending on the light pipe diameter. Also, equations connecting the room dimensions and flux (Φ_i) with illuminance are provided.

Table 14. Relations providing the average illuminance Epipe calculated with the Luxplot method, per light pipe diameter.

Diameter (m)	Equations for the calculation of average Illuminance E_{pipe} (lux)	
0.25	$11.94 - 0.59\,l - 1.81\,w - 1.40\,h + 7.04\,TTE$	(23)
	$11.94 - 0.59\,l - 1.81\,w - 1.40\,h + 0.04\,\Phi_i$	(24)
0.35	$26.07 - 1.37\,l - 3.79\,w - 3.12\,h + 13.78\,TTE$	(25)
	$26.07 - 1.37\,l - 3.79\,w - 3.12\,h + 0.04\,\Phi_i$	(26)
0.375	$30 - 1.56\,l - 4.23\,w - 3.64\,h + 15.41\,TTE$	(27)
	$30 - 1.56\,l - 4.23\,w - 3.64\,h + 0.04\,\Phi_i$	(28)
0.53	$66.24 - 3.67\,l - 9.23\,w - 8.10\,h + 31.47\,TTE$	(29)
	$66.24 - 3.67\,l - 9.23\,w - 8.10\,h + 0.04\,\Phi_i$	(30)
0.65	$104.18 - 5.91\,l - 14.23\,w - 12.85\,h + 47.22\,TTE$	(31)
	$104.18 - 5.91\,l - 14.23\,w - 12.85\,h + 0.04\,\Phi_i$	(32)
0.90	$209.91 - 12.21\,l - 28.01\,w - 26.11\,h + 90.21\,TTE$	(33)
	$240.35 - 13.22\,l - 27.87\,w - 28.61\,h + 0.03\,\Phi_i$	(34)

In the above equations, l is the room length (the largest dimension of the room, m), w is the room width (m), h is the room height (m), TTE is the transmission tube efficiency and Φ_i is the flux emerging from the light pipe diffuser (lm).

The equations described in Table 14, are valid for the conditions for which the calculations were performed (E_{ex}=5,000lux, τ_c=0,82, etc) and can be altered to provide the average illuminance for any external or internal conditions and any light pipe characteristics, by multiplying the result with the following product:

$$a=(E_{ex}/5,000)\,(\tau_{dom}\,\tau_{dif}\,/0.82)\,(MF/0.9) \qquad (35)$$

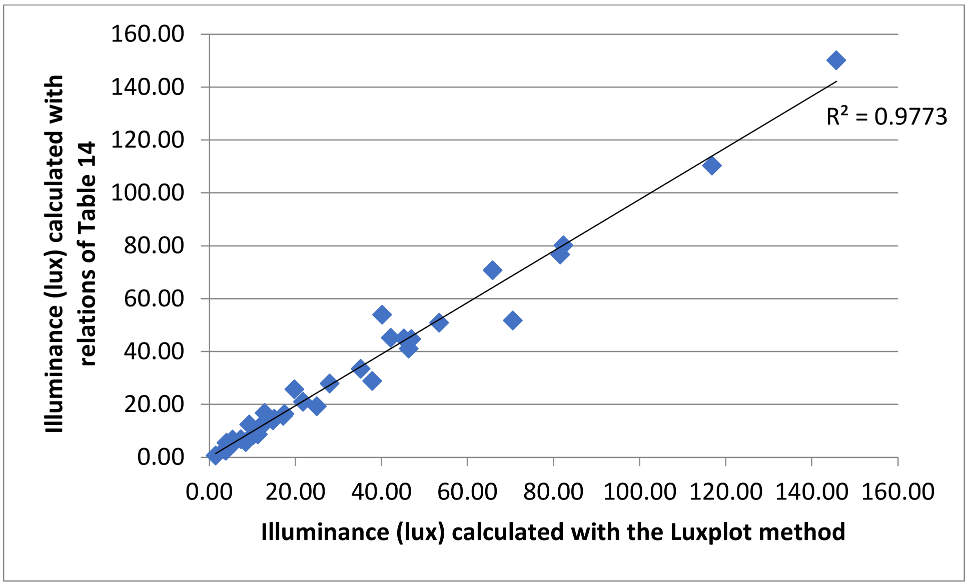
Some of the results from the application of the equations of Table 14, compared to the respective results of the analytical application of the Luxplot method, are given in Table 15 and in Figure 10. More results are provided in Appendix IV.

Table 15. Comparison of the illuminance calculated with the Luxplot method and with the equations of Table 14

Room Length (m)	Room Width (m)	Room Height (m)	Light Pipe Diameter (m)	Light Pipe Length (m)	T_{dome} T_{dif}	E_{ex}	FLUX (lm)	ILLUMINANCE (lux) calculated with the Luxplot method	ILLUMINANCE (lux) calculated with relations of Table 14 using TTE	ILLUMINANCE (lux) calculated with relations of Table 14 using Φ_i
4	4	3	0.25	0.25	0.82	5000	174.95	10.24	8.53	8.53
4	4	5	0.25	0.5	0.82	5000	172.22	4.02	5.63	5.63
6	4	3	0.25	1	0.82	5000	166.88	7.36	7.02	7.02
7	4	3	0.25	3	0.82	5000	147.12	5.74	5.66	5.66
5	5	4	0.25	6	0.82	5000	121.78	3.88	2.65	2.65
6	6	2.5	0.25	12	0.82	5000	83.45	1.46	0.85	0.85
4	3	3	0.35	0.25	0.82	5000	347.31	21.81	21.14	21.14
5	4	3	0.35	0.5	0.82	5000	343.34	17.20	15.83	15.83
6	4	3	0.35	1	0.82	5000	335.53	14.81	14.15	14.15
7	4	3	0.35	3	0.82	5000	306.04	11.94	11.64	11.64
5	5	4	0.35	6	0.82	5000	266.59	8.49	5.93	5.93
6	6	2.5	0.35	12	0.82	5000	202.29	3.53	2.95	2.95
4	4	5	0.375	0.25	0.82	5000	399.48	9.32	12.61	12.61
6	4	3	0.375	0.5	0.82	5000	395.21	17.44	16.61	16.61
7	4	3	0.375	1	0.82	5000	386.80	15.09	14.73	14.73
5	5	4	0.375	3	0.82	5000	354.93	11.31	8.77	8.77
6	6	2.5	0.375	6	0.82	5000	311.97	5.45	6.81	6.81
5	4	3	0.375	12	0.82	5000	241.03	12.08	12.34	12.34
4	4	3	0.53	0.25	0.82	5000	803.27	46.35	41.19	41.19
6	4	3	0.53	0.5	0.82	5000	797.07	35.17	33.61	33.61
5	5	4	0.53	1	0.82	5000	784.81	25.00	19.47	19.47
6	6	2.5	0.53	3	0.82	5000	737.63	12.89	16.90	16.90
4	3	3	0.53	6	0.82	5000	672.12	42.20	45.35	45.35
5	4	3	0.53	12	0.82	5000	558.05	27.96	28.03	28.03
6	4	3	0.65	0.25	0.82	5000	1211.10	53.45	51.05	51.05
7	4	3	0.65	0.5	0.82	5000	1203.56	46.95	44.85	44.85
5	5	4	0.65	1	0.82	5000	1188.60	37.87	29.02	29.02

6	6	2.5	0.65	3	0.82	5000	1130.64	19.75	25.92	25.92
4	3	3	0.65	6	0.82	5000	1048.94	65.86	70.84	70.84
5	4	3	0.65	12	0.82	5000	902.83	45.24	45.07	45.07
5	4	3	0.9	0.25	0.82	5000	2331.67	116.83	110.53	110.27
4	3	3	0.9	0.5	0.82	5000	2320.62	145.71	150.33	151.04
6	6	2.5	0.9	1	0.82	5000	2298.67	40.15	54.08	54.65
5	5	4	0.9	3	0.82	5000	2212.96	70.50	51.84	50.33
7	4	3	0.9	6	0.82	5000	2090.35	81.54	76.82	76.81
6	4	3	0.9	12	0.82	5000	1865.13	82.31	80.38	83.47

Figure 10. Correlation of the illuminance calculated with relations included in Table 14 and with the Luxplot methodology. The calculation parameters are given in Table 15.



3.5.3 Equation derived using computer simulations, modelling light pipes as daylight systems with various dimension/transmittance assumptions

The set of simulations that were performed using the assumption proposed by the light pipe manufacturer have been described in paragraph 3.3.1. Briefly, the assumptions include the enlargement of the diameter by 15%, construction of the pipe with a 0.10 m length and the application of a transmittance of 0.72 for the dome and the diffuser combined. The material of the interior walls of the tube are set to be 98% reflective, as is the actual material of the real tube. The room surfaces have reflectances for walls/floor/ceiling equal to 50/30/70 and the external conditions were of an overcast sky with global illuminance of 5,000 lux. The simulations were performed for eight different types of rooms with their characteristics described in Table 4, as were the two methods that were analyzed before. The method was applied to light pipes of diameters 0.27/0.30/0.35/0.47/0.50/0.70.

The aim of this set of simulations was to produce equations that would provide the flux and the illuminance from every light pipe, for any external illuminance of an overcast sky.

The presence of side windows was also studied, after the results of the calculations with the light pipes as the only daylight source were finished. To each of the rooms presented in Table 4, four types of windows, in terms of window area, were applied and simulated. The details on the dimensions and area of the windows are given in Table 16. The transmittance of the windows was 0.73.

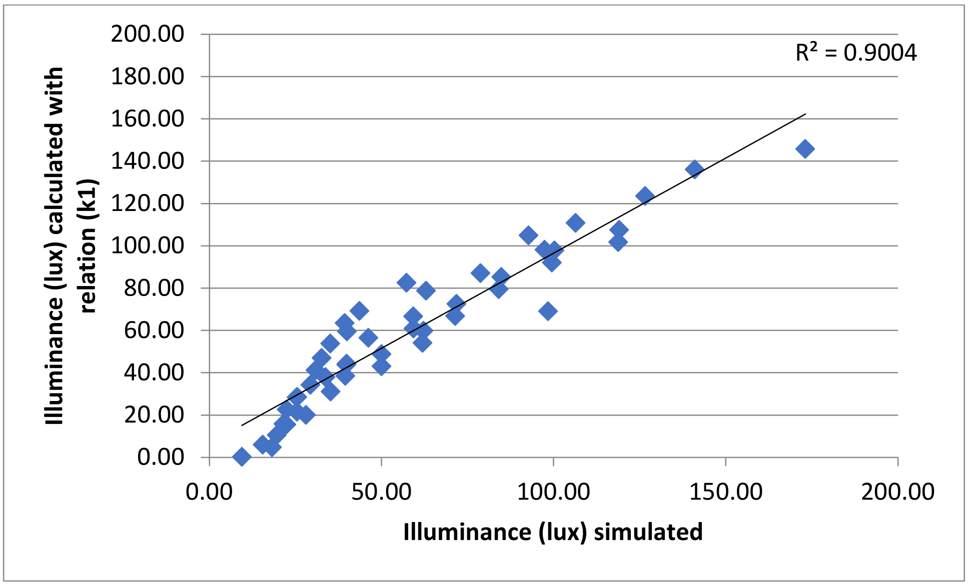
The simulations that were performed led to an equation giving the average illuminance on the working plane (0.85m from the floor) of a room of length l (length is the largest dimension of the rectangular plan of the room), width w, height h when a light pipe of diameter d is used. Table 16 includes illuminance results from simulations and from using eq.(36), while all the results are provided in Appendix V.

$$E_p=126.9-12.66\,l-9.66\,w-26.8\,h+191.44\,d \quad (36)$$

Table 16. Comparison of the illuminance from one light pipe, resulting from simulations and from calculations using eq. (36), for various rooms and light pipe diameters.

Room Length (m)	Room Width (m)	Room Height (m)	Light Pipe Diameter (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with eq. (47)
4	4	3		35.10	54.01
4	4	5		9.47	0.41
6	4	3		25.56	28.69
7	4	3		21.57	16.03
5	5	4		18.19	4.89
6	6	2.5		22.53	22.77
4	3	3		39.34	63.67
5	4	3	0.27	30.90	41.35
4	4	3		40.00	59.75
4	4	5		15.50	6.15
6	4	3		29.39	34.43
7	4	3		25.46	21,77
5	5	4		19,65	10,63
6	6	2.5		25,38	28,51
4	3	3		43.57	69.41
5	4	3	0.3	32.68	47.09
4	4	3		98.37	69.32
4	4	5		22.40	15.72
6	4	3		39.80	44.00
7	4	3		35.27	31.34
5	5	4		28.07	20.20
6	6	2.5		33.73	38.08
4	3	3		62.97	78.98
5	4	3	0.35	46.21	56.66
4	4	3		99.55	92.30
4	4	5		39.48	38.70
6	4	3		71.40	66.98
7	4	3		61.94	54.32
5	5	4		50.03	43.18
6	6	2.5		59.30	61.06
4	3	3		118.75	101.96
5	4	3	0.47	84.04	79.64
4	4	3		100.30	98.04
4	4	5		39.90	44.44
6	4	3		71.77	72.72
7	4	3		62.22	60.06
5	5	4		50.05	48.92
6	6	2.5		59.28	66.80
4	3	3		119.04	107.70
5	4	3	0.5	84.77	85.38
4	4	3		140.97	136.33
4	4	5		57.31	82.73
6	4	3		106.43	111.01
7	4	3		97.38	98.35
5	5	4		78.75	87.21
6	6	2.5		92.68	105.09
4	3	3		173.13	145.99
5	4	3	0.7	126.56	123.67

Figure 11.Correlation of the illuminance from light pipes simulated and calculated with eq. (36). The calculation parameters are given in Table 16.



Respectively, a relation for the calculation of the Illuminance from side windows E_w has resulted.

$$E_w = 302.16 - 34.04\,l - 32.3\,w - 11.01\,h + 47.25\,A_w \quad (37)$$

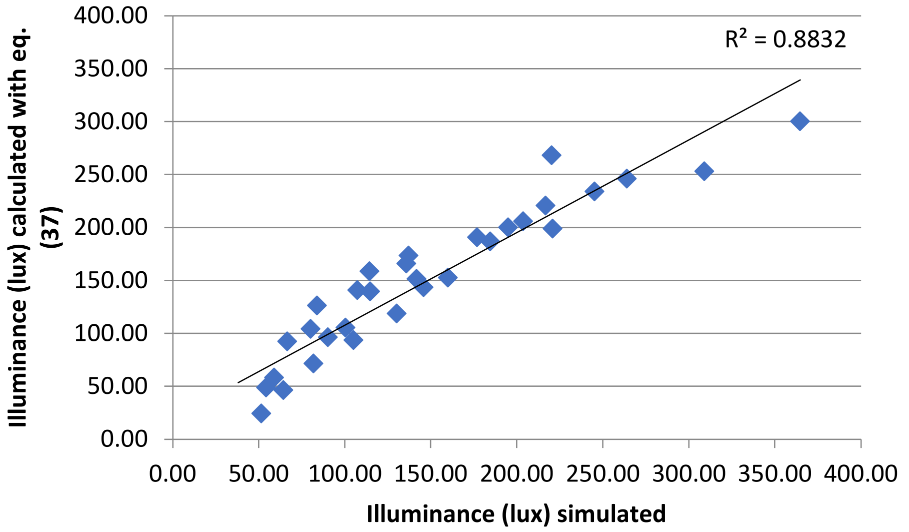
Where A_w is the area of the windows in m^2.

For different window transmittance values, eq. (37) should be multiplied with the quotient of the actual transmittance value divided by 0.73. The illuminance resulting from eq. (37) can be added to the results of eq (36) to calculate the output from both light pipes and windows in a room.

Table 17. Comparison of the illuminance from windows simulated, with the illuminance calculated with eq. (37), for various rooms and window areas.

Room Length (m)	Room Width (m)	Room Height (m)	Window Area (m^2)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with eq. (48)
			1	83.82	126.72
			2	137.00	173.97
			3	216.80	221.22
4	4	3	4	220.20	268.47
			1	80.24	104.70
			2	141.66	151.95
			3	220.84	199.20
4	4	5	4	263.92	246.45
			1	58.98	58.64
			2	100.42	105.89
			3	159.96	153.14
6	4	3	4	194.88	200.39
			1	51.43	24.60
			2	81.79	71.85
			3	130.25	119.10
7	4	3	4	135.86	166.35
			1	54.32	49.37
			2	90.16	96.62
			3	145.84	143.87
5	5	4	4	176.96	191.12
			1	38.04	-0.46
			2	64.40	46.79
			3	105.04	94.04
6	6	2.5	4	107.22	141.29
			1	114.30	159.02
			2	203.64	206.27
			3	308.92	253.52
4	3	3	4	364.64	300.77
			1	66.58	92.68
			2	114.78	139.93
			3	184.45	187.18
5	4	3	4	245.12	234.43

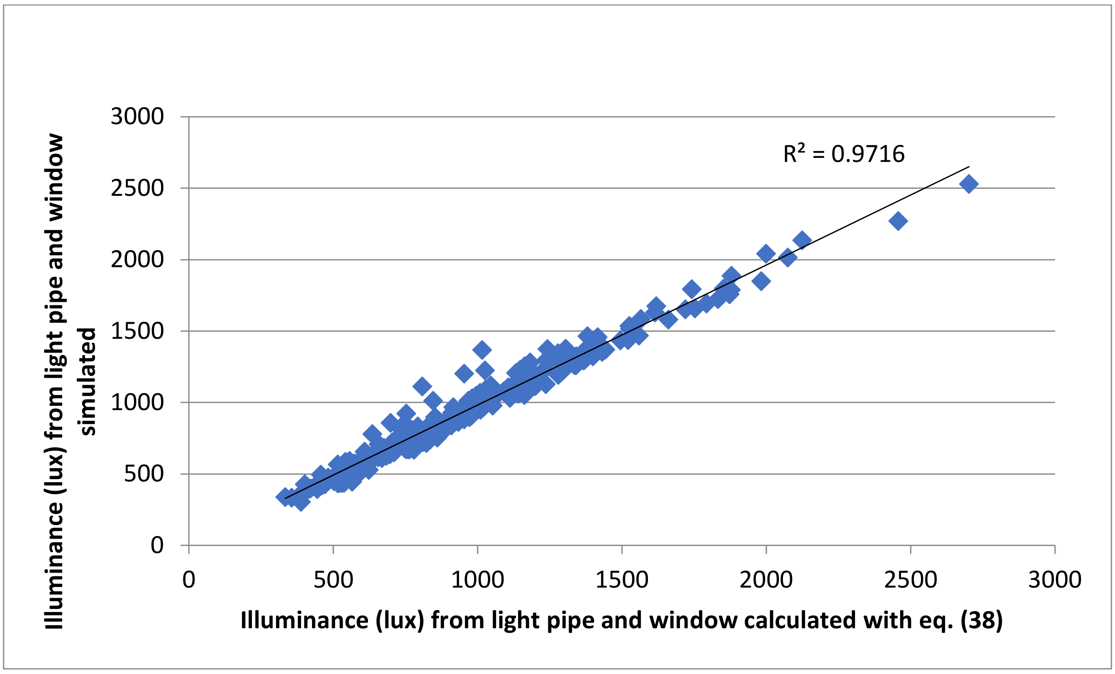
Figure 12. Correlation of the illuminance from windows, calculated with eq. (37) and of the illuminance simulated. The calculation parameters are given in Table 17.



Eq. (36) and (48) are combined in a single equation, giving the average illuminance (E_{av}) on the working plane in a room, with a light pipe and a window, for overcast sky conditions. This equation incorporates the length of the light pipe by using the Transmittance Tube Efficiency (TTE) term of the TTE method. The concurrence of the illuminance values simulated with those calculated with the final eq. (38) is significant. This equation provides a direct and quick way to calculate the interior illuminance by light pipes and windows with the assumptions previously mentioned, without performing simulations.

$$Esum = \frac{Eex}{5000}\left[\left(\frac{tdome * tdif}{0,72} * TTE * Eq.(\mathbf{36})\right) + Eq.\text{Error! Reference source not found.})\right] * \frac{MF}{0,9} \quad (38)$$

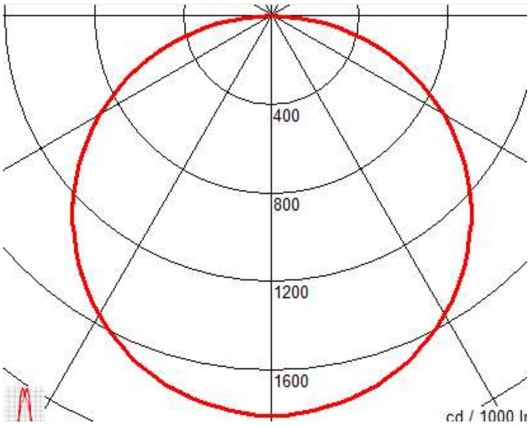
Figure 13. Correlation of the illuminance from windows and light pipes, calculated with eq. (38) and of the illuminance simulated.



3.5.4 Equations derived using computer simulations, modelling a light pipe as a luminaire with cosine luminous intensity distribution

The simulations were performed as described in paragraph 3.3.2. For the rooms described in Table 4, light pipes of diameters 0.25, 0.35, 0.53, 0.65 and 0.9m, were modelled as luminaires with cosine luminous intensity distribution. The Utilization Factors of the luminaire were set equal to those provided by the CIE Technical report on light pipes (CIE, 2012), depending on the Room Index and for room surface reflectances: walls/ceiling/reference plane=50/70/30. The lumen output of the luminaire was replaced by the Flux (lm) calculated with the TTE method, for external illuminance of 5,000lux.

Figure 14. The luminous intensity distribution of the luminaire used for the simulations



The performed simulations led to equations giving the average illuminance on the working plane of a room of length l (length was the largest dimension of the rectangular room plan), width w, height h when a light pipe of diameter d is used (all in metres). The results from the application of eq. (39)-(48) are given in Appendix VI.

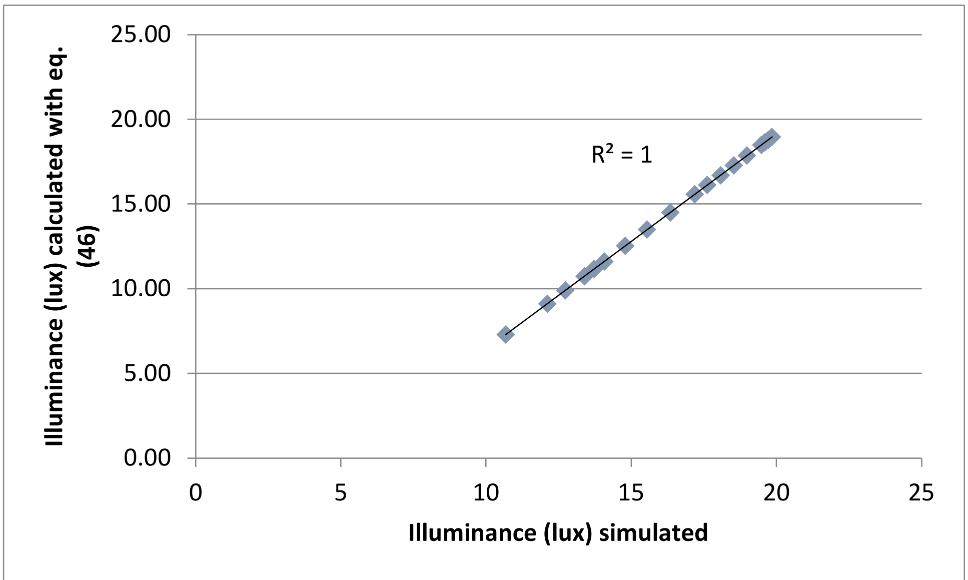
Table 18. Equations providing the average illuminance E_{pipe} simulated with the light pipe emulating a luminaire, per light pipe diameter.

Diameter (m)	Equations for the calculation of average illuminance Epipe	
0.25	$5.73-0.64\ l-0.31\ w-0.95\ h+4.34\ TTE$	(39)
	$5.73-0.64\ l-0.31\ w-0.95\ h+0.024\ \Phi_i$	(40)
0.35	$14.22 - 0.90\ l - 1.29\ w- 2.30\ h+ 7.59\ TTE$	(41)
	$14.22 - 0.90\ l - 1.29\ w- 2.30\ h+0.022\ \Phi_i$	(42)
0.53	$34.63-2.96\ l-2.29\ w-6.02\ h+ 19.03\ TTE$	(43)
	$34.63-2.96\ l - 2.29\ w-6.02\ h+0.023\ \Phi_i$	(44)
0.65	$59.79-4.52\ l-4.08\ w- 10.06\ h+25.53\ TTE$	(45)
	$59.79-4.52\ l-4.08\ w- 10.06\ h+0.02\ \Phi_i$	(46)
0.90	$101.68-6.26\ l-9.59\ w- 18.08\ h+ 58.22\ TTE$	(47)
	$101.68-6.26\ l-9.59\ w- 18.08\ h+ 0.023\ \Phi_i$	(48)

Table 19. Comparison of the simulated illuminance from one light pipe, with the illuminance calculated with equations in Table 18.

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with eq. (46)
5	5	4	0.65	0.25	19.85	18.97
				0.5	19.73	18.82
				0.75	19.6	18.66
				1	19.48	18.50
				2	18.99	17.89
				3	18.53	17.29
				4	18.08	16.71
				5	17.62	16.14
				6	17.19	15.59
				8	16.35	14.52
				10	15.55	13.51
				12	14.8	12.54
				14	14.08	11.62
				15	13.73	11.18
				16	13.39	10.75
				18	12.73	9.92
				20	12.11	9.13
				25	10.68	7.32

Figure 15. Correlation of the illuminance from light pipes calculated with eq. (46) and of the illuminance simulated. The calculation parameters are given in Table 19



3.6 Discussion on the development of the data-driven calculation methodologies

The algorithms that were developed after the application of the various performance calculation methodologies enable the estimation of the average illuminance provided by light pipes in a space, permit the calculation of the number of the light pipes needed as well as of the supplementary illuminance that should be provided by artificial lighting to cover specific lighting needs. However, not all algorithms that resulted from the previous analysis have the same level of accuracy or applicability.

As previously mentioned, the illuminance calculated with the TTE method or with eq. (21) and (22), is not considered to be indicative of the average illuminance on the reference plane of a room, as the calculation is based on the DPF resulting in a limited magnitude of results.

Also, the simulations made with the assumptions that the light pipe has a fixed length and transmittance, can only be applied to limited cases, and is based on rather random assumptions.

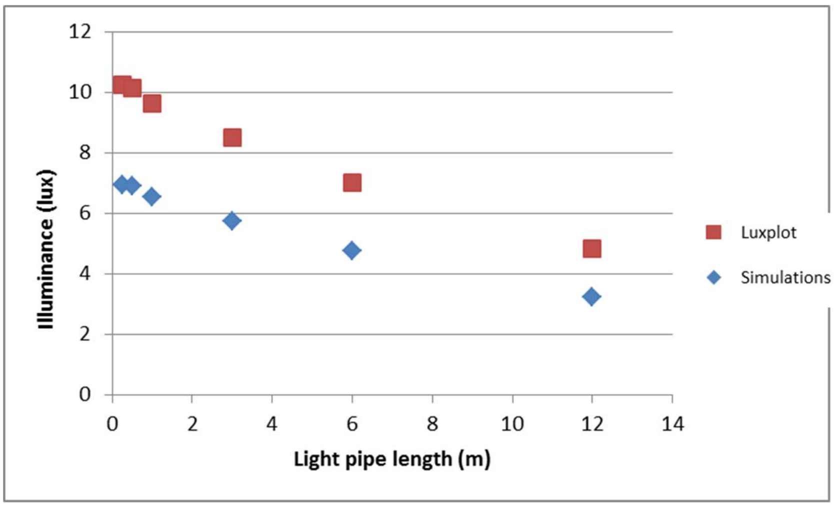
The Luxplot method, as well as the simulation replacing the light pipe with a luminaire of specific luminous distribution, seem to be the most reliable methodologies for the interior illuminance. However, the magnitude of difference between the illuminance results of the two methods can reach 80%, with the Luxplot method giving higher values. Data from measurements under laboratory conditions should be used to verify the results from the analytical and simulation methodologies that were tested and from the equations derived from them.

Tables with the illuminance values calculated with all the methodologies are given in Appendix VII.

Table 20. Comparison of the illuminance calculated with the Luxplot method and with simulations, replacing the light pipe with a luminaire with cosine luminous intensity distribution

Room Dimensions (length/width/height,m)	Light Pipe Diameter (m)	Light Pipe Length (m)	ILLUMINANCE (lux) - LUXPLOT Method	ILLUMINANCE (lux) – Light Pipe simulated as a luminaire
6/4/3	0.25	0.25	7.72	4.48
		0.5	7.6	4.35
		1	7.36	4.23
		3	6.49	3.72
		6	5.37	3.09
		12	3.68	2.1
	0.35	0.25	15.33	8.77
		0.5	15.15	8.67
		1	14.81	8.49
		3	13.5	7.74
		6	11.76	6.75
		12	8.93	5.11
	0.53	0.25	35.45	20.24
		0.5	35.17	20.09
		1	34.63	19.79
		3	32.55	18.6
		6	29.66	16.94
		12	24.63	14.07
	0.65	0.25	53.45	30.46
		0.5	53.11	30.29
		1	52.45	29.89
		3	49.9	28.44
		6	46.29	26.37
		12	39.84	22.7
	0.9	0.25	102.9	60.76
		0.5	102.41	60.47
		1	101.44	59.88
		3	97.66	57.57
		6	92.25	54.24
		12	82.31	48.22

Figure 16. Illuminance (lux) calculated with the Luxplot method and with simulations as a function of light pipe length



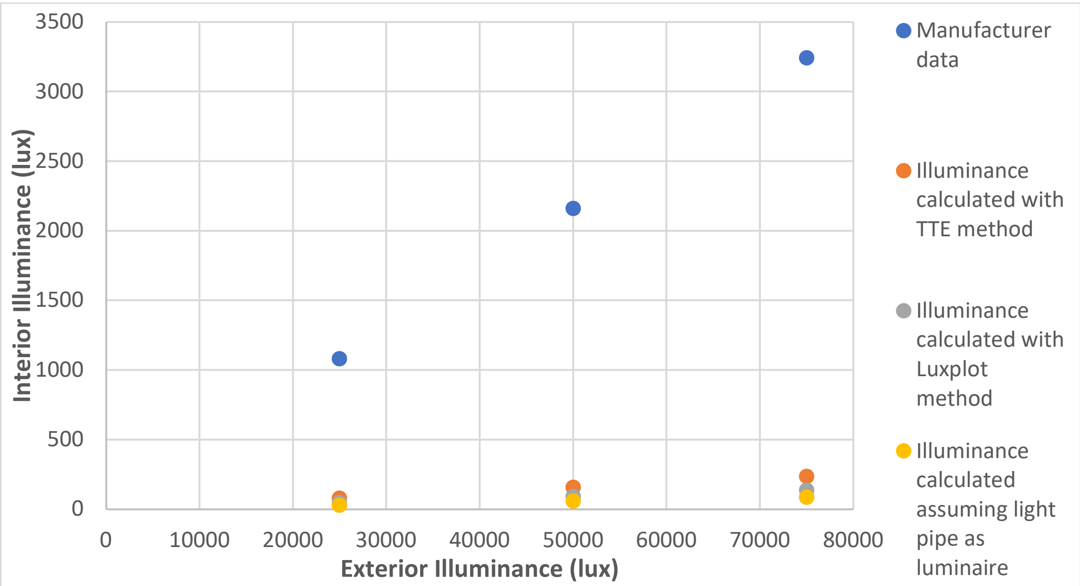
3.7 Conclusions

This chapter included the analysis, application, and comparison of four different methodologies for the calculation of a light pipe performance. The methodologies that were applied for a number of rooms and light pipe characteristics are the TTE method, analyzed in the CIE Technical Report 173:2012 (CIE, 2012) and the Luxplot method, developed by Jenkins and Muneer (Jenkins and Muneer, 2004; Jenkins, Muneer and Kubie, 2005) and two types of simulations, using the IES VE pro software. The first type of simulation begun with the realistic modelling of the light pipe, while the second uses the flux Φ_i (calculated with the TTE method), as the lumen output of a luminaire with cosine luminous intensity.

Modelling and simulating the light pipe with the IESVE software did not provide reliable results. To compare the illuminance results from the three remaining methodologies with manufacturer's data, the methodologies were applied for a light pipe of 0.35m diameter and 1.00m length, for three exterior illuminances. Monodraught provides Flux values for the Sunpipe model with a diameter 0.30m, for exterior illuminances of 25, 50 and 75 klux (BRE and Monodraught, 2020). These Flux values were used with eq.(26) to provide illuminance in Room 1 (l w h=4x4x3).

The three calculation methods tested in this chapter give comparable results, as shown in Figure 17. It is also evident that the Flux values provided by Monodraught, lead to much higher illuminance values than the mathematical calculation methods. The reason behind this difference is that manufacturer's data is taken from actual measurements, where the sky was not perfectly overcast, as assumed for the mathematical calculations. Another parameter that makes the comparison weak is that Monodraught does not provide the length of the light pipe from which the measurements were taken. The mathematical methodologies have been applied for a light pipe with length of 1,00m.

Figure 17. Comparison of the tested methods (TTE, Luxplot, simulation of light pipe as a luminaire) with manufacturer's data



The above analysis leads to the conclusion that the results of the mathematical methodologies need to be compared with measurements from a controlled environment, where all the design parameters are known. This comparison, which will show which mathematical calculation method is the most accurate and how different the theoretical results are from the real data, is provided in the following chapters of this Thesis.

Chapter 4: Experimental procedure

4.1 Synopsis

The necessity of carrying out measurements of the performance of light pipes in controlled conditions has been highlighted in the previous chapter. These measurements will be used as indices to assess the quality and quantity of the lighting provided by light pipes installed in Greek buildings. Moreover, they will enable the comparison between the theoretical performance, calculated with the mathematical methodologies analysed in the previous chapter, and experimental/measured values.

This chapter describes the developed lighting system and the experimental procedure used to monitor the performance of this system. In brief, the system consists of a light pipe and LEDs controlled by a daylight sensor, providing relatively stable interior lighting levels and energy savings for lighting, compared to more conventional daylight components and systems that do not exploit daylight.

The objectives of the monitoring of the developed lighting system under different operating conditions in the lab, are:

- To assess the daylight performance of the light pipe;
- To compare the experimentally acquired light pipes performances with those calculated with the mathematical methods already mentioned, and with simulations;
- To assess the lighting environment created by the light pipe/LED system;
- To assess the performance of the controls;
- To define the lighting energy savings from the use of the lighting system and of the controls.

4.2 Experimental Methodology

The developed lighting system was designed in 2013 and constructed in January 2015. Its performance was tested from the 28/11/2014 to 29/12 2014 and from 13/2/2015 to 7/8/2015. The test-cell where the lighting system was constructed, installed, and tested was in the campus of the National Kapodistrian University of Athens in Zografou, Greece. The following paragraphs describe the experimental layout and the test-cell as well as the measuring equipment.

4.2.1 Relevant Standards

The lighting and energy related parameters that were measured and recorded in the test room, are:

1. Illuminance
2. Energy consumption and power.

The European Standards with information and directions on the measurement of lighting parameters in real or experimental conditions are very few and are predominantly concerned with the preparation of surveys. The little information available is given by the following documents:

- ISO 28802:2012(en) (*ISO 28802:2012. Ergonomics of the physical environment — Assessment of environments by means of an environmental survey involving physical measurements of the environment and subjective responses of people*, 2012).

The parameter that is examined in this Standard is the horizontal illuminance. The guidelines describe the placement of illuminance sensors, which should be such as to measure the light levels available at the user's field of view and not to be shaded by the person conducting the measurement. Task-specific measurements should be taken at an appropriate reference level. Since the distribution of light by a light source is usually not uniform, as many sensors as possible should be placed and the exterior conditions (external horizontal illuminance) should also be monitored.

- CIE 69-1987: Methods of Characterizing Illuminance Meters and Luminance Meters (CIE, 1987).

This is a Technical Report describing the necessary characteristics of illuminance and luminance meters.

Other useful documents that were used for setting up the environment where the measurements were taken, are:

- ASHRAE, Performance measurement protocols for commercial buildings (ASHRAE, 2010).

This guide describes the process of conducting detailed illuminance measurements. It gives a quantitative parameter for the placement of sensors, which indicates that the maximum spacing between measurement points should be less than one-fourth the spacing between luminaires. The guide sets the height of the measurement points at the height of the reference plane, depending on the tasks performed and indicates that the sensors should not be placed too close to the room walls.

Also, the ASHRAE document provides information on how to perform detailed luminance measurements. For the specific experimental layout, the luminance measurements can be performed with a luminance meter, measuring what the users of a space might see (field of view) and especially the luminance (brightness) of the diffuser of the innovative system.

Finally, this document includes general instructions on the energy consumption and power recordings for lighting retrofits.

The instructions of the above-mentioned Standards and Guides have been followed for the preparation of the experiment.

4.2.2 The test-cell

The test room (Image 1) is a modular, prefabricated room, located at the campus of the University of Athens (latitude: 37.97, longitude: 23.79). The room is 5.76 m long by 2.75 m wide, with a height of 2.35m. All the surfaces of a space 3.81m by 1.86m inside this room were covered with black matt fabric, to prevent interreflections and to avoid the need to measure the surfaces' reflectances. The room has one window facing south-east, which was shaded by horizontal fins and covered with the same black fabric. The ceiling of the room was painted with black, matte paint. No exterior light could enter the space.

Image 1. The test-cell

Image 2. The test-cell and its surrounding environment

The light pipe was installed in the centre of this 3.81 m by 1.86 m space. Below the light pipe, an area 3.40 x 1.48 m was occupied by desks, with a height of 0.74m. The desks were covered with the same black fabric, as the one covering the walls.

Because of the construction material of the room (from outside: metal plate, 5cm of insulation, plastic interior surface), the temperatures inside the test room could be relatively high, especially during the summer months. An air-conditioning unit was installed, that was switched on when the temperatures went over 40^{o} C, or when someone was inside the room. The AC unit is the only element inside the room with a light colour (white).

The test-cell is in a rural environment, surrounded by low plants and a few trees. One of the trees is situated close to the room, the foliage of which shaded the light pipe dome after 4:00 pm during the testing period. The sensor placed externally, on the roof was not shaded by trees or other obstacles.

4.2.3 The measuring instruments

Illuminance sensors: Thirteen sensors measuring illuminance were placed on the desks, inside the test cell, while one sensor was placed externally, on the room flat roof. The characteristics of the sensors are given in Table 21.

All the illuminance sensors were connected to a data logger (Image 3), which took measurements every 15 seconds and recorded average, maximum and minimum values every minute (during the first two months the data logger was programmed to take measurements every minute and record every 15 minutes). Temperature was also recorded every minute from a sensor placed inside the data logger case. The data logger was connected to a multiplexer and a wireless modem, making the data retrieval from a distant computer possible. Practically, the data was retrieved every day. The sky conditions were recorded through observations and weather parameters (Air Temperature- °C, Total Solar Radiation – W/m^2, Diffuse Solar Radiation - W/m^2, Exterior Illuminance – Lux, Relative Humidity – mm, Precipitation – mm) were later provided by the National Observatory of Greece. The data logger had batteries which could supply energy for about ten hours from fully charged.

Table 21. Characteristics of the illuminance sensors

Dimensions	**Weight**	**Construction**	**Cable**	**Sensor**	**Detector**	**Filters**
Height:38mm, Diameter: 34mm	130gr (with 3m cable)	Dupont “Derlin” fully sealed to IP68	2 core screened DEF std 61-12/4.5	Cosine corrected head	Silicon photocell. Low fatigue characteristics	Optical Glass
Linearity error-to above level	**Absolute calibration error**	**Cosine error**	**Azimuth error**	**Temperature coefficient**	**Longterm stability**	**Response time – voltage output**
<0.2%	Typ. <3% 5% max	3%	<1%	±0.1%/°C	±2%	10ns
Sensitivity-current	**Sensitivity-voltage**	**Working range**	**Internal resistance - voltage output**	**Operating range**	**Humidity range**	
1.4μA/ 10 kLux	1mV/ 10 kLux	0-500 kLux	c. 650 ohms	-35 to +75°C	0-100% RH	


Image 3. Left: One of the illuminance sensors. Right: The data logger.

The illuminance sensors were placed horizontally on the top of the desks below the lighting system, as shown in Image 4 and Image 5. The distance of the peripheral sensors was approximately 0.25 m from the curtains that covered the room walls. The largest horizontal distance between a sensor and the centre of the diffuser was 1.50 m, approximately.

The sensor that measured the exterior illuminance was placed horizontally on the roof, on an unobstructed spot. The silicon head was regularly cleaned, to avoid loss of performance.

Energy meter: A smart meter was installed on the electric panel of the room. The smart meter measured the energy consumed and the power of the working devices in the room every minute and recorded the average values of energy and power every 15 minutes. The only energy consumption in the room was from the electrical equipment of the lighting system, except from the periods when the air-condition was on. The smart meter also measured the interior temperature.

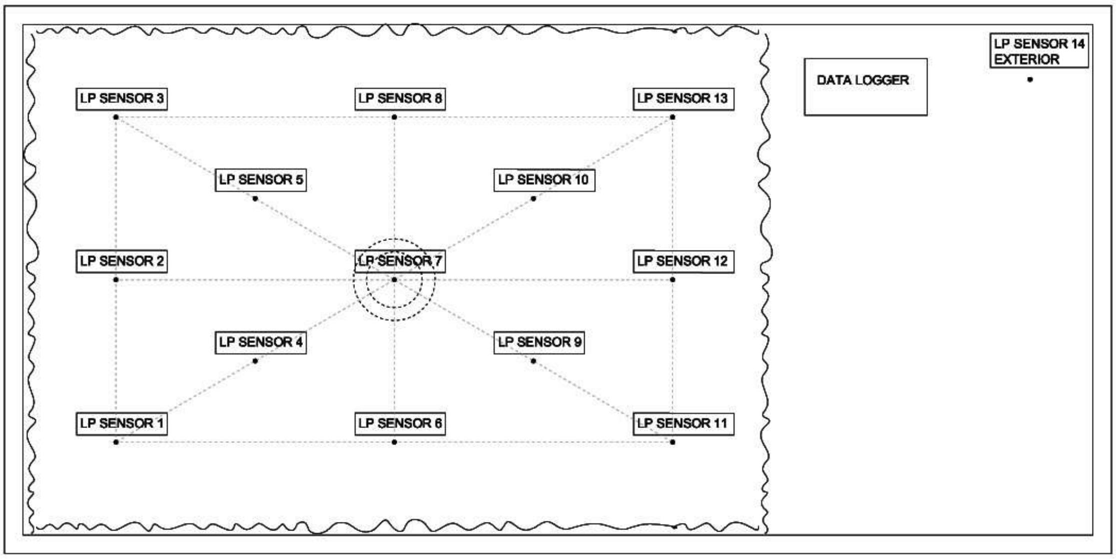


Image 4. Plan of the test room, showing the experimental setting

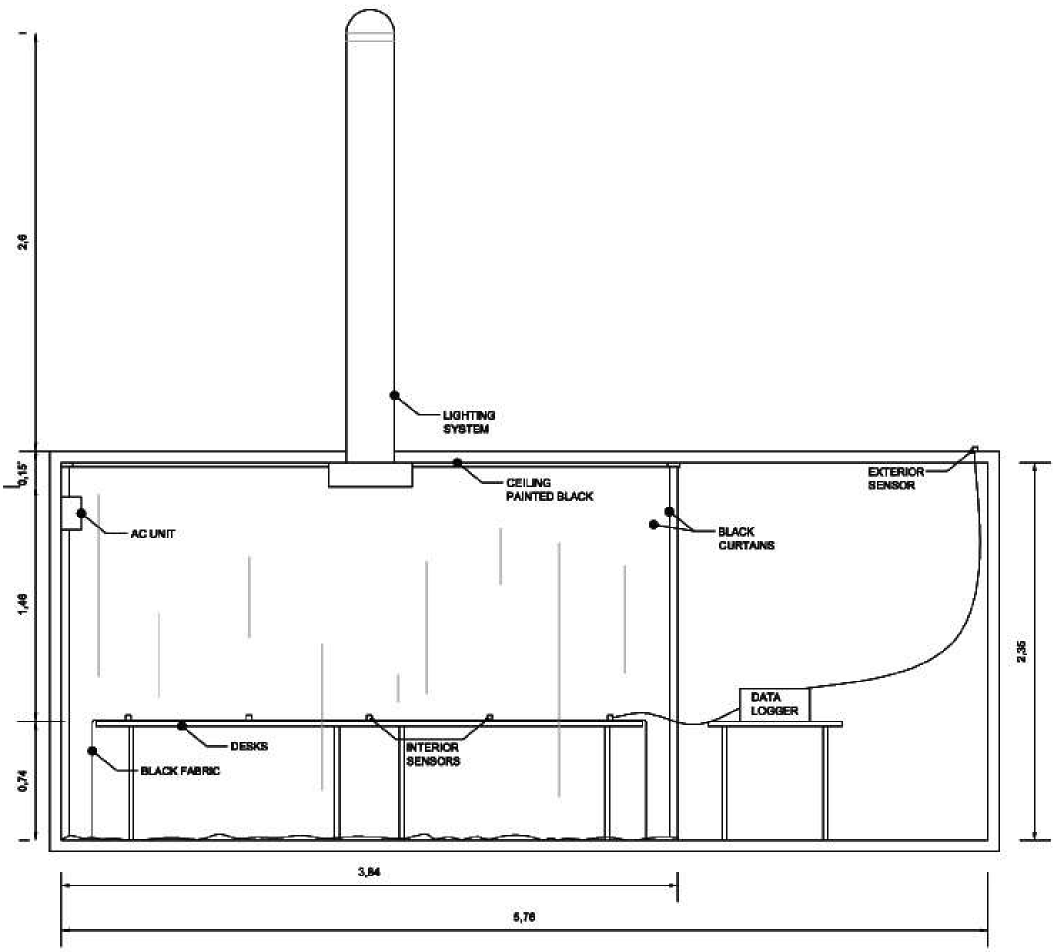


Image 5. Section of the test room, showing the experimental setting

4.3 The developed system

The aim of the testing procedure was to measure and assess the lighting performance of an ordinary light pipe under the weather/sky conditions of Greece and compare this with the performance calculated by other research groups, using experimental and/or mathematical methodologies. Moreover, the lighting levels achieved, the energy savings and the operation of LED modules operated by daylight linked controls, enabling the lighting levels in the studied room to be relatively stable irrespective of the exterior lighting conditions, needed to be studied.

4.3.1 Design and description of the experimental lighting system components

During the last few years, light pipe manufacturers have tried to incorporate artificial lighting into traditional light pipes, so that the final product can provide the desired interior illuminance levels any time of the day and under any sky conditions. In the most common versions, the artificial lighting is provided by spotlights (either halogen or LED lamps), located about 0.20-0.50m above the diffuser, inside the reflective tube (Image 6). The more sophisticated versions incorporate LED lamps, with specially designed optical systems for the maximization of the system performance, combined with daylight linked controls, situated inside the tube.

The disadvantages of the commercially available systems include, for the simpler systems, the internal shading of the diffuser from the artificial light source and the relatively high energy consumption because of the conventional type of lamps and for the more sophisticated systems, the difficult maintenance and that the sensors sense the daylight only inside the light pipe and not in the room, thus ignoring other daylight sources' contribution and reducing the system's flexibility.

Image 6. Monodraught light pipe with artificial lighting. (Konstantina Vasilakopoulou, 2013).

The developed and tested lighting system combines a light pipe and artificial lighting, placing the lamps outside of the tube, so that natural light is not reduced by the additional lamp-supporting equipment. The tested system is not intended to be an alternative to the commercial products but a compact unit that simplifies laboratory testing.

The principles that were followed for designing the experimental lighting system, were:

- Low cost of production/ maintenance/ replacement of each of the system elements;
- Use of electric equipment easily found in the market;
- Ease of assembly;
- Layout of technology that enables the theoretical and experimental testing of its performance;
- Aesthetically acceptable form.

The main steps that were followed, are:

1. Examination of existing, commercially available energy efficient lighting solutions, consisting of light pipes and artificial lighting and identification of disadvantages and aspects for improvement.
2. Initial concept design of the integrated light pipe and LED system.

3. Familiarization with the light pipes system, their performance, and the requirements for installing this system in the test-cell or a retrofit scenario. For that reason, a visit at Monodraught, a British company, well known for its light pipe systems was performed. The experts in Monodraught presented all the different light pipe systems, explained the installation process, and shared their lighting simulation experience. This step was very useful for the development of the system, as it helped assess the light pipes' performance and the commercial systems' electric light incorporation.
4. Development of an optimised design for the energy efficient lighting technology using LED lamps and light pipes. In particular, the system includes a light pipe, LED lamps attached to the light pipe body with a custom designed element and daylight linked controls, which enable the lighting levels to be stable on a working surface.
5. Research and purchase of commercially available and appropriate light tube and other components of the system
6. Testing of various alternative solutions for the LED lamps and electric components and identification of appropriate solutions. The main criteria for choosing LED lamps have been: a. the small size of the lamps, as this would lead to smaller size of the system, b. the ability of the lamps to be dimmed with the minimum number of elements (transformers, dimmers, etc), c. small heat dissipation during operation and/or their ability to be combined with heat-sinks, d. lamps of medium light output, as high intensity could lead to glare problems, e. appropriate colour rendering and colour temperature characteristics and, f. relatively low cost of the lamps. Equipment from many companies was considered and the solution that combined most of these criteria was chosen.
7. Performing lighting calculations. After choosing the most appropriate lamps the space was modelled and the lighting conditions were simulated with Relux. These calculations helped with the assessment of whether the chosen power of the lamps, their light distribution and their luminance would be appropriate for a domestic application and for the experiment that would be carried out.
8. Research and identification of an appropriate control system.
9. Refinement of the metal casing. Identifying the electrical parts of the system enabled the refinement of the metal casing and its manufacture.
10. Ordering of different diffusers. An opal and two types of prismatic diffusers were ordered and tested. The final decision was made considering aesthetic criteria and transmittance values of the variations.
11. Integration of the different system components and construction of the prototype in the test cell.

The main element of the tested lighting system is the ***light pipe*** (Passive zenithal light guide or Tubular Daylight Guidance System). The light pipe was bought by Monodraught and is comprised of three basic elements: 1. the light collector, 2. the highly reflective light tube and 3. The diffuser, i.e., the element that distributes daylight and/or sunlight into the space (Image 7).

The **light collector** is usually a glass or polycarbonate dome of high transmittance. The dome of the light pipe can either be hemispherical or have a diamond shape. The collector that was used for the testing was a diamond shaped polycarbonate dome, designed to maximise the penetration of sunlight during the early morning and late afternoon hours. The light transmittance of the material is usually over 80%.

The light transport element, which is a **tube** with reflectance value greater than 0.95. The tube of the light pipe is made of aluminium. The interior surface is coated with substances (PVD) and films that enhance reflectance and UV durability and provide good colour rendition. The tube is provided by manufacturers in pieces which are put together during installation. The tube pieces for the specific testing were straight, however that can also be bended (elbows).

The element which distributes daylight into the space is usually a clear, opal or prismatic **diffuser**. More often, this diffuser is an acrylic glass. The use of the diffuser is very important as it distributes daylight into a space more evenly and it covers the interior of the tube from view, eliminating glare issues. The light transmittance of the various types of diffusers varies significantly; a clear cover admits more daylight but will cause glare issues, especially during sunny days, the opal diffuser is very good at dispersing light rays and at providing a uniform environment but has low transmittance and the prismatic diffusers offer even distribution and greater transmittances. The diffuser used for this experiment was a prismatic one.

The tested light pipe was equipped with a shutter, which is an optional element. The shutter covers (shades) the tube whenever black-out conditions are required.

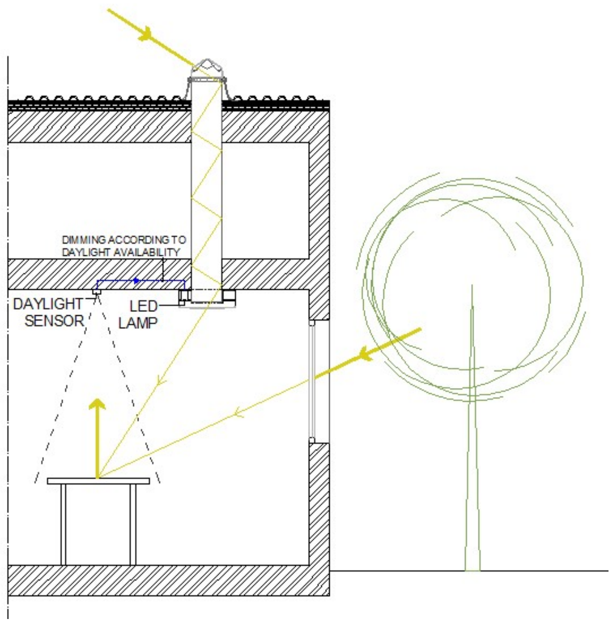


Image 7. Operational principles of the lighting system

Light Emitting Diodes (LEDs). LEDs are semiconductor devices which convert electricity into light. LEDs are characterized by their low energy consumption in relation to other lamps used in domestic environments, their long life which can be greater than 100,000h, their ability to be fully dimmable without colour changing and the fact that they are durable and small. Their disadvantages are related to their sensitivity to environmental temperature, which when high could reduce the performance and the useful life of the lamp. LEDs can be more expensive compared to more simple and inefficient technologies.

Smart Controls refer to systems that enable the control of one or group of luminaires/lamps, based on the user's needs, but with minimum intervention from the user. These controls might include switching on/off, dimming, changing the colour of the emitted light, etc. In this case, the control needed is one that changes the amount of light emitted by the LEDs, depending on the natural light coming from the light pipe and from other natural light sources in the room.

4.4 Final Development Overview

After the analysis of the development methodology of the system and the final amendments that have been made for it to be functional and easily installed and maintained, the lighting system and the works for its installation are described in the following section.

One aperture was made on the roof of the test-cell for the system to be installed. The aperture on the roof, is covered by the light pipe dome, which receives light from the sun and the sky. The dome that has been chosen is one with a diamond shape, which enables the maximization of the incoming light early in the morning and late in the afternoon. The light transmittance of the material is about 90%.

The reflective tube (tube with aluminium film, 98% reflective) has 0.30m diameter, runs through the aperture of the roof and the intermediary floors of the building until it reaches the ceiling level of the space that will be lit by the system. No sun-tracker is added to the system, as this would lead to unnecessary increase of the cost and shading of the tube when the sky is overcast or cloudy.

The tube is provided in 0.60 m long pieces, which are welded together with a special tape, provided by the manufacturer. Since the test room has a single story, and to get more realistic results, the tube that has been used has a height of 2.60 m above the room roof. This height was chosen as it was considered to be typical of a light pipe penetrating the floor above the room that has to be lit, in a real application. The part of the light pipe outside the room was supported by metal beams, as shown in Image 12.

The lower edge of the tube is supported by a metal casing. The casing also has the role of supporting the LED lamps and containing the power supply element. Also, the casing has apertures, necessary for the ventilation of the LEDs. The cooling of the lamps is also achieved with the use of heat sinks, attached to every lamp. Heat sinks are low-cost components that ensure the long life of the lamps. The combination of the LED lamps with the attached heat sinks imposes the height of the metal casing (approximately 0.15 m). The metal casing remained in its natural colour (polished silver).

The lamps that were finally chosen are 8 LED spotlights, with wide distribution, that fit into MR16 luminaires (Image 9). The Correlated Colour Temperature of the emitted light needs to be around 4,000K, to blend satisfactorily with the natural light coming through the light pipe. Lighting simulations showed that, 7.5 Watt lamps, combined with a prismatic diffuser, offer glare free lighting of spaces with small dimensions. The lamps are symmetrically allocated around the opening of the tube, supported by a metal “ring”, which is part of the metal casing. Accidentally, the Correlated Colour Temperature of the lamps that were bought was much lower (the colour of the emitted light is warmer) than the one that was initially ordered. This had little, if any, effect on the system performance, however, the colour of the light from the LEDs did not blend satisfactorily with the colour of daylight.

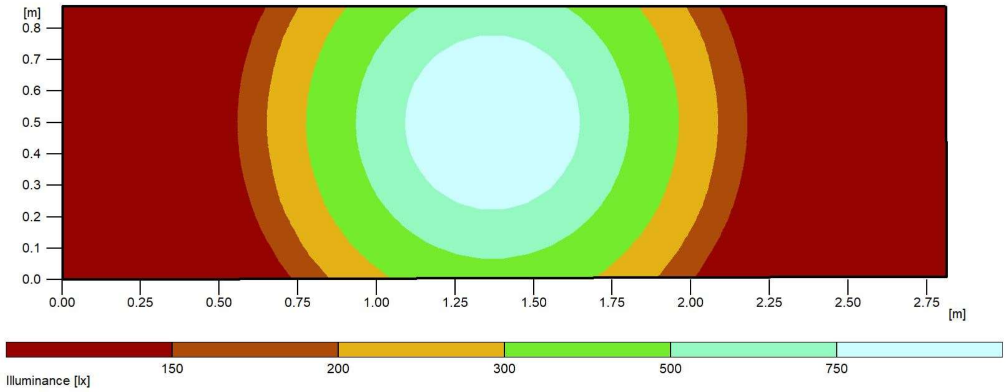


Image 8. The Illuminance distribution in the test cell with the use of the selected LED lamps. Eav=300 lux

The chosen LED lamps need a driver to be dimmed according to the input signal from the daylight sensor. Even though other lamps could communicate directly with the sensor, without needing a driver, the specific lamps were chosen because of their smaller size, which enables a lighting system of smaller diameter and height. The driver can be contained by the metal casing, above or between the lamps. The specific driver can take up over 10 of the selected LED lamps, which are more than enough to light a domestic space.

Image 9. Left: The diffusers that were considered. Right: The LED lamps used.

The daylight sensor was chosen to be able to communicate with the specific lamps. One of its advantages is that it enables a delay between the change in the perceived light levels and the dimming of the LEDs, as quick fluctuations of lighting levels are usually not acceptable in interior environments (Chartered Institution of Building Services Engineers (CIBSE), Society of Light and Lighting (SLL) and Institution of Lighting Engineers and the Lighting Industry Federation, 2002). The sensor can be easily programmed, even by non-experienced users. Also, the chosen daylight sensor is at the same time a movement sensor, which can be activated or deactivated, according to application, for maximum energy savings.

The parts of the light pipe must be suitably supported on the adjacent structural elements and the created connections must be insulated from water and humidity. The light pipe manufacturers provide parts that support the dome and the upper part of the tube, for each type of roof and “rings” that hold the tube on place, as it runs vertically through the building levels. The metal casing that supports the lower part of the tube and the electric equipment is screwed on the ceiling of the room to be lit (Image 10). The daylight sensor is attached to the ceiling, where it can perceive the light levels on a reference surface.

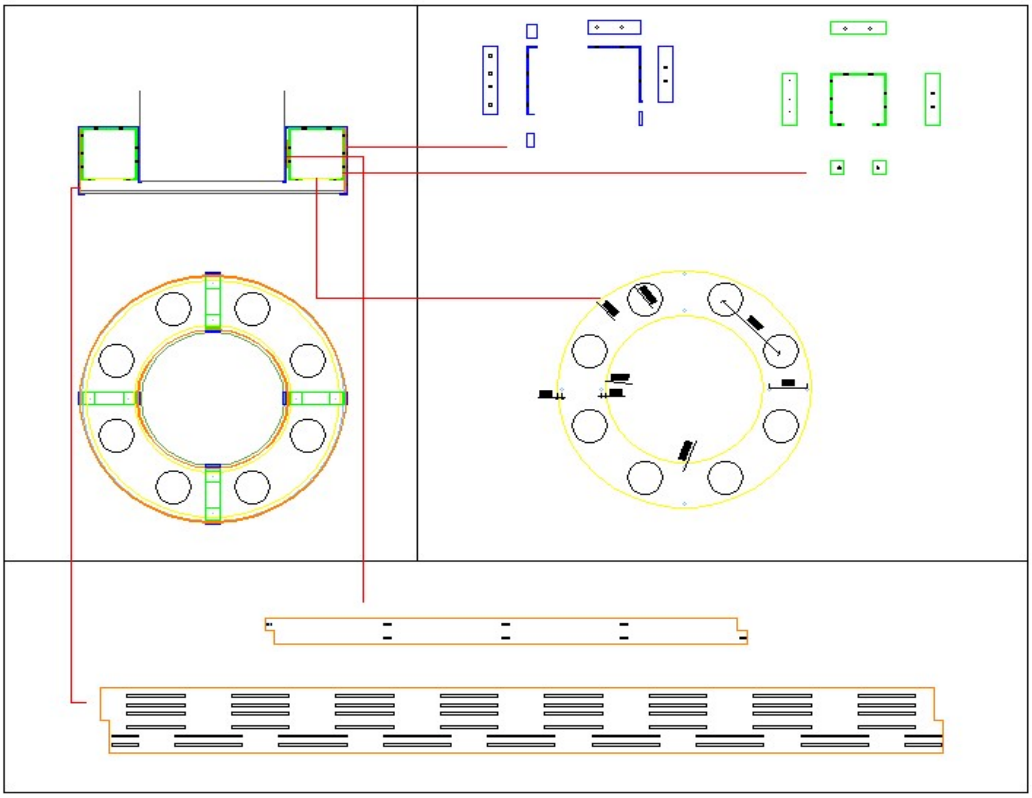


Image 10. The final design of the metal casing. Even though this element could be manufactured as a single piece, its production would increase the cost of the system significantly.

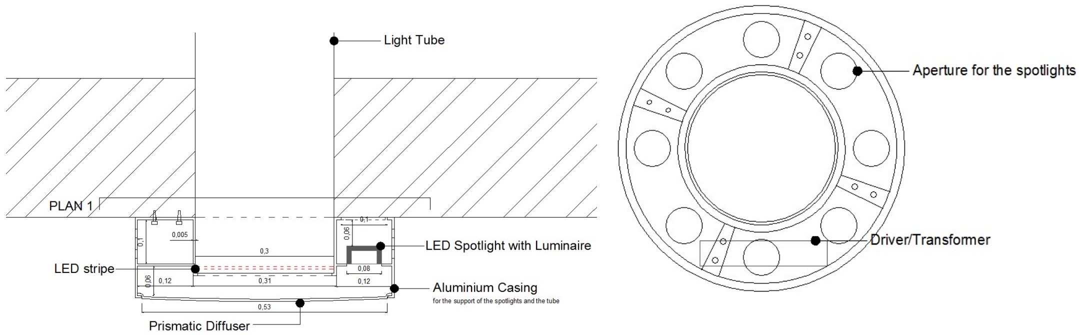


Image 11. Left: Section/detail of the lower part of the system, including the metal casing, the LED lamps, the LED stripe, and the diffuser. Right: Upward plan of the system housing eight lamps.

Image 12. The exterior of the test cell after the installation of the lighting system

Image 13. The experimental area

Image 14. The diffuser installed.

4.5 Conclusions

An experiment was set up, to test the performance of a light pipe in the Mediterranean climate and more specifically in the weather/sky conditions of Athens, Greece. A lighting system, consisting of a light pipe, LED lamps and daylight linked controls was designed and constructed in a test cell, located at the Kapodistrian University campus. The testing period lasted for approximately 7 months, from November 28th, 2014 until the beginning of August 2015 (no data was recorded in January 2015). The parameters monitored are the exterior and interior illuminance, the luminance, and the energy consumption of the designed system. The results of the experiment are discussed in the following chapter.

Chapter 5: Analysis of the experimental data & assessment of the light pipe performance

5.1 Synopsis

The present chapter includes the analysis of the lighting performance of the experimental lighting system. More specifically, the illuminance data acquired by the experiment was initially cleaned; the outliers and the errors, mainly due to instrument inaccuracy, were specified and removed from the sample. Following an initial analysis of all the recorded values, the data set was split into 10 clusters, according to the value of the diffuse solar radiation clearness index, K_d. The performance of the light pipe in terms of lighting levels on the horizontal reference plane for each of these clusters is studied and presented in the following paragraphs.

In short, numerous trials and statistical analysis showed that the performance of the daylight system, i.e., the interior illuminance on the reference plane, greatly depends on the outdoor illuminance, on sky clearness, or the diffuse solar radiation clearness index (K_d), as is usually called, and the position of the sun (azimuth, altitude). The temporal variability of the illuminance on the measuring surface was found to depend significantly on the sky conditions, i.e., on the K_d index and on the exterior illuminance. The spatial distribution of the interior illuminance presented quite high inhomogeneity, which was evident especially around noon for clear sky conditions. The lighting levels were higher right below the light pipe and lower on the edges of the measuring surface. For overcast sky conditions, the distribution was rather symmetrical around the light pipe, with the higher values being present directly below the diffuser.

The Daylight Penetration Factor (DPF) of the system increases significantly for decreasing K_d values. There was also a clear correlation between the average DPF with the solar altitude and the azimuth, for clear sky conditions but not for cloudy skies. The variability of the maximum DPF on the reference plane was important for clear sky conditions and insignificant for overcast skies. On the contrary, the minimum DPF presented very low values for both clear and overcast skies.

Part of this chapter was published in the journal Energy and Buildings (Vasilakopoulou *et al.*, 2017).

5.2 Analysis of the performance of the experimental lighting system

The testing of the performance of the experimental lighting system took place for approximately 7 months, between November 2014 and August 2015, as mentioned in the previous chapter of this Thesis. The relatively long period of testing enabled the recording of interior illuminance levels under all types of the Athenian sky. The modification of the test cell's bright reflective surfaces into dark-coloured matte surfaces allowed for minimum reflections, thus almost cancelling the effect of the space. Also, this type of analysis facilitates the scaling of the interior illuminance distribution to spaces with more than one light pipes.

5.2.1 Illuminance and Uniformity

The data set comprising all measurements was cleaned using screening, diagnosing, and editing procedures for the suspected data abnormalities and all outliers and discern errors were removed. Data for exterior illuminances lower than 5 klux were also excluded, as they did not result in significant average interior illuminances and increased the volume of data and the processing time substantially.

The maximum indoor illuminance recorded by a sensor throughout the testing period was 8.4 klux (sensor 4), on 26/04/2015, 12:15 pm. At the same moment, the minimum illuminance was 38 lux (sensor 11), the average illuminance in the space was 1043 lux, while the exterior illuminance 120 klux (Table 22). So, the Uniformity (E_{min}/E_{av}) in the space was 0.036. The Uniformity was poor, due to the very bright patterns (patches) that the intense sunlight reflected in the tube was creating on the reference plane. However, the Uniformity can change significantly under different sky conditions, even for relatively high exterior illuminances, when no patches of light are present. For example, for recorded exterior illuminance equal to 122 klux and the same value of diffuse solar radiation (K_d=0.18), the Uniformity was recorded to be 0.23 (E_{av}= 173.42 lux, E_{min}= 40.76 lux) (Table 23).

The average illuminance in the room ranged between 2 and 1043 lux. The variability of the average indoor illuminance versus the outdoor illuminance is shown in Figure 18. The Uniformity on the reference plane varied between zero and 0.54.

The maximum illuminances that were recorded on the reference plane belonged to sensor 4 (8.4 klux) and then to sensor 9 (5.03 klux). The horizontal distance of Sensor 4 and Sensor 9 from the centre of the light pipe diffuser is 0.75m approximately for both sensors. Sensors 4 and 9 are on the east side of the room; Sensor 4 is placed south while Sensor 9 is placed north of the light pipe. The highest values of Sensors 4 and 9 were recorded at clear sky days of late April at and around noon, which is consistent with observations from other studies (Li *et al.*, 2010). This probably means that the interreflections in the tube at noon cause sunlight beams to be redirected towards the south and east side of the room.

However, the area with the highest average illuminance on the reference plane is the area directly below the light pipe diffuser (Sensor 7, average illuminance= 166.90 lux). This was expected as Sensor 7 is directly underneath the diffuser and receives “direct” light from the diffuser and the dome, under any sky conditions. Figure 19 presents the maximum and average illuminances recorded by each one of the 13 sensors that were placed inside the test cell.

Table 22. Point Illuminances and exterior conditions for the maximum average interior Illuminance (1043.03 lux) throughout the experiment duration. All illuminances are in lux.

Sensor_1	Sensor_2	Sensor_3	Sensor_4	Sensor_5	Sensor_6	Sensor_7	Sensor_8	Sensor_9	Sensor_10	Sensor_11	Sensor_12	Sensor_13
56.15	75.42	68.26	**8416.58**	1392.76	**1697.19**	673.26	536.74	203.68	302.22	**37.98**	57.80	41.29
Date/ Time	**Average interior Illuminance**	**Exterior Illuminance**	**Altitude**	**Azimuth**	**Kd**							
26/04/2015 12:15	**1043.03**	**120,412**	65.4	175.3	**0.18**							

Table 23. Point Illuminances and exterior conditions for 31/03/2015, 10:48 am. All illuminances are in lux.

Sensor_1	Sensor_2	Sensor_3	Sensor_4	Sensor_5	Sensor_6	Sensor_7	Sensor_8	Sensor_9	Sensor_10	Sensor_11	Sensor_12	Sensor_13
52.33	66.65	52.88	241.26	239.06	312.87	380.62	355.83	160.29	252.28	46.27	53.43	**40.76**
Date/ Time	**Average interior Illuminance**	**Exterior Illuminance**	**Altitude**	**Azimuth**	**Kd**							
31/03/2015 10:48	**173.42**	**122,000**	49	139.4	**0.18**							

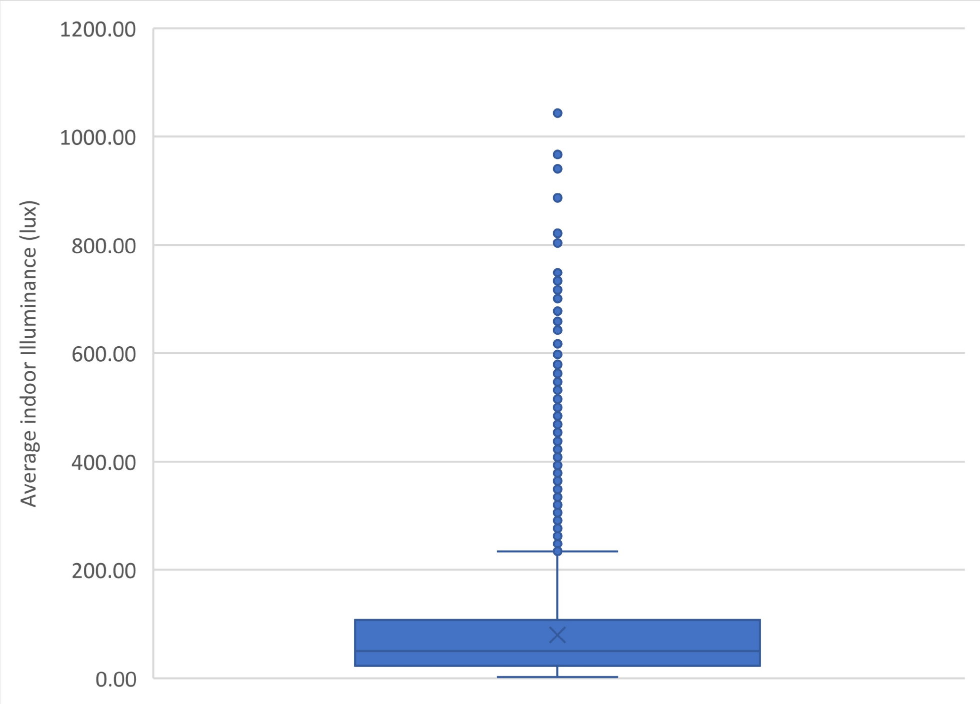


Figure 18. Boxplot of the average indoor illuminance during the experiment period. Median: 49.93, σ=79.79

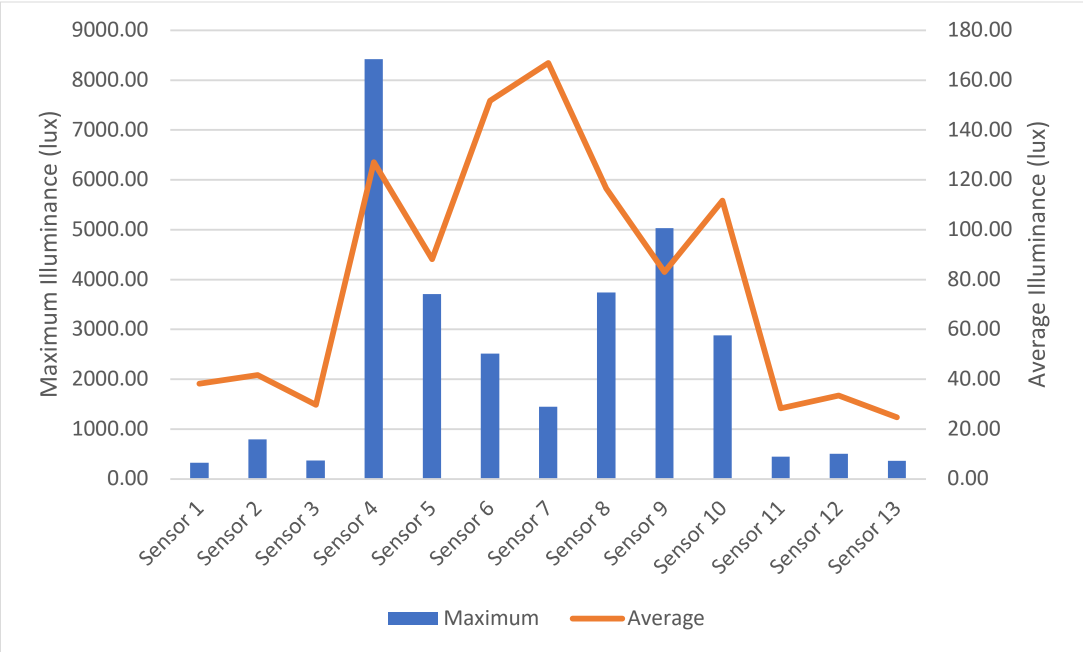


Figure 19. Maximum and average illuminances for the 13 interior sensors, throughout the testing period

5.2.2 Clustering of the collected data

The analysis of the data and the correlation with the main parameters affecting the performance of the light pipe, has revealed a very strong dependence of the performance on the sky conditions (exterior illuminance and sky clearness) and the characteristics of the incident solar radiation (azimuth and altitude). Given that, the cleaned data set was split into 10 clusters, according to the value of the diffuse solar radiation clearness index, K_d. K_d is defined as the ratio of the diffuse solar radiation incident on a horizontal surface, against the corresponding total solar radiation and it provides information about the percentage of the diffuse solar radiation in the total radiation. High K_d values are associated with high diffuse and low beam solar radiation, while small K_d values are related to high beam and low diffuse radiation. Values of K_d during the whole experimental period varied between 0.07 and 0.97, a range proving the variety of the sky conditions during the experimental period.

Due to the great volume of the collected data (the interior illuminance values were recorded every minute) the analysis included in the paragraphs below was performed for hourly averaged data. Fuzzy clustering techniques were used to classify these hourly data in ten different clusters (Yager and Dimitar, 1994). The number of the clusters was defined after repetitive trials aiming to optimize the shape and scale of the distribution of points in the clusters. The optimum number was determined as the one over which the addition of a new cluster could not increase the total variance significantly. The centres and the relative size of the clusters are provided in Figure 20. The second cluster was the biggest one including 280 values, while the 8th cluster was the smallest, with just 60 values. The outdoor illuminance during the considered daytime experimental period varied between 5 klux to 120 klux, with an average value close to 60 klux. The probability of the exterior illuminance during the considered experimental period is given in Figure 21. As shown, about 75 % of the data are below 100 klux, 50 % are below 60 klux and 25% below 30 klux.

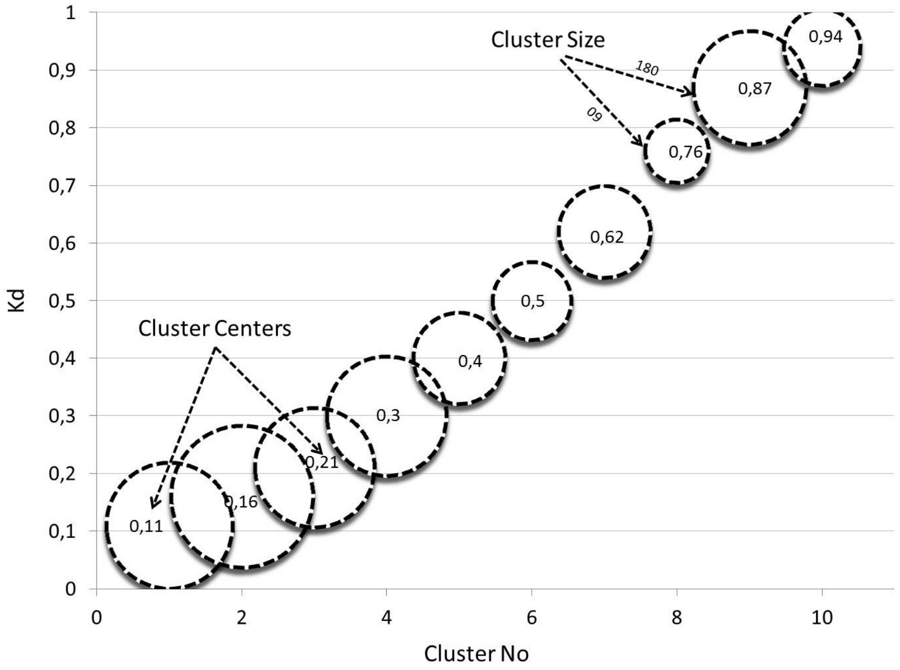


Figure 20. Centres and relative sizes of the ten defined clusters

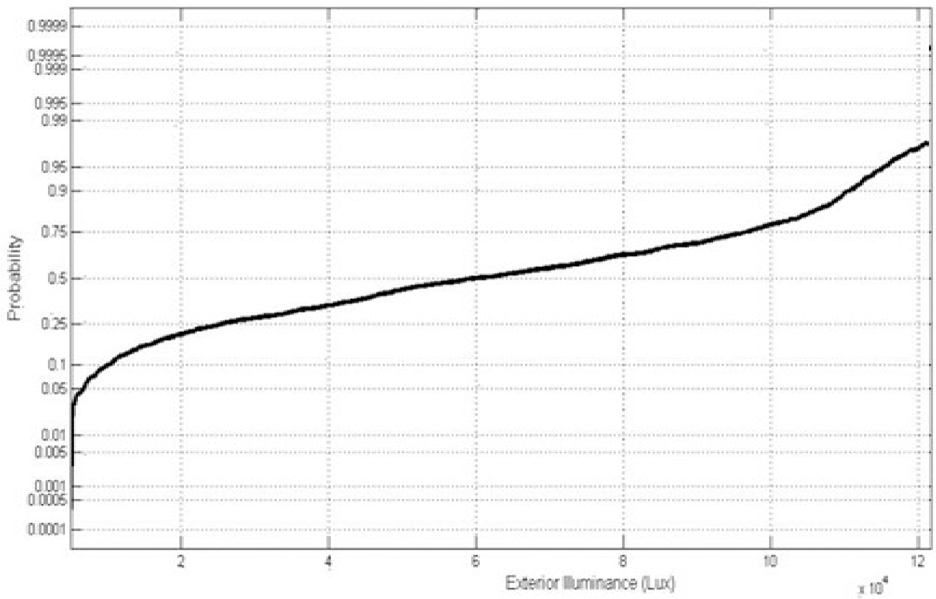


Figure 21. Cumulative probability of the exterior illuminance during the considered experimental period

5.2.3 Temporal variability of the indoor illuminance

The hourly average indoor illuminance recorded anywhere on the reference plane during the considered experimental period varied between zero and 1,704 lux[1] with an average value close to 100 lux and a median value of 62.95 (hourly average values). The variability of the indoor illuminance versus the outdoor illuminance is provided in Figure 22. The mean hourly illuminance, i.e., the average of all the sensors in the experimental room, varied between 5 and 393 lux.

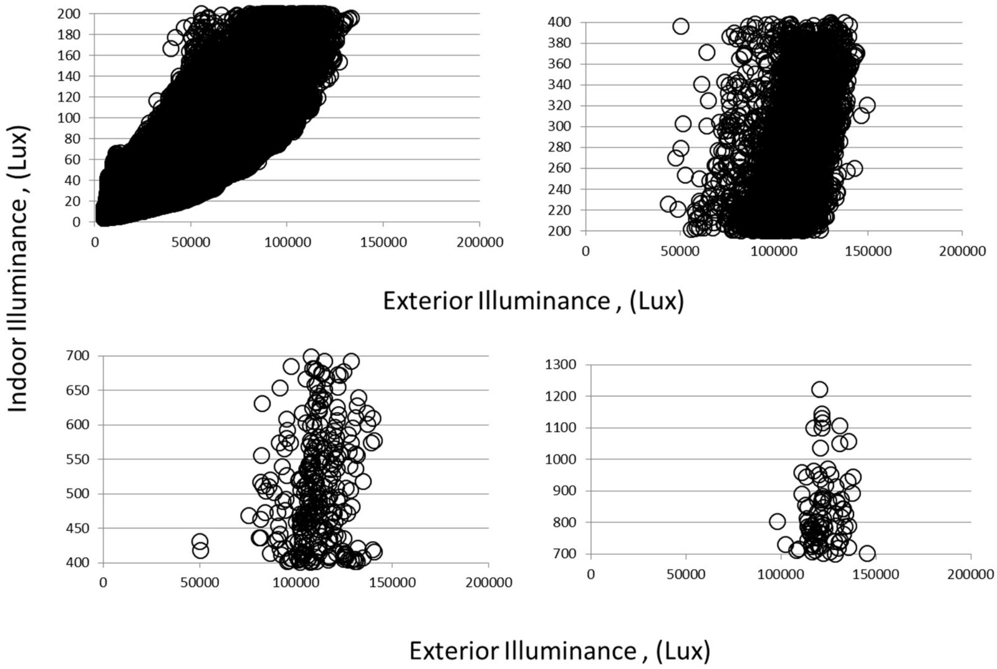


Figure 22. Hourly average indoor illuminance (lux) for the corresponding outdoor illuminance

[1] Note that in respective journal paper the value is 1,204 lux, due to typographic error.

The indoor illuminance values were found to present a strong temporal and spatial variability. The analysis showed that the average indoor illuminance varies strongly as a function of K_d, (

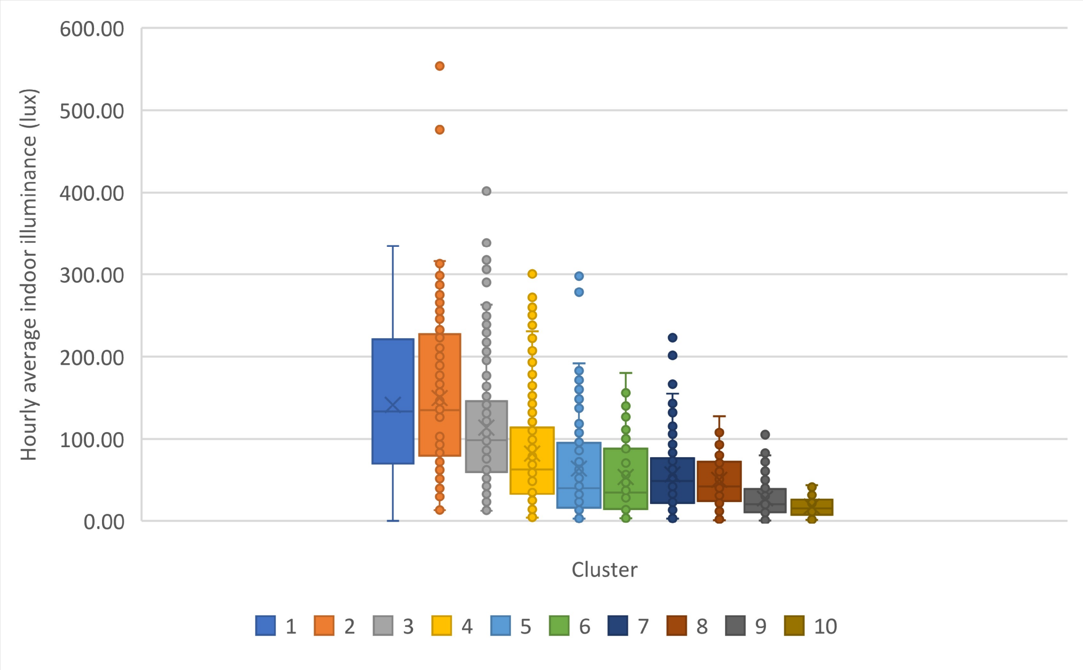


Figure 23). A significant reduction of the average indoor illuminance is observed for increasing K_d values, i.e., for cloudy skies. As measured, under clear sky conditions ($0.07 < K_d < 0.14$), the average indoor illuminance was about nine times higher than during the almost fully cloudy period ($0.84 < K_d < 0.93$).

The variation of the average indoor illuminance is strongly related to the mean outdoor illuminance in the corresponding K_d cluster, as it is also found in other studies (Malet-Damour *et al.*, 2016b). It is found that the relation between the average indoor and outdoor illuminance is almost exponential (Figure 24). A similar exponential relationship is also observed between the average outdoor illuminance and the corresponding maximum and minimum indoor illuminances in the room, as measured in sensors 7 and 1 respectively (Figure 25). The exponential relationship is stronger for the maximum than for the average and minimum indoor illuminance. This is because the decreasing trend of the maximum indoor illuminance regarding K_d, i.e., sensor 7, is much more intense than that of the minimum indoor illuminance, which is recorded in sensor 1 (Figure 25). It is also observed that for clear sky conditions, i.e., for low K_d values, the relation between the average interior illuminance and the exterior illuminance is almost perfectly exponential. However, as the solar radiation is getting more diffuse (K_d is increased) the relation between interior and exterior illuminance is becoming linear (Figure 37 - Figure 56).

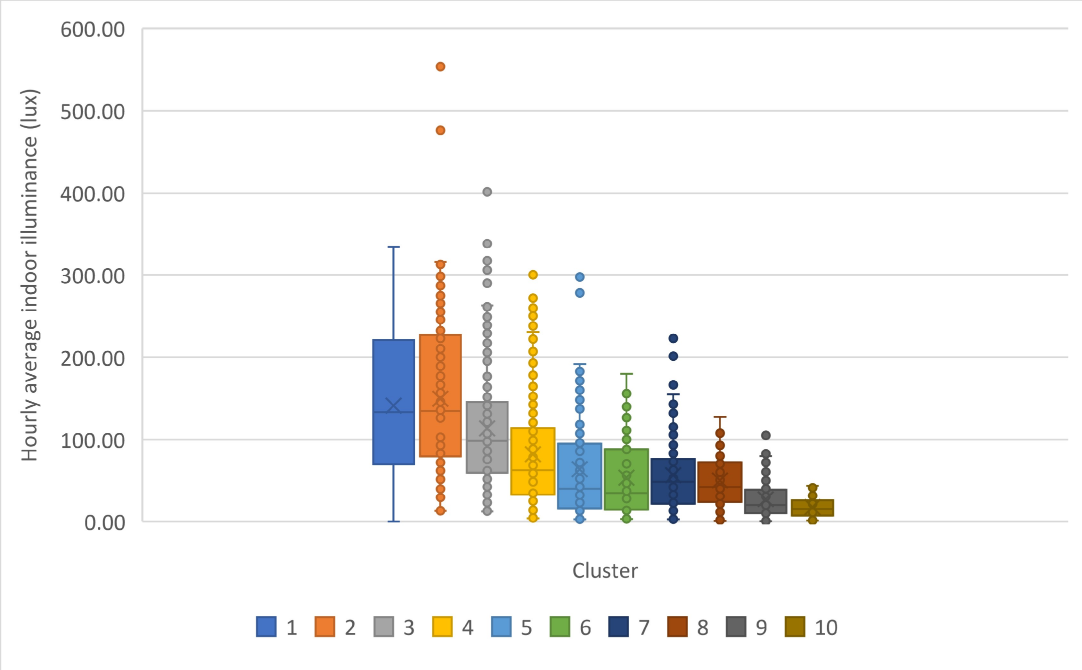


Figure 23. Variability of the average indoor illuminance for the 10 clusters of K_d

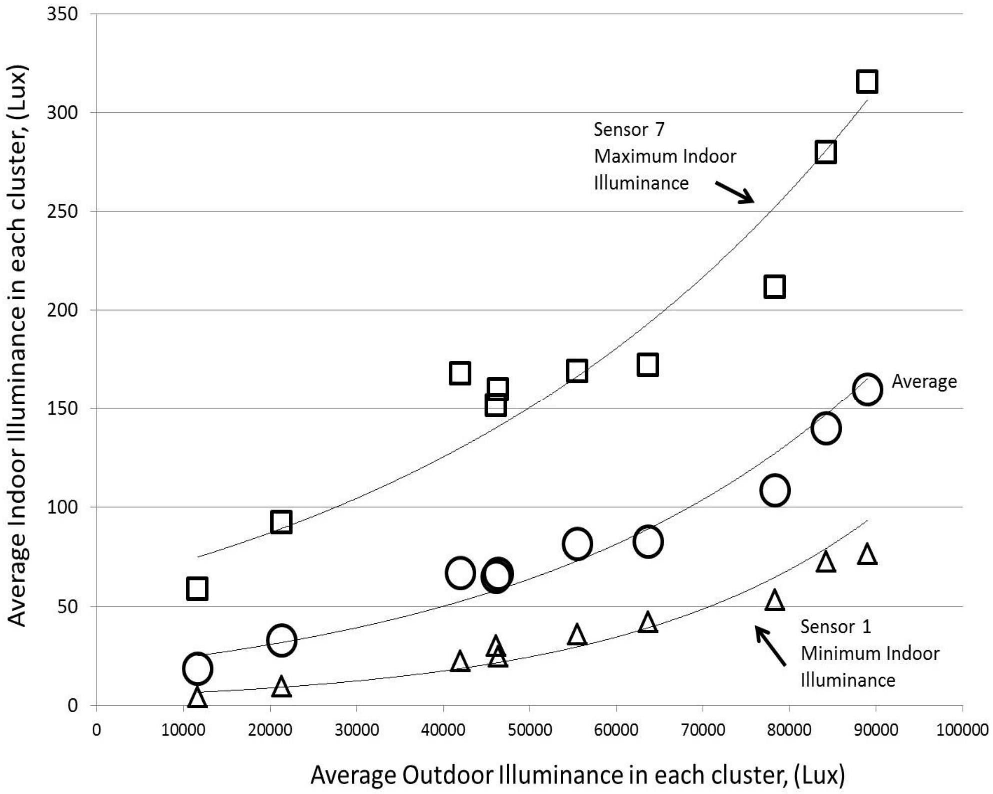


Figure 24. Correlation between the average, maximum and minimum indoor and the corresponding outdoor illuminance, for each K_d Cluster

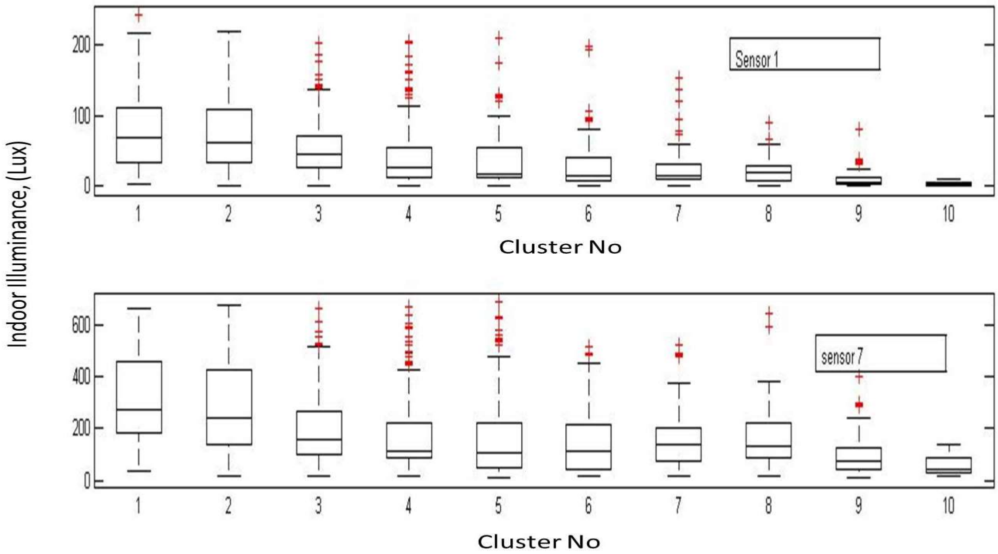


Figure 25. Variability of the maximum (Sensor 7), and minimum (Sensor 1) indoor illuminances for the 10 K_d clusters

As supported by other studies, the indoor illuminance was also found to have a strong dependence on solar altitude (Tsangrassoulis, 2008). Figure 26and Figure 27 show the exponential relation of the hourly average indoor illuminance with solar altitude, while Figure 28 and Figure 29 include the relation of DPF with solar altitude.

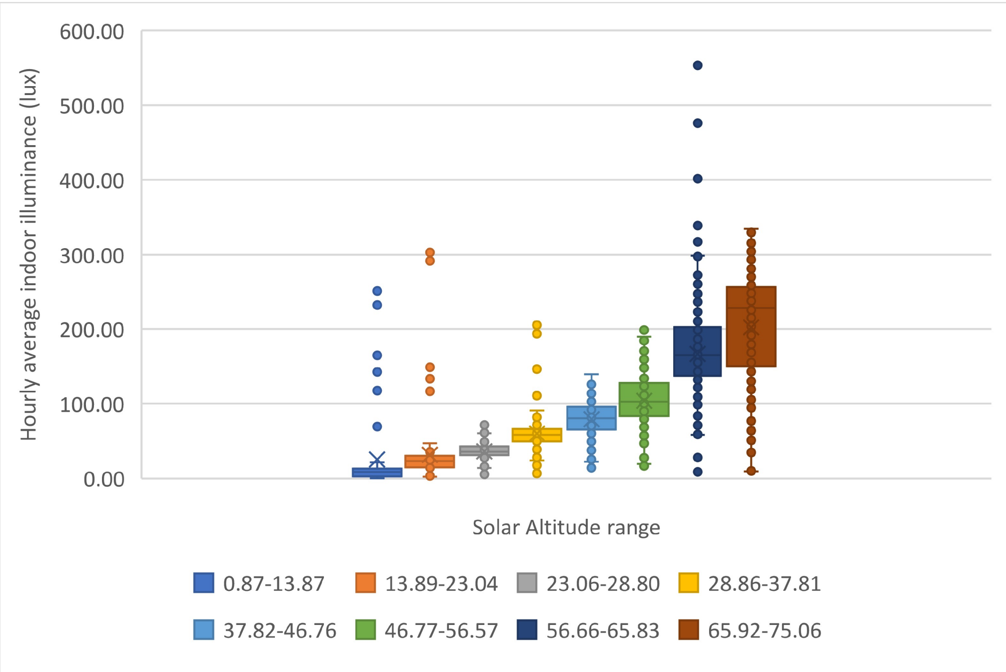


Figure 26. Variation of the hourly average indoor illuminance for 8 groups of solar altitude

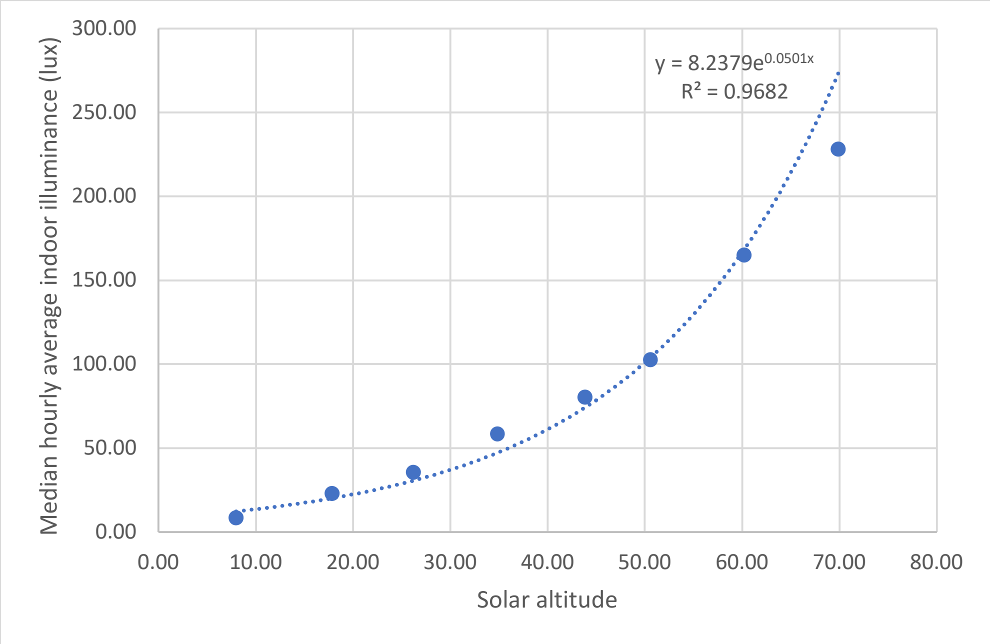


Figure 27. Variation of median hourly mean spatial indoor illuminance as a function of the respective solar altitudes

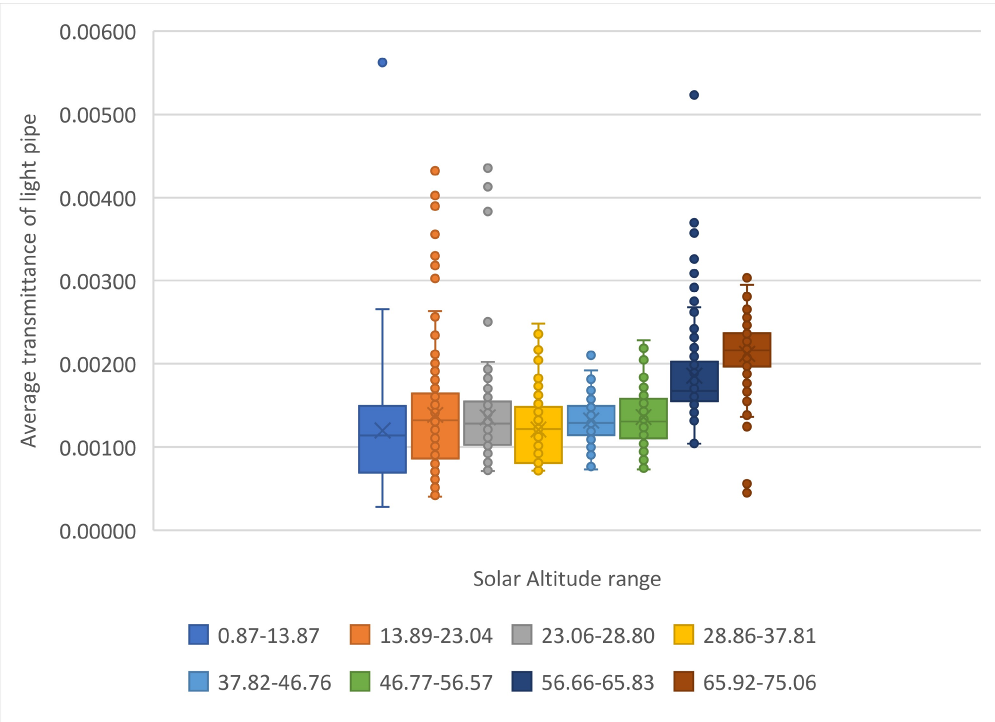


Figure 28. Boxplot of DPF for 8 solar altitude groups

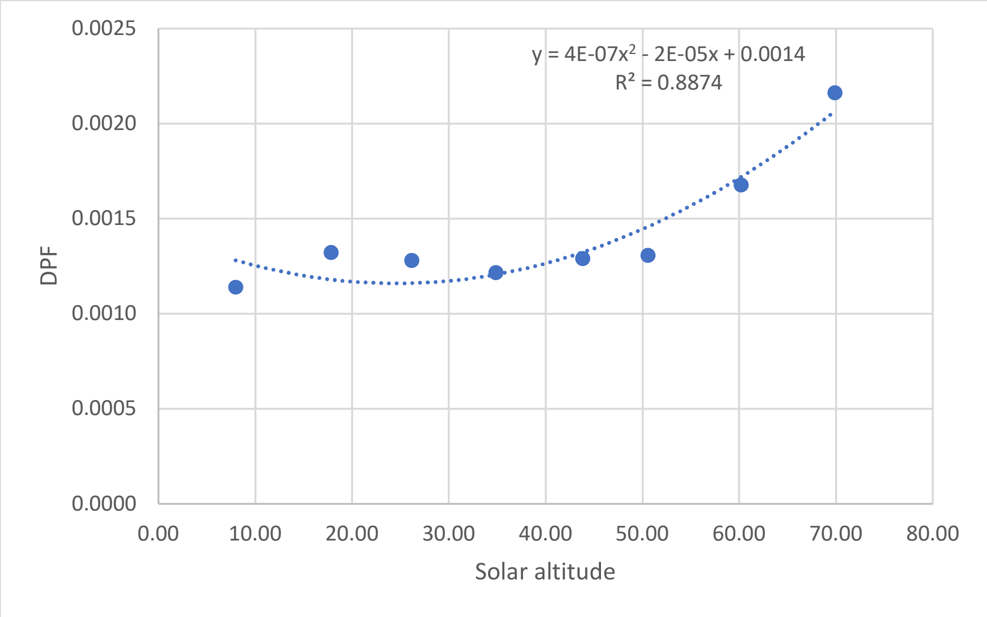


Figure 29. Variation of median hourly spatial mean DPF as a function of solar altitude

5.2.4 Variability of the Daylight Penetration Factor

The light pipe Daylight Penetration Factor (DPF) is the ratio of the average indoor illuminance due to a light pipe against the corresponding exterior illuminance. The maximum and minimum DPFs are defined as the ratio of the maximum or minimum indoor illuminance against the corresponding exterior illuminance, respectively. As a term corresponding to Daylight Factor for interiors with light pipes, DPF is occasionally associated to overcast sky conditions, however, DPF was initially introduced for use with the total external illuminance (Zhang and Muneer, 2000).

DPF values calculated from all the experimental data are quite low, ranging from 0.0003 to 0.009, with the average value being 0.0015, approximately. The average DPF (hourly average interior illuminance to hourly average exterior illuminance) was calculated for every hour and for each of the ten K_d clusters previously defined. The representative daily variation of the DPF during the clear, (Cluster 1 – $0.07<K_d<0.14$), cloudy, (Cluster 9 - $0.84<K_d<0.93$), and intermediate conditions, ($0.37<K_d<0.48$), is given in Figure 30. The daily variation of DPF for high K_d is almost insignificant, ranging between 0.14 and 0.16 %. Average DPF, however, increases highly for decreasing K_d values. During the clear sky days, the average DPF varies between 0.08 % and 0.22%. During the early morning and afternoon hours, the clear sky average DPF is quite lower than the corresponding value under cloudy sky conditions, mainly because of the position of the sun and the distribution of the light in the sky. The maximum values of DPF under clear sky conditions, are presented during the midday period when the solar altitude is increasing. The values of the PDF for the rest of the clusters are varying between the previously given limits.

It is found that there is a very clear correlation of the average clear sky DPF of the light pipe, with solar altitude, (Figure 31), and the solar azimuth, (Figure 32). As expected, under clear sky conditions, the higher the solar altitude the higher the average DPF. Also, the DPF gets its higher value when the solar azimuth corresponds to southern directions. Not a significant variability of the average DPF against the solar altitude and the solar azimuth, is observed during the cloudy days because of the diffuse character of the solar radiation.

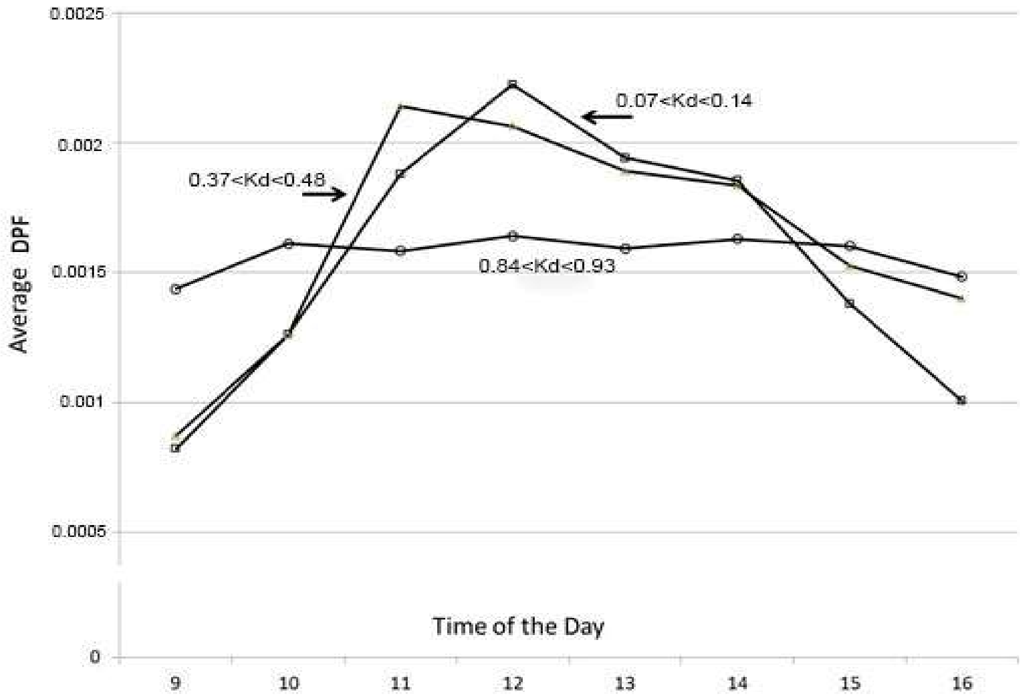


Figure 30. Daily variation of the average DPF of the light pipe during representative clear, cloudy and intermediate conditions

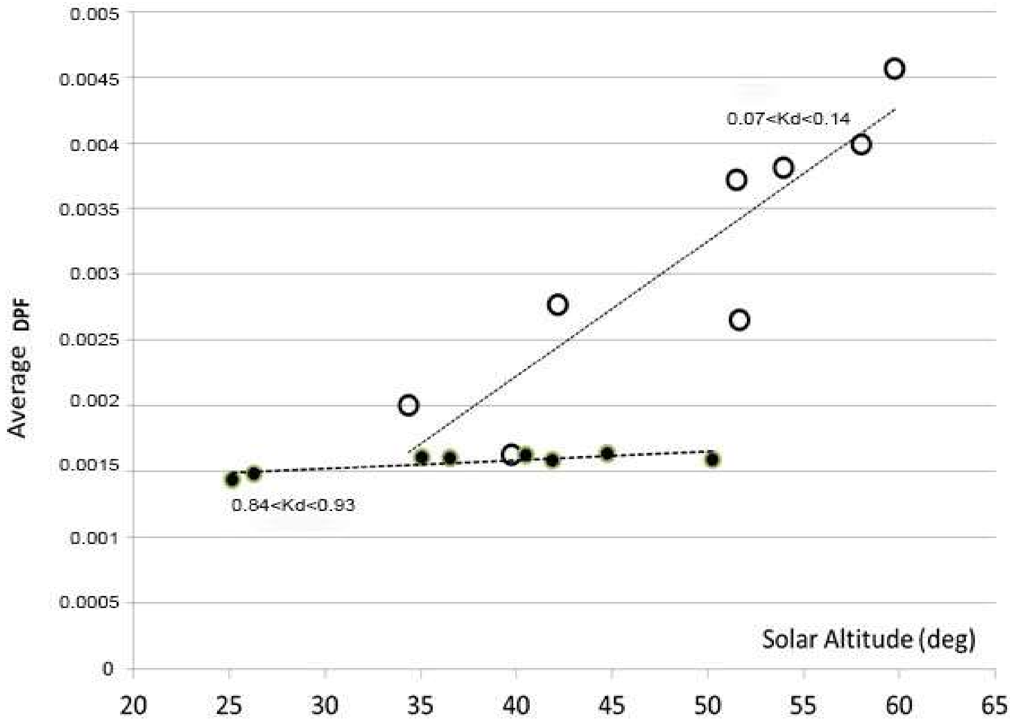


Figure 31. Variation of the average DPF of the light pipe as a function of the solar altitude for clear and cloudy conditions

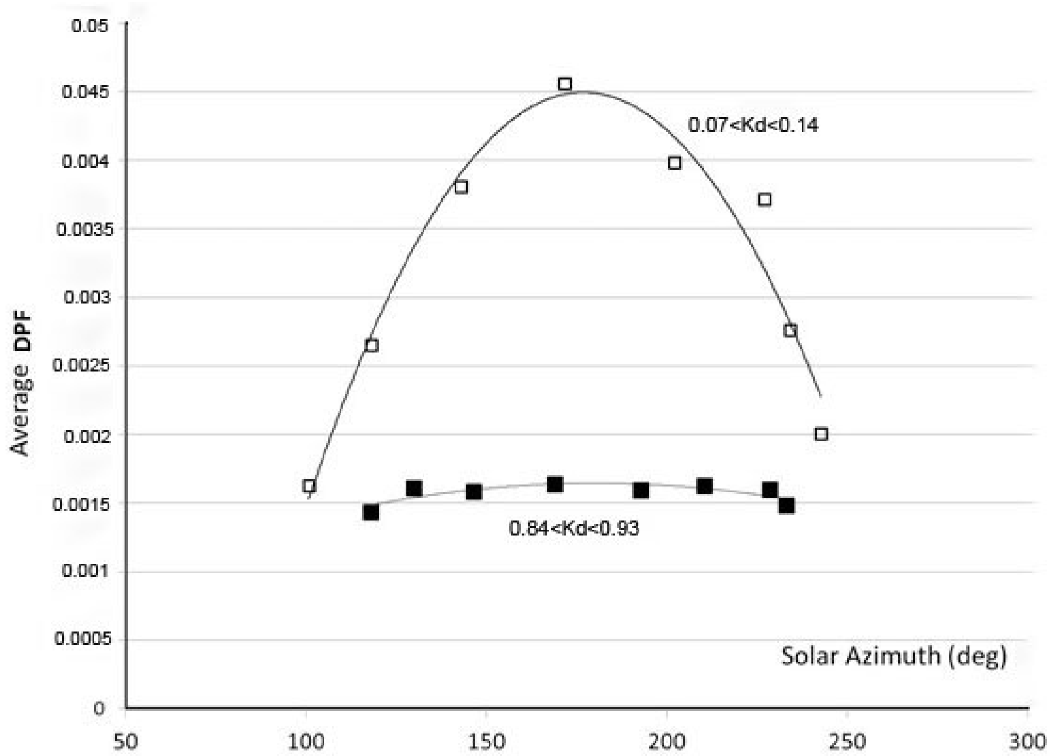


Figure 32. Variation of the average DPF of the light pipe as a function of the solar azimuth for clear and cloudy conditions

Figure 33 presents the daily variability of the maximum and minimum DPF on the reference plane under cloudy and clear sky conditions. The minimum DPF corresponds always to sensor 13 (Illuminance at sensor to exterior illuminance), which is at the edge of the room, while the maximum corresponds to sensor 7, located directly under the light pipe's diffuser. As shown, the daily variability of the minimum DPF under both clear and cloudy conditions is almost negligible. As it concerns the maximum DPF, like the average DPF, its daily variability is very important under clear sky conditions and almost insignificant under cloudy skies. The magnitude of the maximum DPF during the midday period, is quite similar under clear and cloudy sky conditions. During the rest of the day, the maximum DPF under cloudy sky conditions is higher than the corresponding value under clear sky conditions, due to the light distribution in the sky dome and probably because the light collection efficiency of the dome under low incident angles of the beam radiation, is quite reduced.

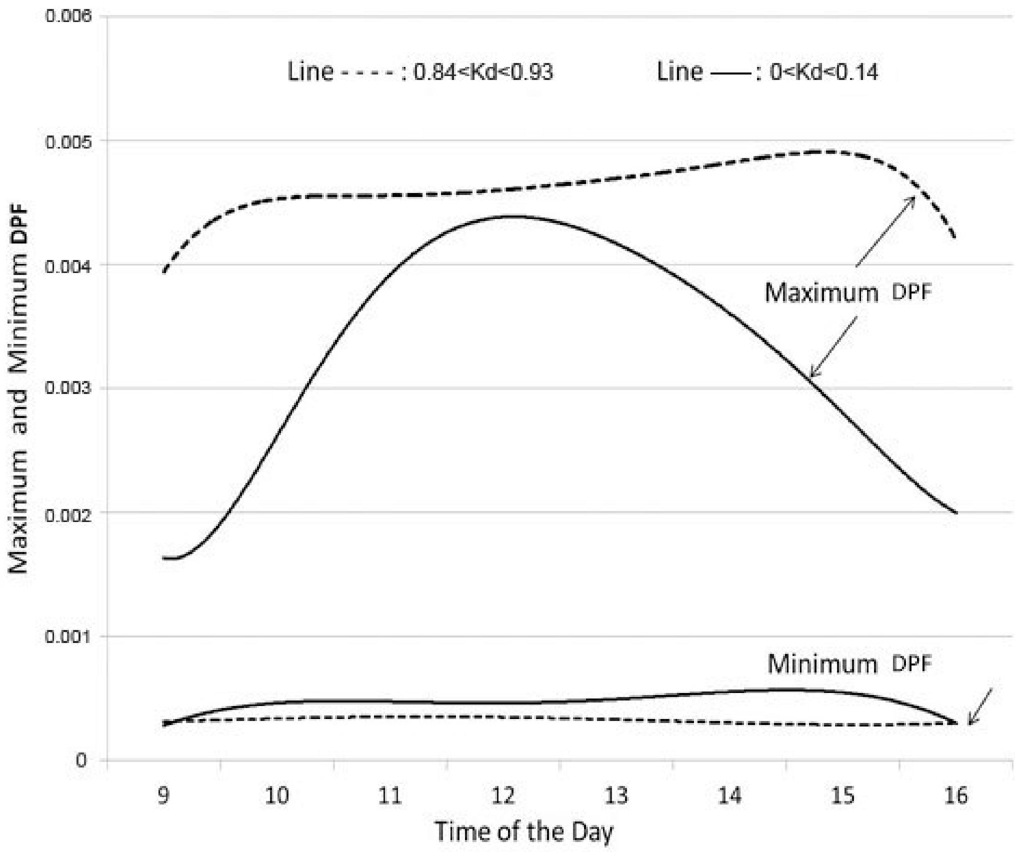


Figure 33. Daily variation of the maximum and minimum DPF during representative clear and cloudy conditions.

5.2.5 Spatial distribution of the indoor illuminance

One of the most interesting parameters for lighting designers and architects apart from the quantity, is the quality of the light in a space. The distribution of the lighting levels on a reference plane, which is one of the qualitative indices of lighting, determines to a great extend how useful the light source is, if more than one lighting sources would be required for the type of tasks undertaken, when artificial light is needed, etc.

The overall efficiency of the light pipe, including the illuminance distribution it provides, is dynamic, as it depends on constantly changing parameters, such as the exterior illuminance, the position of the sun and the sky clearness (Zhang, Muneer and Kubie, 2002). As expected, the distribution of the interior illuminance on the reference plane of the test cell was found to vary as a function of these dynamic conditions. Figure 34, Figure 35 and Figure 36 present the hourly distribution of the interior illuminance under clear sky conditions, (Cluster 1 – $0.07<K_d<0.14$), cloudy sky conditions, (Cluster 9 - $0.84<K_d<0.93$) and intermediate conditions (Clusters 2,3,4,5 - $0.24<K_d<0.37$), respectively.

Under clear sky conditions (Figure 34), the interior illuminance, varies between zero and 450 lux. The highest value is observed around noon and the minimum in early morning and afternoon. The highest values were recorded at the centre of the room and under the light pipe while the minimum values were always recorded towards the edge of the room, (sensors 1 and 13). During the early morning and afternoon periods, the non-homogeneity factor (maximum to minimum illuminance) varied between 4 and 5. The distribution of the illuminance in the room was not symmetrical around the tube, because of the reflections of direct sunlight in the tube and the ring carrying the LED lamps. In fact, the transmitted beam radiation was reflected towards the east-west axis of the room as shown in Figure 34, which is consistent with the observations for the maximum illuminance values during clear sky conditions for the detailed data (Paragraph 5.2.1).

During cloudy days, the interior illuminance varied between zero and 150 lux. As expected, the highest values were recorded around noon, directly under the diffuser. The ratio between the maximum and minimum illuminance in the room varied between 12 and 14 for the whole day period. The spatial distribution of the illuminance was symmetrical around the light pipe because of the diffuse incoming light and contrary to the patterns that occurred during the sunny days (Figure 35).

During the intermediate period, the interior illuminance varied between zero and 450 lux, similar to the conditions occurring during the clear sky days. The ratio of the maximum to minimum interior illuminance varied between 5, in the early morning and afternoon periods, to 11 during noon time. The spatial distribution of the indoor illuminance followed a quite similar pattern as during the clear sky days, mainly because of the reflections of direct sunlight on the reflective parts of the lighting system (Figure 36).

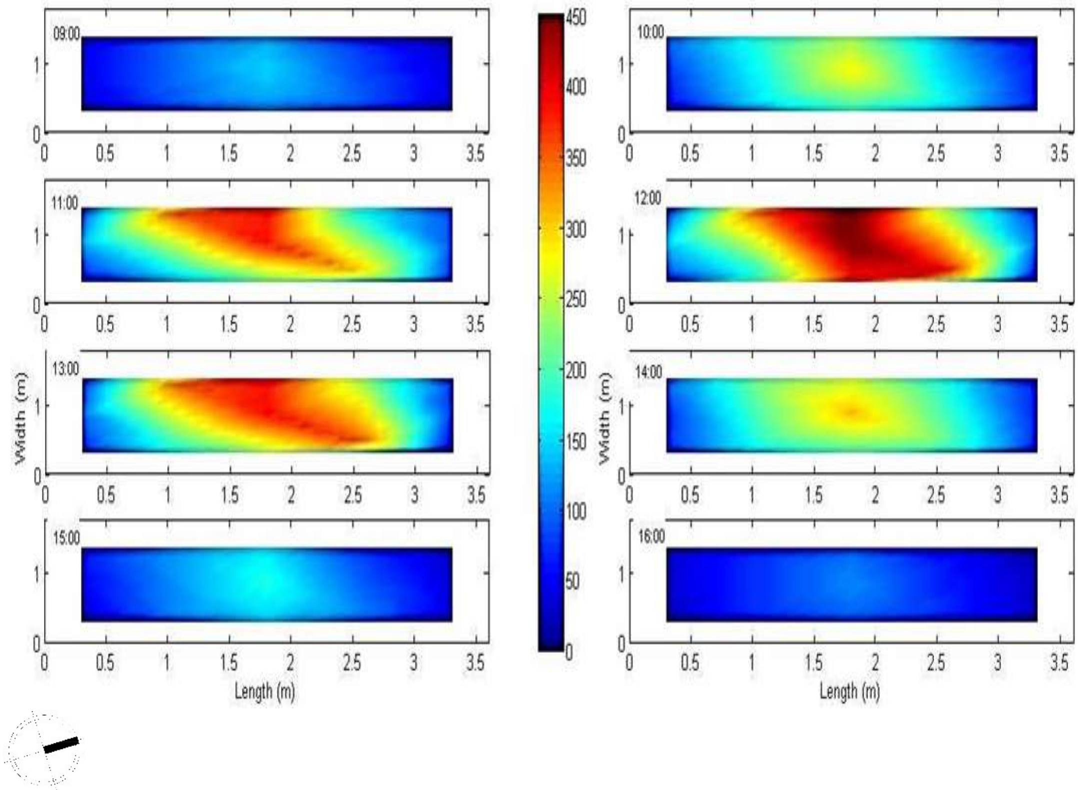


Figure 34. Spatial distribution of the indoor illuminance during a representative clear sky day (K_d cluster 1)

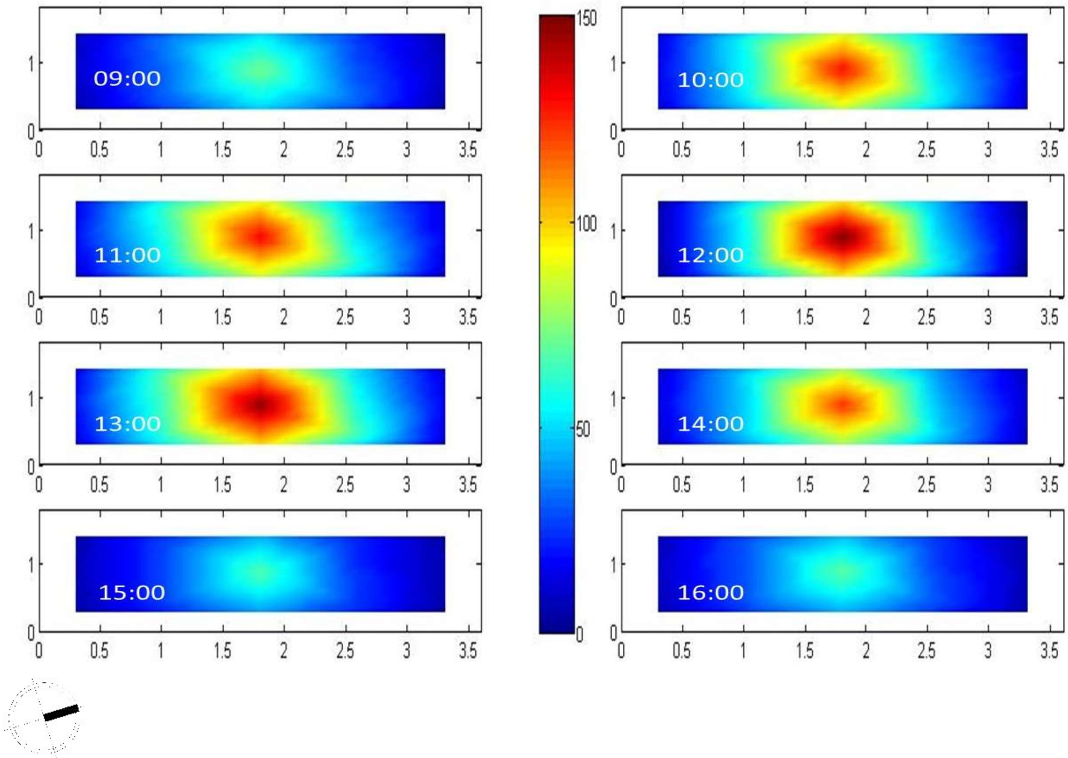


Figure 35. Spatial distribution of the indoor illuminance during a representative cloudy sky day (K_d cluster 9)

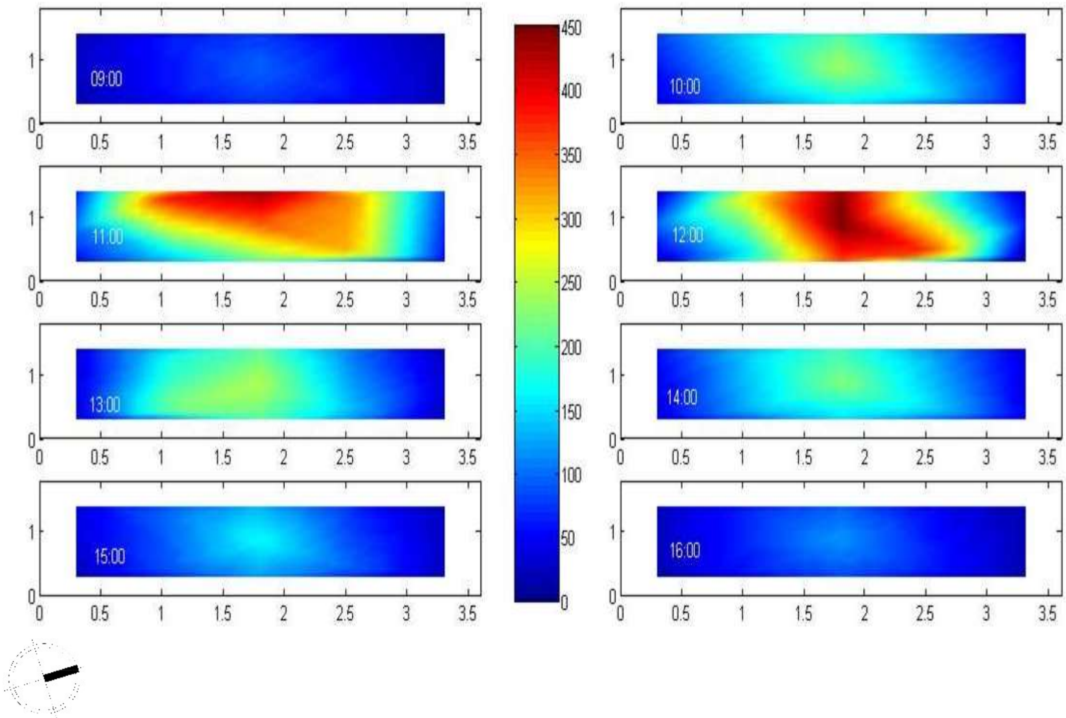


Figure 36. Spatial distribution of the indoor illuminance during a representative intermediate day (cluster 4: 0.24<K_d<0.37)

5.3 Equations describing the experimental data

The developed equations providing the performance of the experimentally tested lighting system are valid for the specific geographic location and room and for the light pipe used for the experiment. However, the use of empirically derived equations can be used from engineers and designers to approximate the performance of a light pipe in a hypothetical modular space with the size (area) of the reference plane, in Athens, Greece and other locations with comparable sky conditions. The efficiency of the light pipe can be modified and individualized by using a parameter including the experimental light pipe's efficiency (0.85 approximately) to the efficiency of the theoretical light pipe (CIE, 2012).

To develop a relation providing the indoor illuminance in the test cell due to the tested light pipe, the hourly average values of the experimental data were used. The analysis was performed for each K_d cluster separately, to include the effect of the sky clearness and acquire more precise prediction formulae. Even though the clusters were created using fuzzy techniques, an approximation of each cluster K_d value range was used, as described in Table 24.

Table 24. K_d groups (clusters) used for the light pipe performance calculation equations

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7	Cluster 8	Cluster 9	Cluster 10
0-0.14	0.14-0.18	0.18-0.24	0.24-0.37	0.37-0.48	0.48-0.52	0.52-0.72	0.72-0.84	0.84-0.93	0.93-1

The hourly average indoor illuminance values of all sensors on the reference plane were calculated for each K_d group. These values were divided into 10 groups of equal amounts of data. Regression analysis was performed for the indoor illuminance data for the respective hourly average values of the measured exterior illuminance. The graphs and regression lines that resulted, along with the formulae that describe them are provided in Figure 37-Figure **56**.

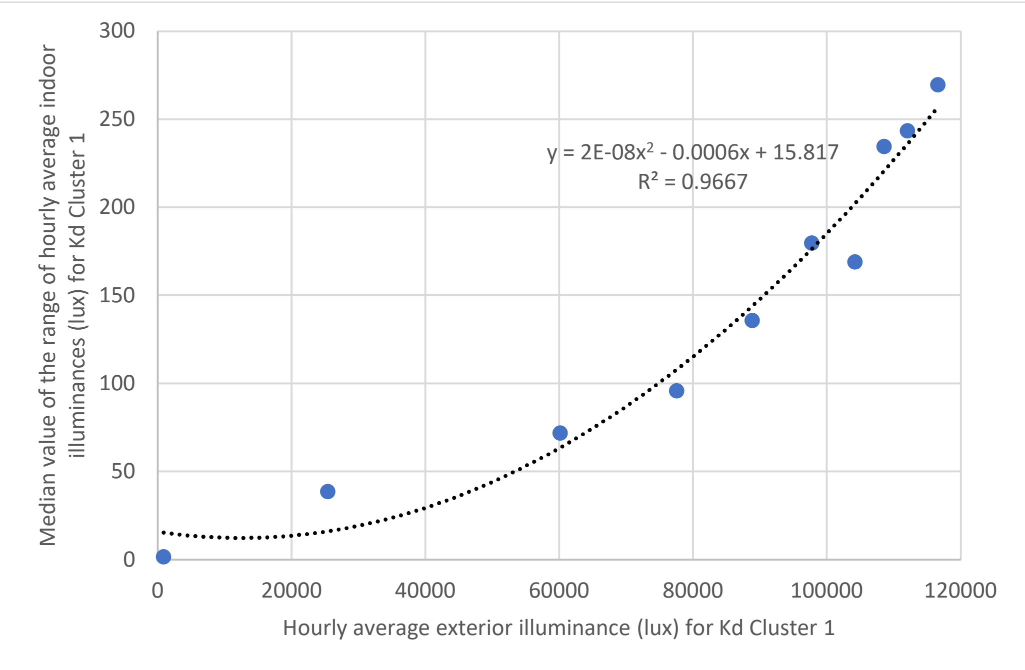


Figure 37. Median values of hourly average indoor illuminance (lux) vs hourly average exterior illuminance (lux) for 10 equal number data groups for K_d Cluster 1

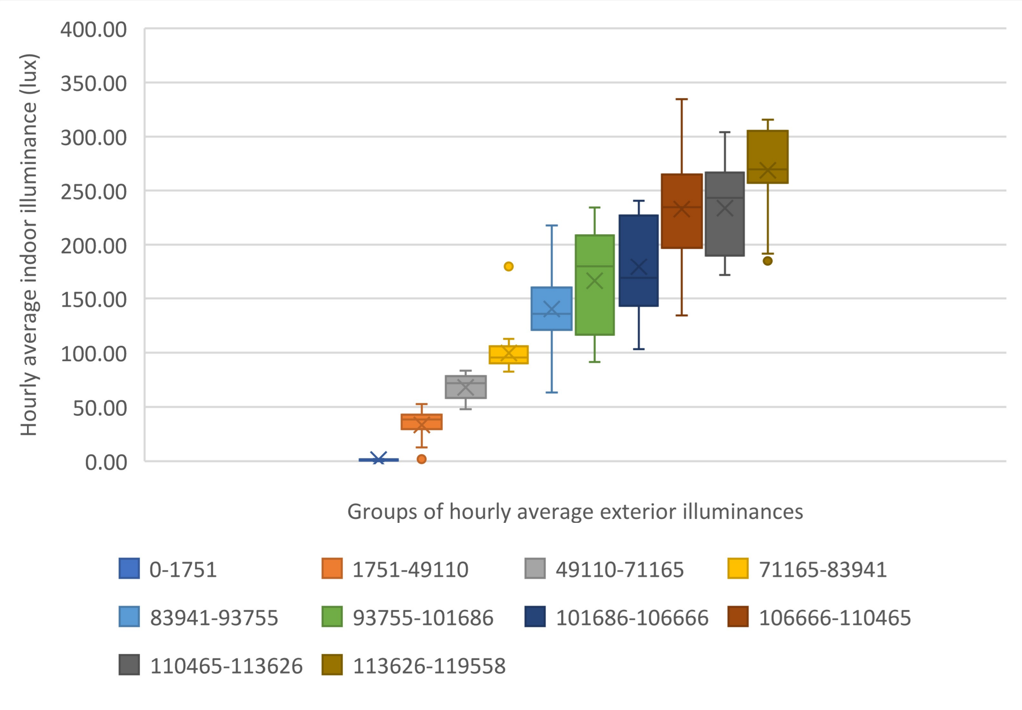


Figure 38. Variability of hourly average indoor illuminance for the 10 exterior illuminance groups for Kd Cluster 1

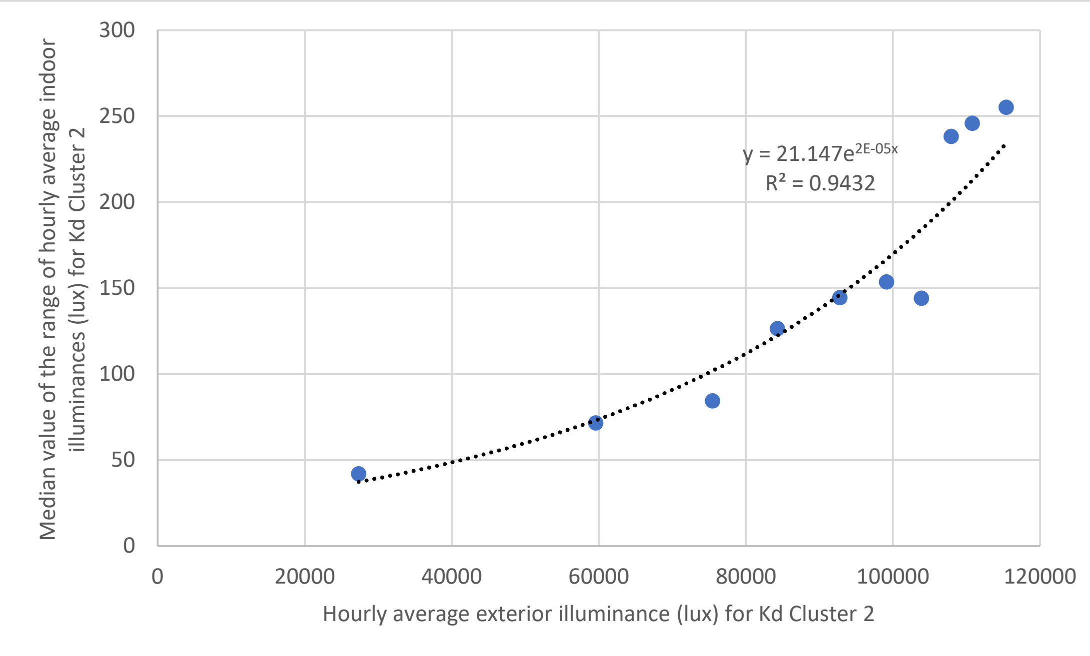


Figure 39. Median values of hourly average indoor illuminance (lux) vs hourly average exterior illuminance (lux) for 10 equal number data groups for K_d Cluster 2

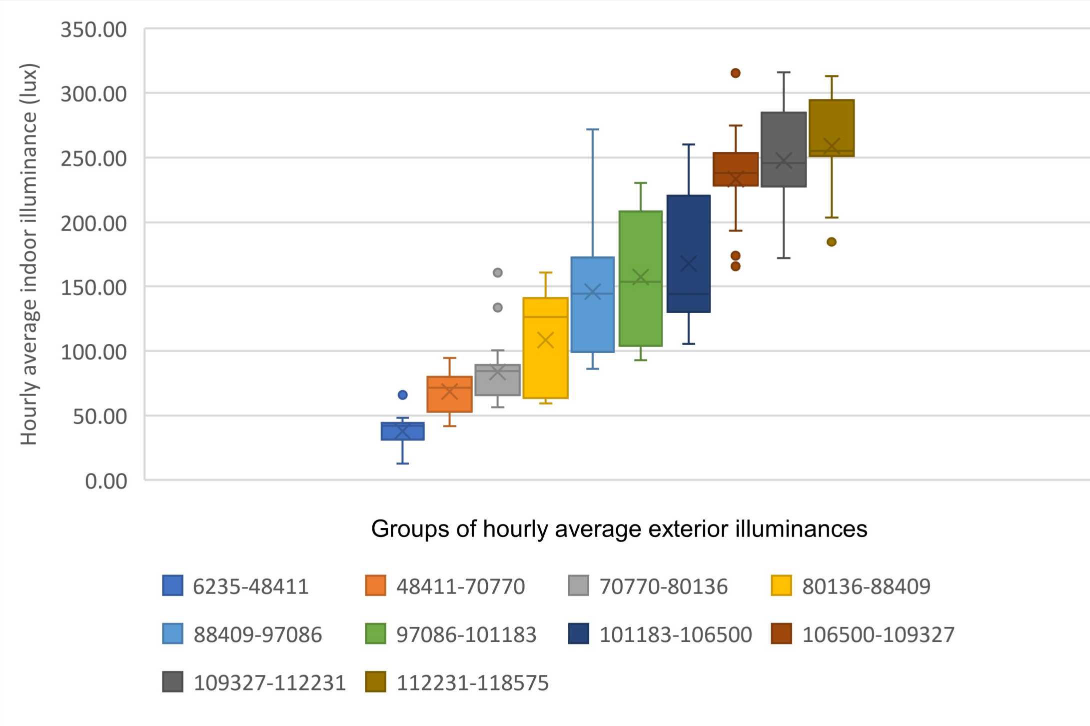


Figure 40. Variability of hourly average indoor illuminance for the 10 exterior illuminance groups for Kd Cluster 2

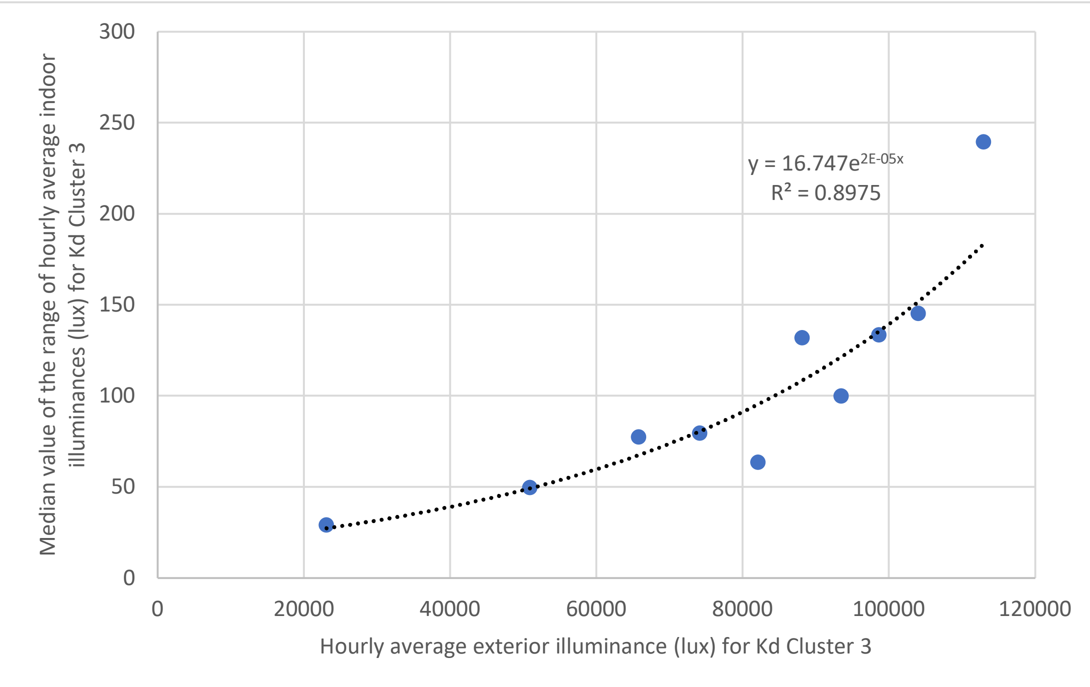


Figure 41. Median values of hourly average indoor illuminance (lux) vs hourly average exterior illuminance (lux) for 10 equal number data groups for K_d Cluster 3

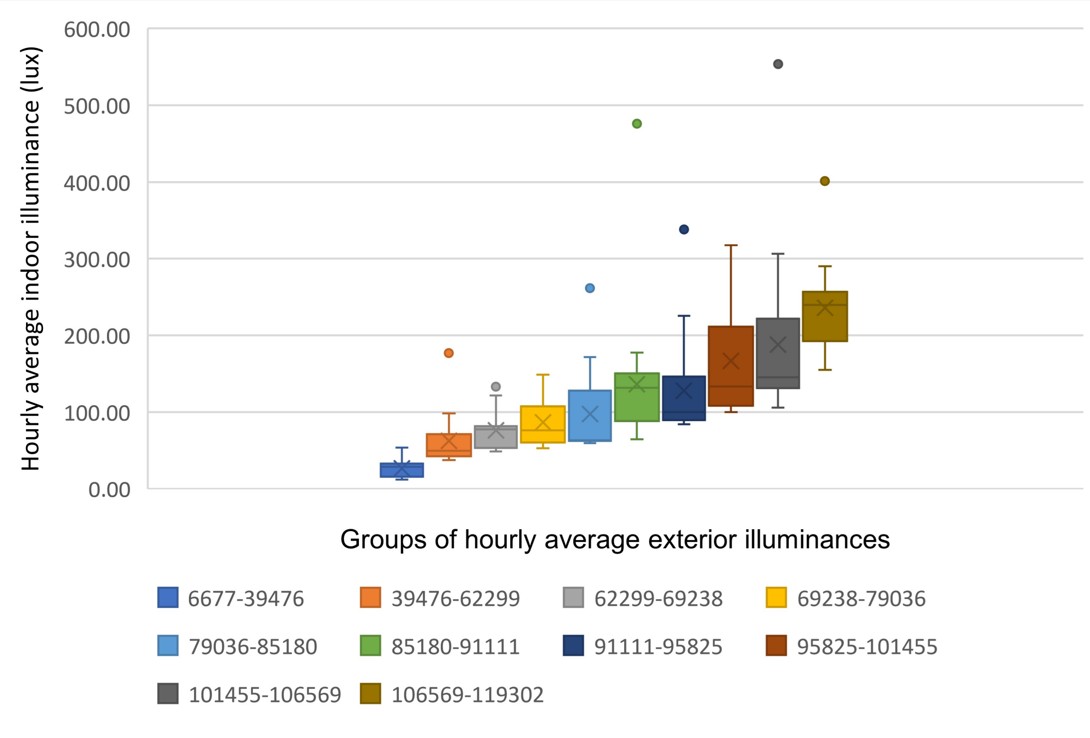


Figure 42. Variability of hourly average indoor illuminance for the 10 exterior illuminance groups for K_d Cluster 3

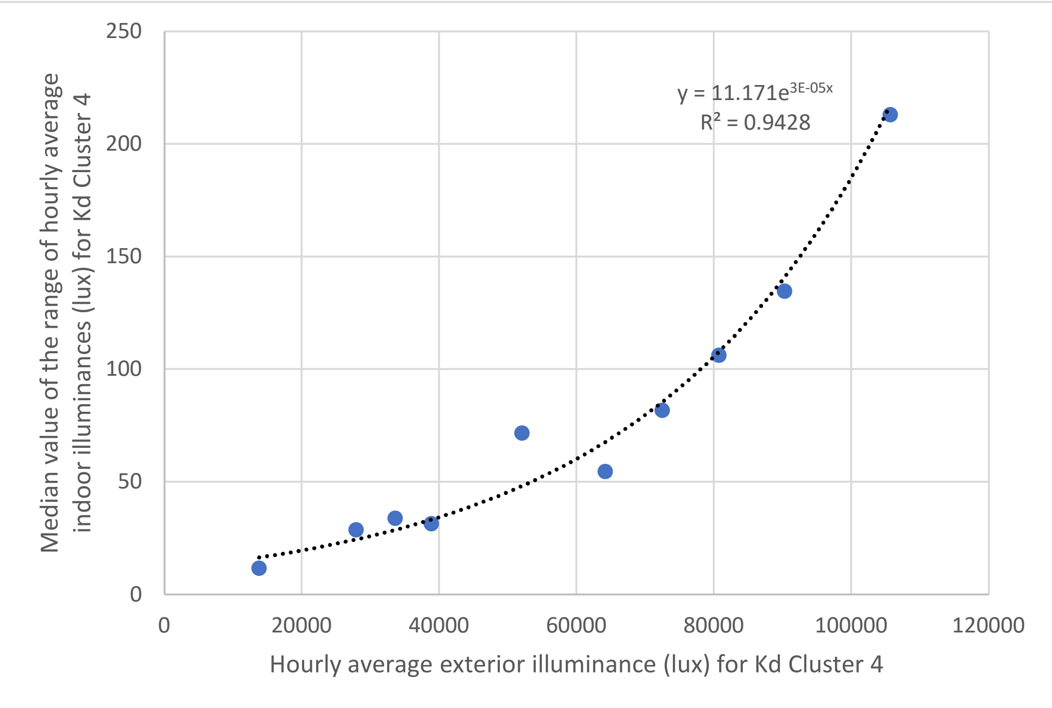


Figure 43. Median values of hourly average indoor illuminance (lux) vs hourly average exterior illuminance (lux) for 10 equal number data groups for K_d Cluster 4

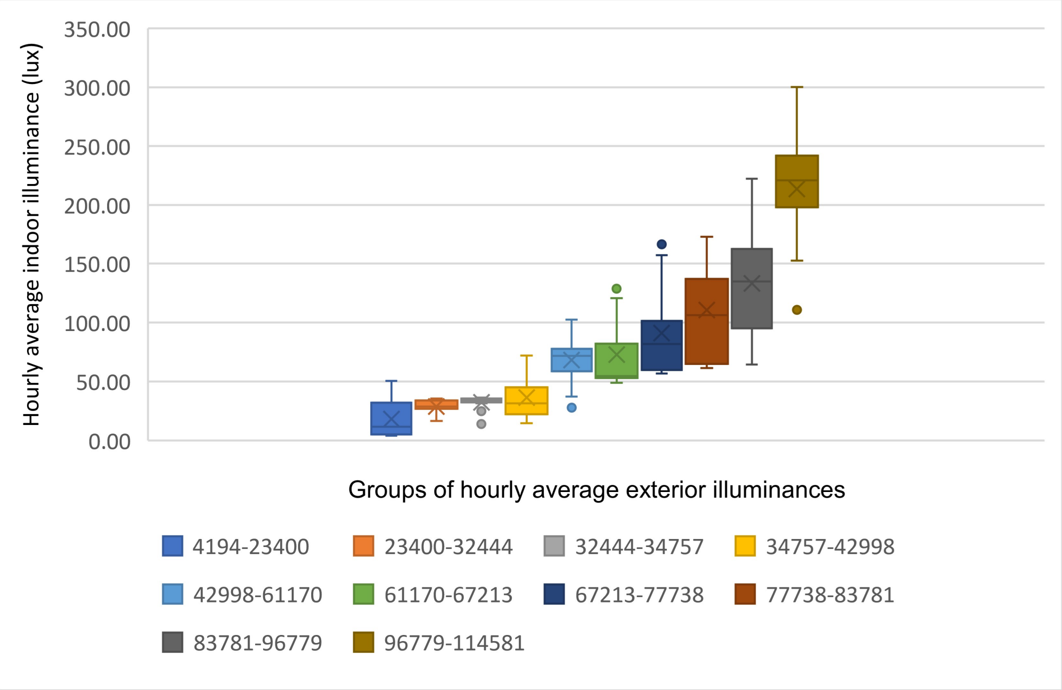


Figure 44. Variability of hourly average indoor illuminance for the 10 exterior illuminance groups for K_d Cluster 4

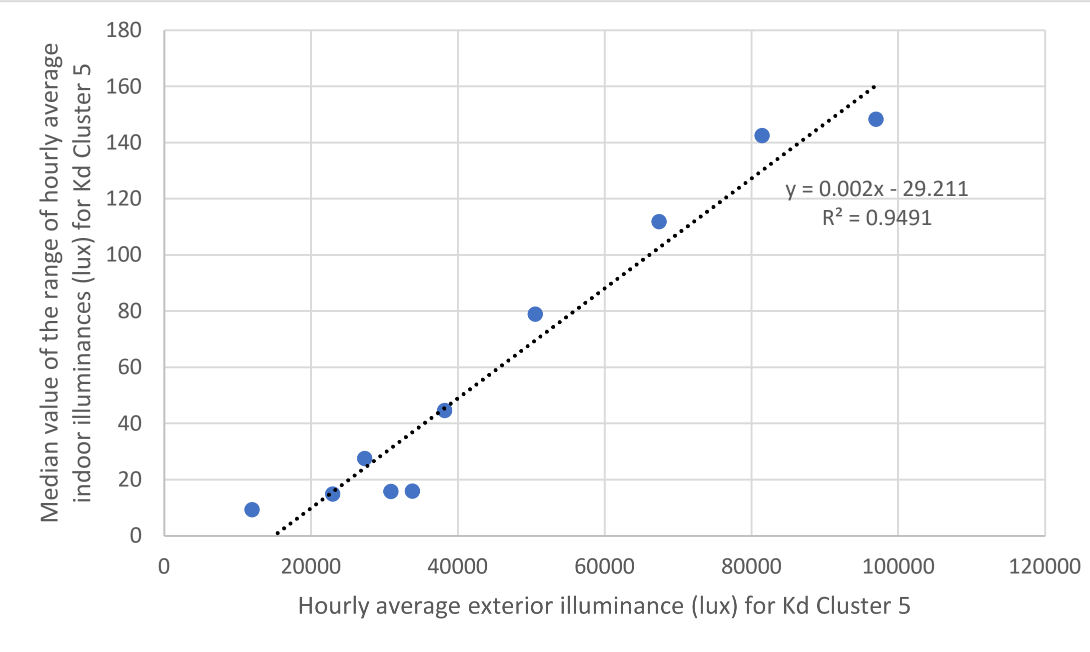


Figure 45. Median values of hourly average indoor illuminance (lux) vs hourly average exterior illuminance (lux) for 10 equal number data groups for K_d Cluster 5

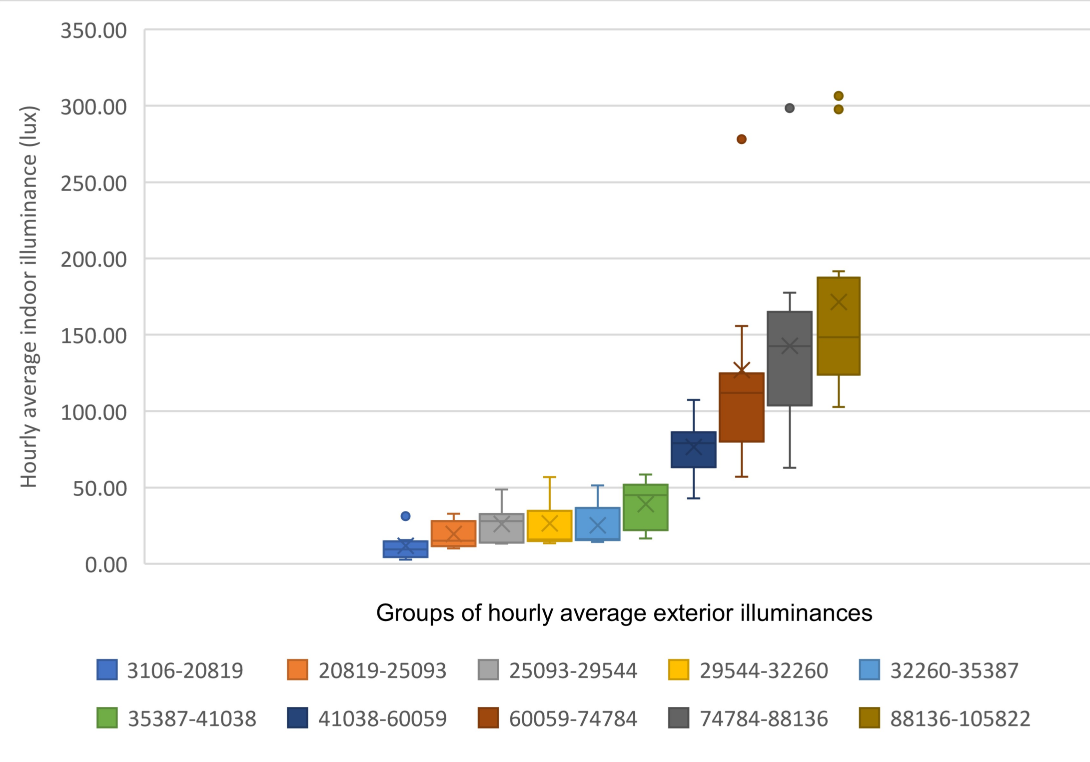


Figure 46. Variability of hourly average indoor illuminance for the 10 exterior illuminance groups for K_d Cluster 5

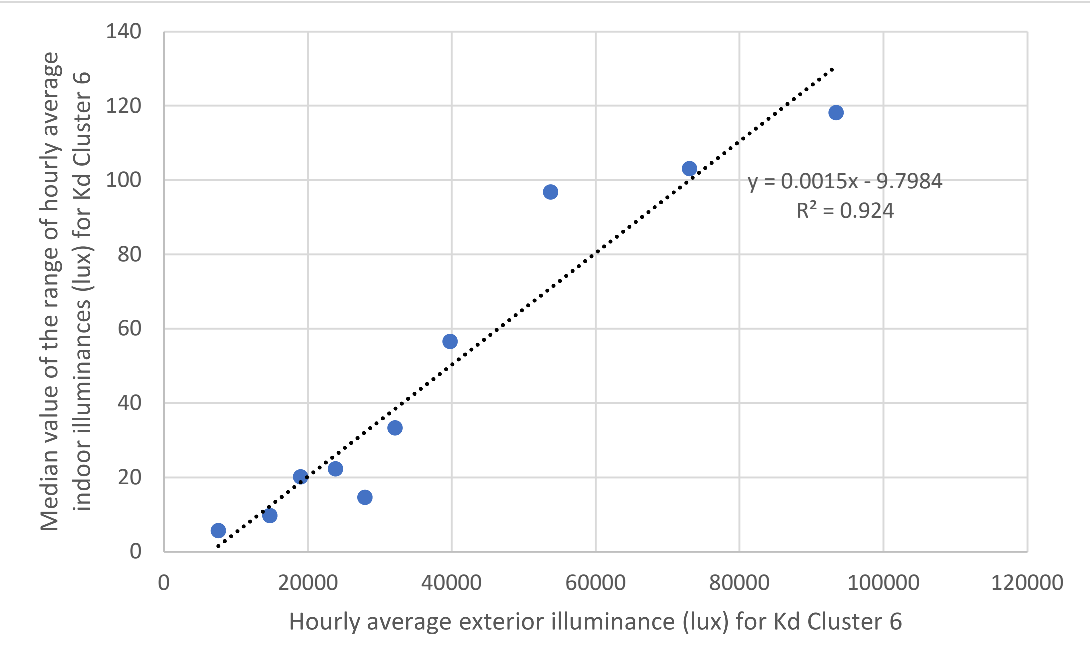


Figure 47. Median values of hourly average indoor illuminance (lux) vs hourly average exterior illuminance (lux) for 10 equal number data groups for K_d Cluster 6

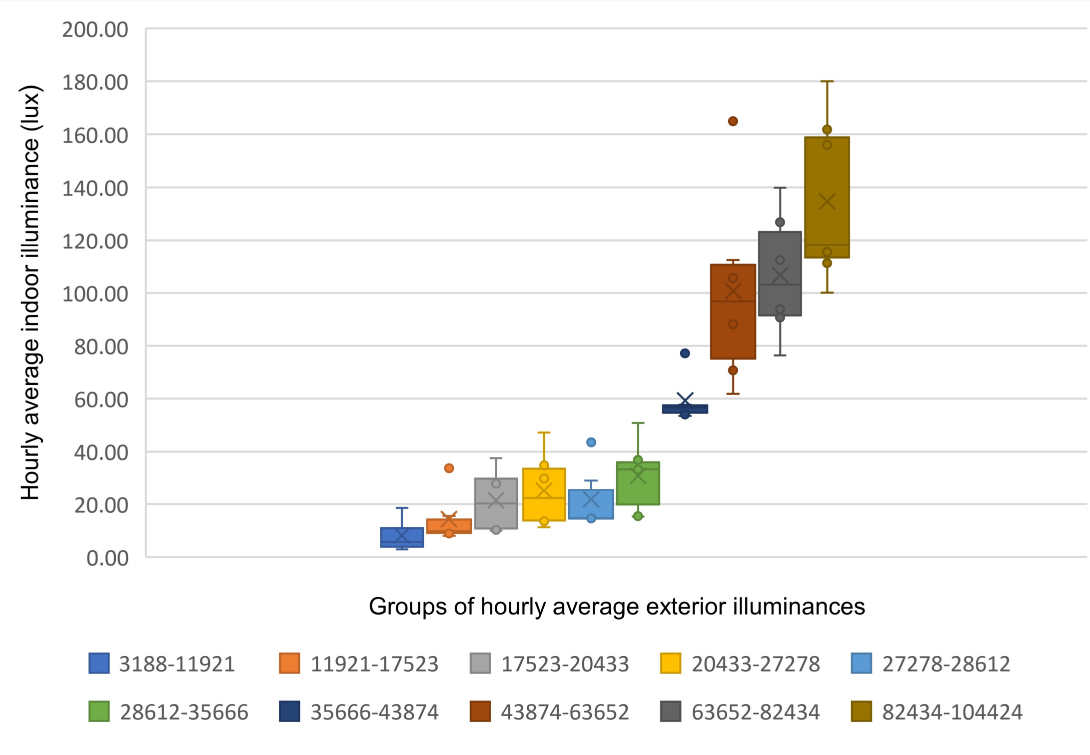


Figure 48. Variability of hourly average indoor illuminance for the 10 exterior illuminance groups for K_d Cluster 6

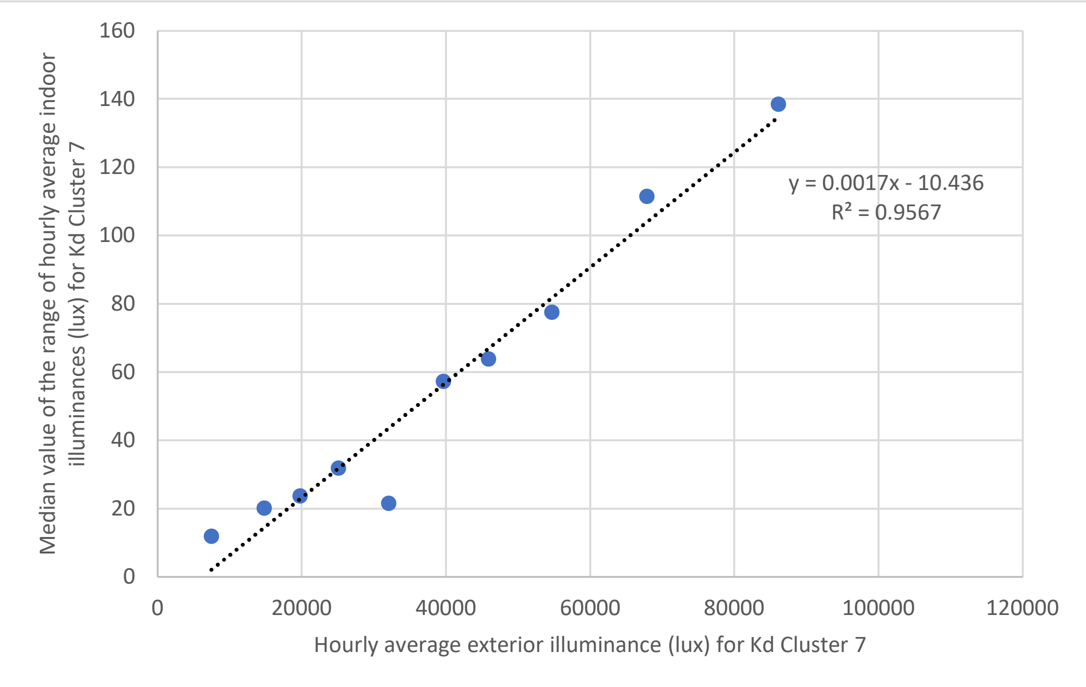


Figure 49. Median values of hourly average indoor illuminance (lux) vs hourly average exterior illuminance (lux) for 10 equal number data groups for K_d Cluster 7

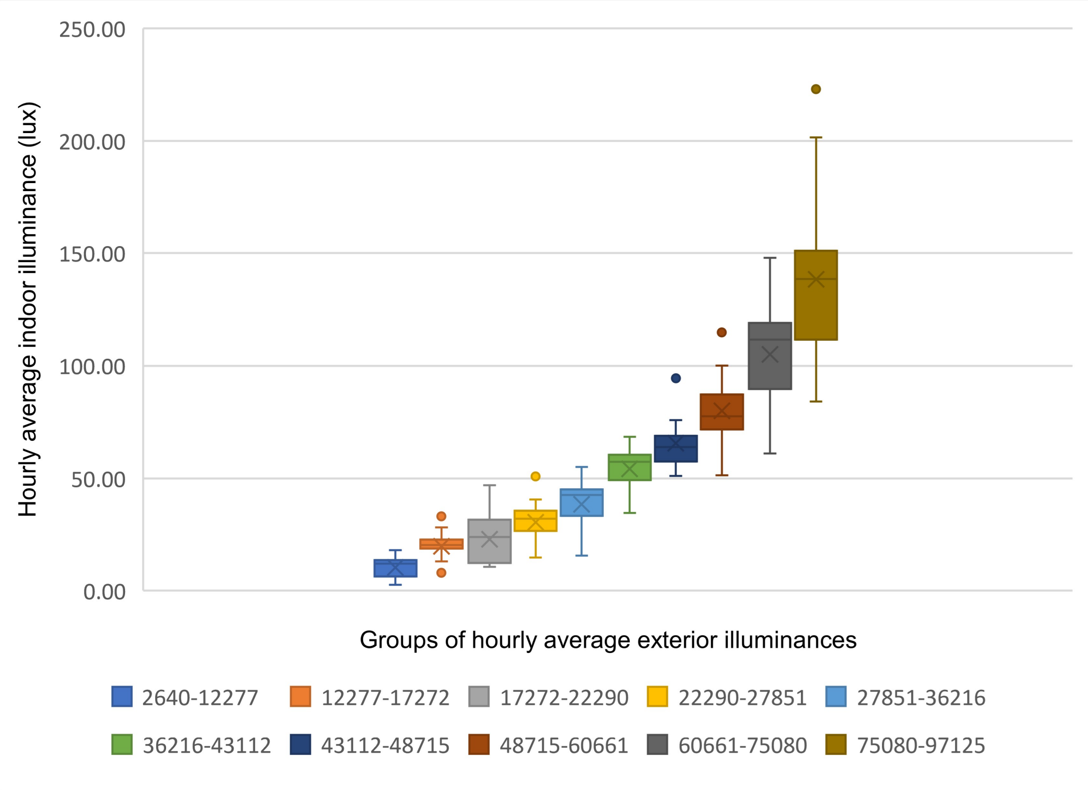


Figure 50. Variability of hourly average indoor illuminance for the 10 exterior illuminance groups for K_d Cluster 7

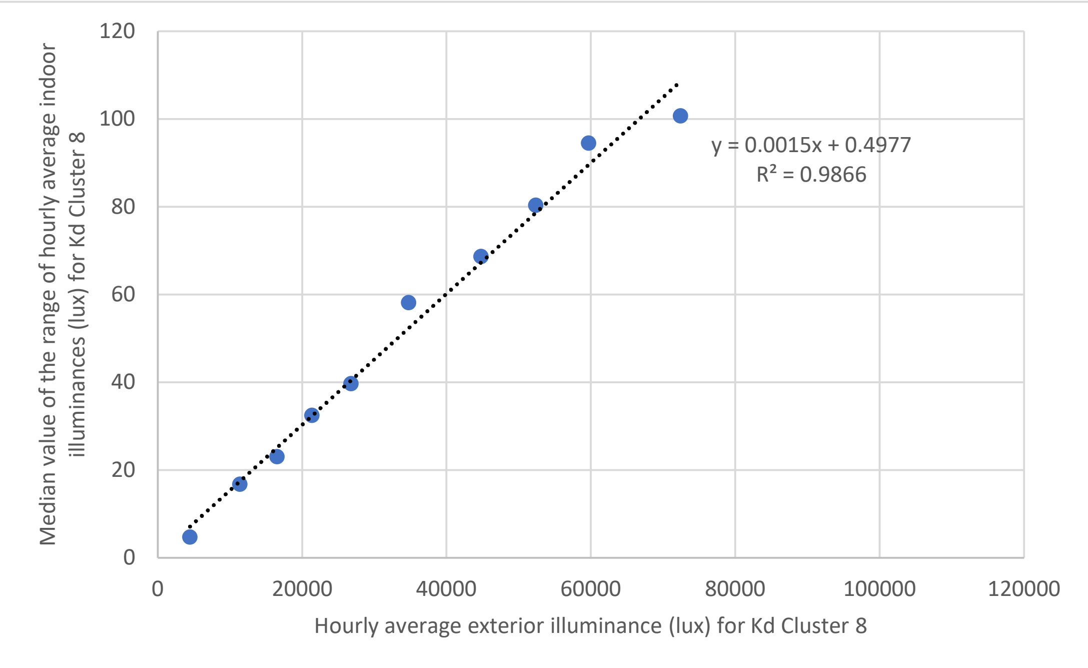


Figure 51. Median values of hourly average indoor illuminance (lux) vs hourly average exterior illuminance (lux) for 10 equal number data groups for K_d Cluster 8

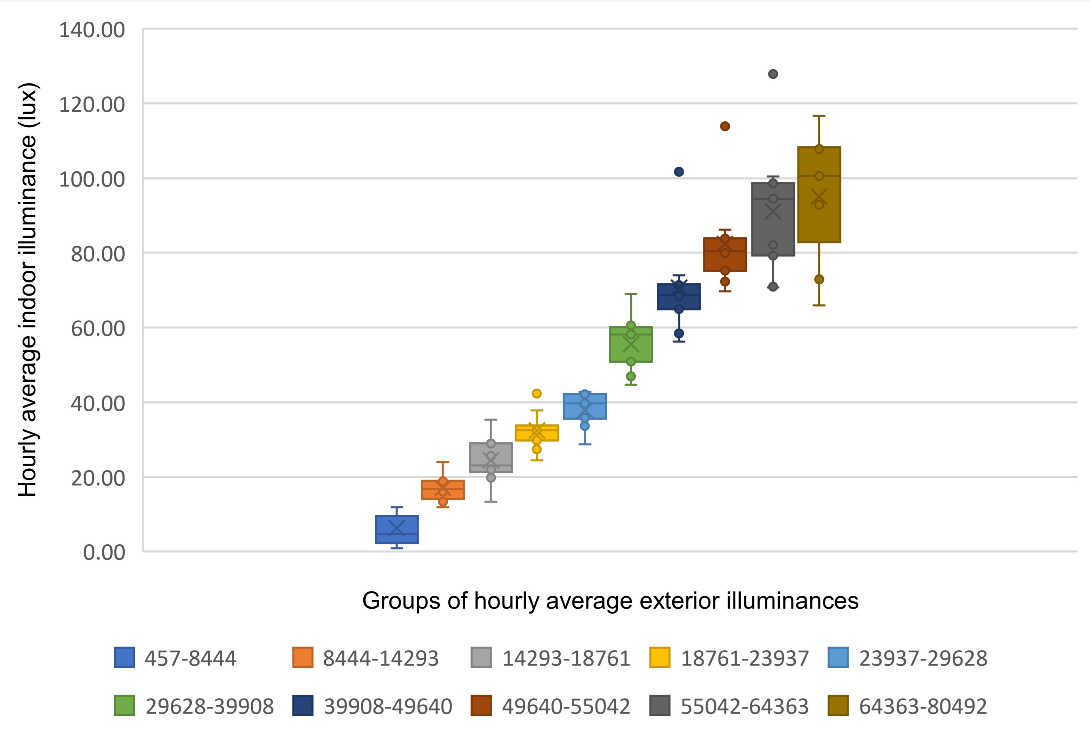


Figure 52. Variability of hourly average indoor illuminance for the 10 exterior illuminance groups for Kd Cluster 8

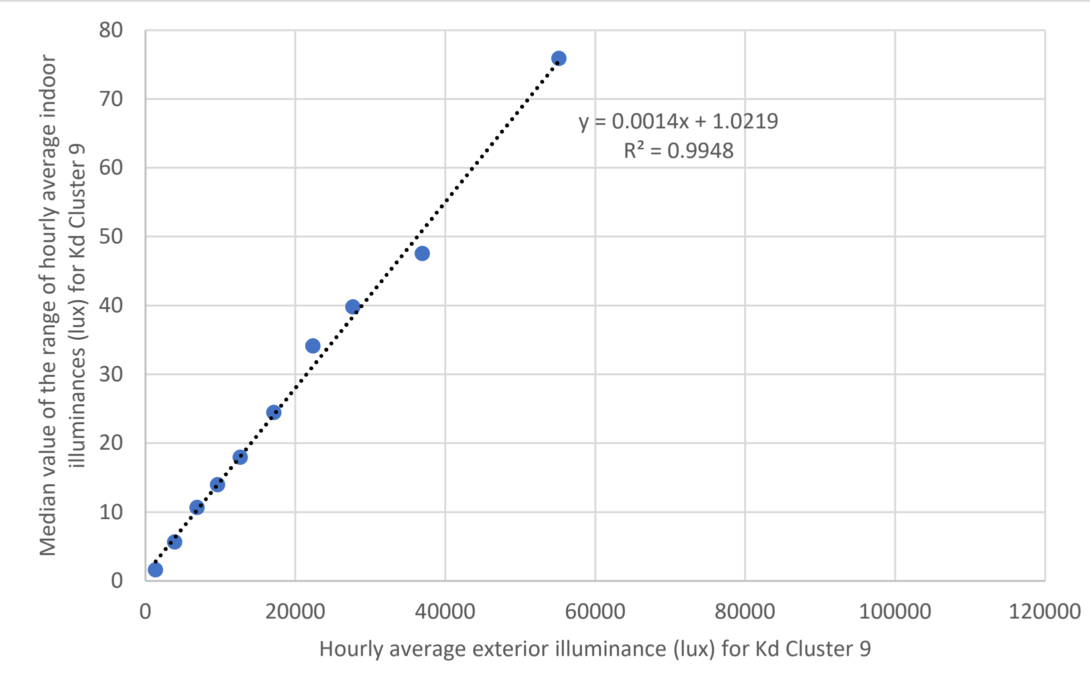


Figure 53. Median values of hourly average indoor illuminance (lux) vs hourly average exterior illuminance (lux) for 10 equal number data groups for Kd Cluster 9

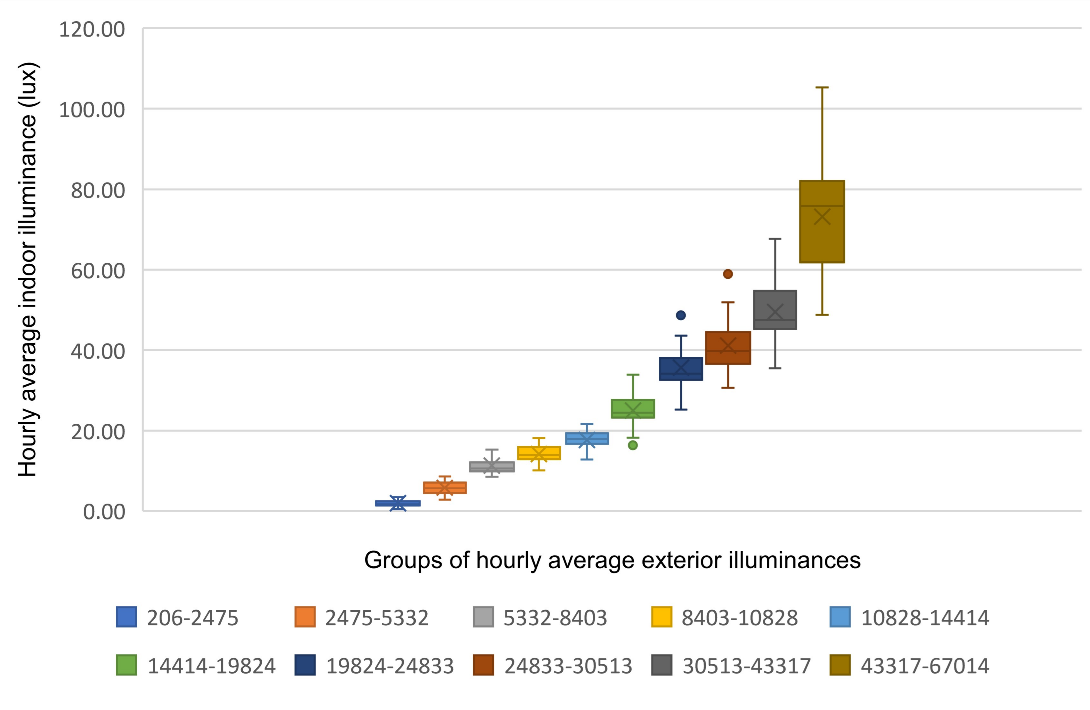


Figure 54. Variability of hourly average indoor illuminance for the 10 exterior illuminance groups for Kd Cluster 9

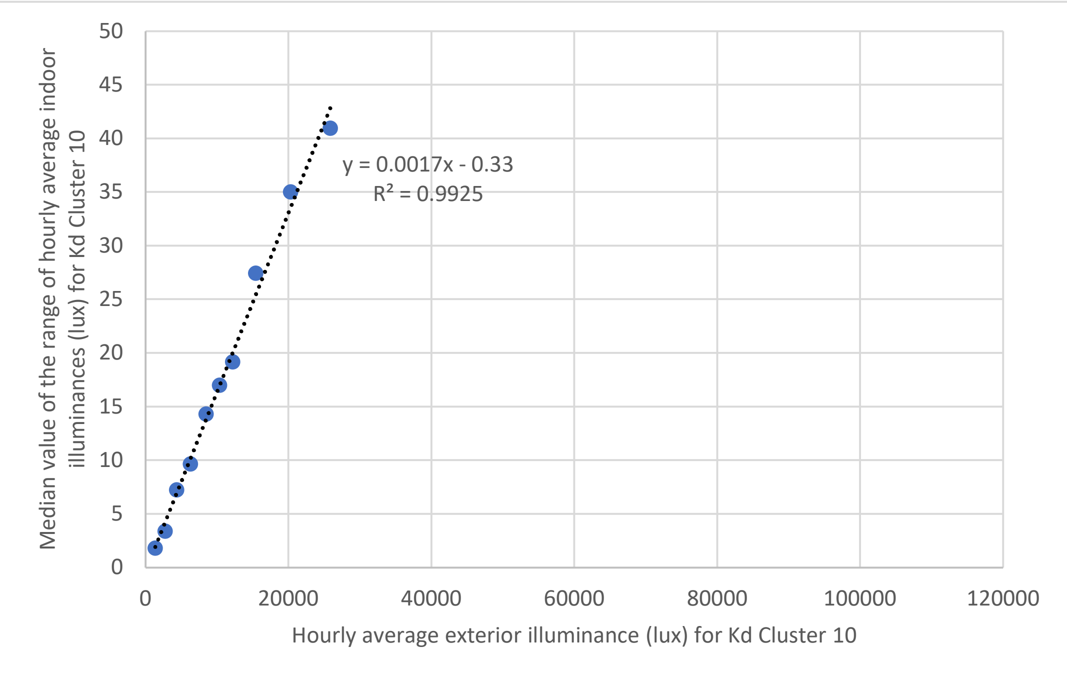


Figure 55. Median values of hourly average indoor illuminance (lux) vs hourly average exterior illuminance (lux) for 10 equal number data groups for Kd Cluster 10

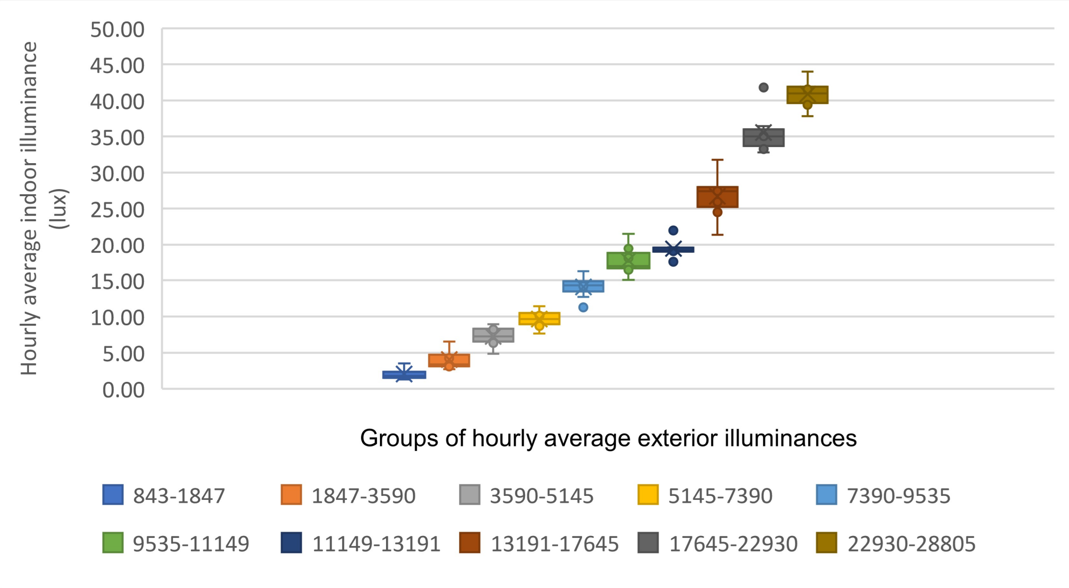


Figure 56. Variability of hourly average indoor illuminance for the 10 exterior illuminance groups for Kd Cluster 10

5.4 Conclusions

Extensive testing has been carried out to measure, record, analyse and assess the efficiency and performance of a light pipe. The data acquired show that the light pipe installed in the test cell offers 100 lux of interior illuminance on average, while the average DPF is around 0.15%. The spatial and temporal performance of the system varies considerably as a function of the sky conditions. Under clear skies, the average indoor illuminance is almost five times higher than the corresponding value under fully cloudy conditions (

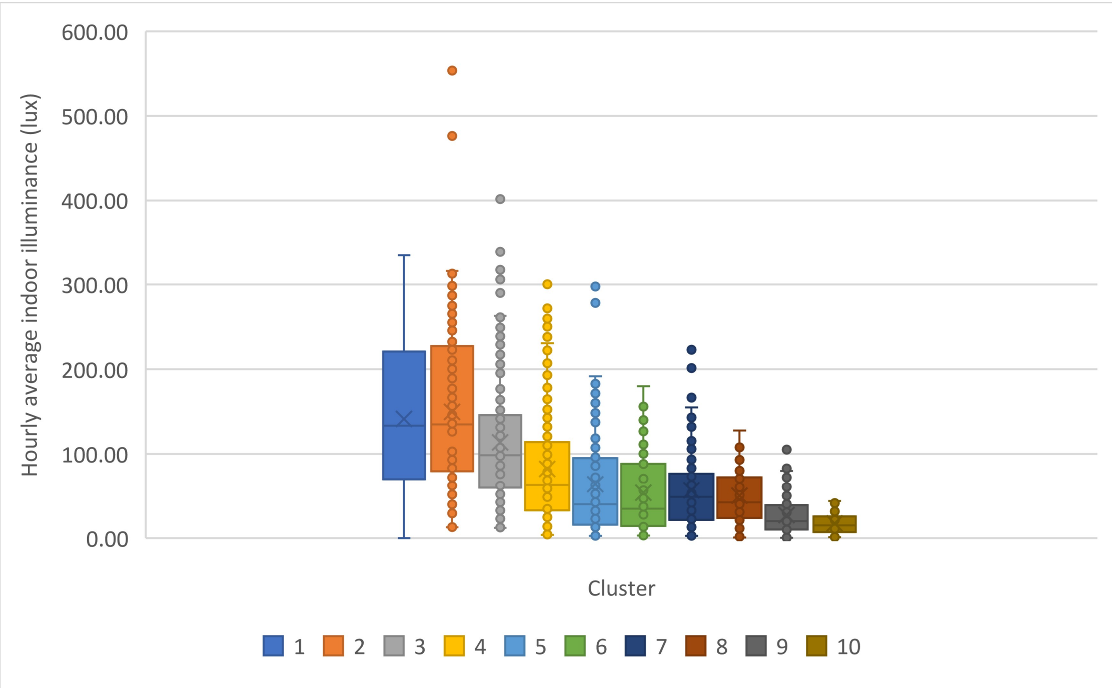


Figure 23). A clear exponential relation is observed between the indoor illuminance under clear sky conditions, while the relation is gradually becoming linear as K_d increases.

The Daylight Penetration Factor presents important variation as a function of the sky conditions and the position of the sun. Under clear sky conditions, the higher transmissivity is observed under the midday period and increases for increasing solar altitudes while it presents its maximum for solar azimuths corresponding to south. Under cloudy conditions, the daily variation of the DPF is non-significant, mainly because of the nature of diffuse solar radiation.

The average uniformity in the room was 0.26 (0.25 for the hourly average data). The experimental data showed that the uniformity is better (higher) when the sky is relatively clear, i.e., for clusters 4 and 5 (Figure 57). This can probably be explained by the geometry of the lighting system and the way the light is reflected into the tube and distributed into the space through the prismatic diffuser. For clear sky conditions, the intense sunlight entering the dome is undergoing multiple inter-reflections on the walls of the tube and then redirected by the diffuser, reaching a wide area of the reference plane. During overcast sky conditions, the light is more diffuse, and its intensity is lower. The light is mainly directed downwards and since the testing environment did not favour reflections from the room surfaces, the rest of the reference plane was receiving low lighting levels. On the other hand, the main source of spatial inhomogeneity of the indoor illuminance for high exterior illuminance and low K_d values is the presence of bright patches of light (Darula *et al.*, 2010). However, when the reference area becomes smaller (values from sensors 1,2,3,11,12,13 are excluded) the uniformity is greatly improved; the average value is 0.64 while the maximum is 0.84. Uniformity is expected to be much improved in environments with more reflective interior surfaces and greater number of light sources.

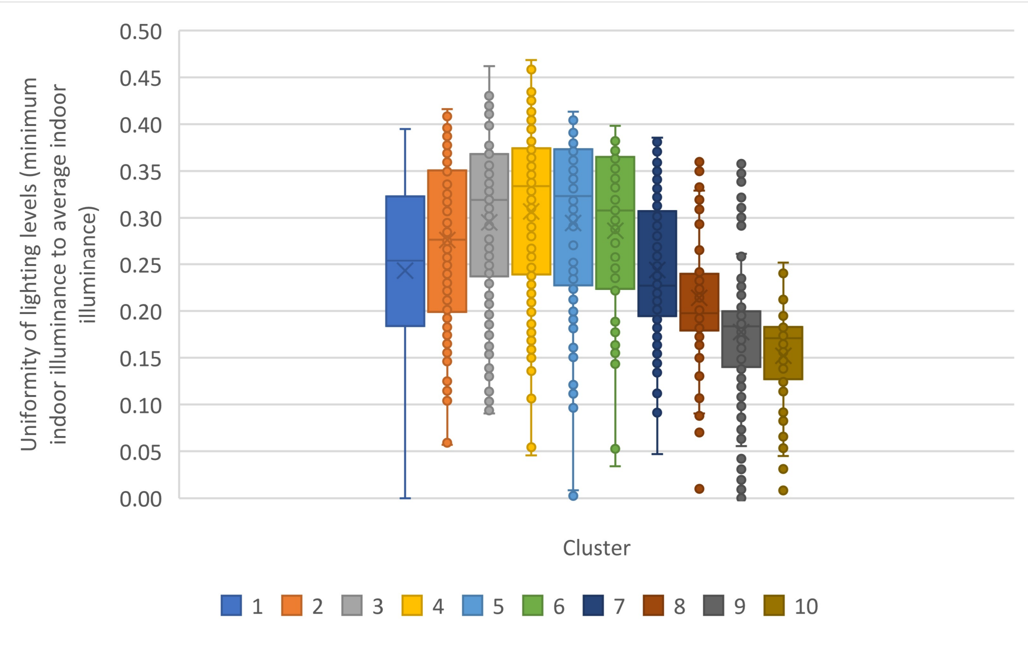


Figure 57. Uniformity on the reference plane for the hourly average illuminance values for all the K_d clusters (median: 0.25, σ=0.09)

The performance of the light pipe, in terms of indoor illuminance, for the specific conditions under which the experiment was carried out, is described by formulae that relate the average indoor illuminance with the exterior illuminance. The sky clearness is also considered, as each of the 10 developed formulae corresponds to one of the 10 K_d clusters. The generalization of the formulae to be used as prediction methods for other environments and light pipe characteristics can be a challenging process. The effect of the light pipe geometry can probably be accounted for by incorporating the efficiency values of guides of various diameters, lengths and reflectance properties provided by the CIE Technical Report:

Tubular daylight guidance systems (CIE, 2012) in the calculations. However, the effect of the space characteristics on the lighting levels would require many testing layouts or simulations. Instead, this study provides the minimum light pipe performance for the weather/sky conditions of Athens, which can be used as a replicable unit for larger applications, by increasing the number of lighting systems and superimposing their performance on the reference plane.

Chapter 6: Comparison of experimental data with theoretical methodologies and simulations

6.1 Synopsis

As described in Chapter 2: and Chapter 3: of this Thesis, the great number of inter-reflections in the light pipe make the accurate performance prediction using simulations difficult. Emulating the light pipe with a luminaire of cosine luminous intensity distribution was proven to be the most accurate of the tested methodologies. However, this method requires experimental data for the construction of the luminaire intensity distribution curve, which makes the application of the method limited. Forward raytracing is a method that can calculate the lighting levels from a light pipe more accurately than backward raytracing (Farrell, Norton and Kennedy, 2004). Forward raytracing was made more easily applicable through the software DIVA, which is a plug-in for the design software Rhinoceros.

This Chapter describes the simulation of the lighting performance of the experimental light pipe using forward raytracing and compares the results to the experimental data. Additionally, the experimental data describing the performance of the light pipe under the sky conditions of Athens is compared to the interior illuminance values calculated using the equations developed in Chapter 3: from the TTE, Luxplot methods and from and simulating the light pipe as a luminaire.

6.2 Light pipe performance prediction using the Radiance forward raytracing method

As mentioned in Chapter 2: the performance of light pipes cannot be accurately predicted using backward raytracing, due to the geometry and the multiple bounces that light rays undergo in the tube. Forward raytracing is providing accurate results when calculating the lighting performance of a light pipe, compared to other methods or software. DIVA-for-Rhino is a plug-in for Rhinoceros, enabling accurate and dynamic simulations of daylighting and energy. DIVA uses Radiance to perform lighting simulations and contrary to other software, provides both backward and forward raytracing techniques.

To conduct simulations in DIVA, the layout and surfaces of the test cell were accurately reproduced in Rhino. Each element of the light pipe (dome, tube, diffuser) was modelled, and materials of different characteristics were assigned to each element. Forward raytracing was used to simulate the light pipe performance which was then compared to the experimental values. The materials that were found to give interior illuminances closer to those acquired from the experiment are described in Table 25.

Table 25. Radiance material properties

	Walls/Ceiling/Floor (plastic)	Dome (glass)	Diffuser (glass)	Tube (mirror)
Reflectance	0	-	-	-
Roughness	0.05	-	-	0
Specularity				0.95
Visual transmittance	-	88%	80%	-
Visual transmissivity		96%	87%	-

Simulations were performed for dates and times when the exterior illuminance recorded during the experiment were the same with these of the weather file used for the simulations. The widest possible range of exterior illuminances was used for each month, depending on the number of matching values. The time could differ by up to 30 minutes and the Global Horizontal Irradiance was set equal to that during the experiment. The sky type that was used for the simulations was the Perez all-weather sky model (Perez, R et al. 1993).

When DIVA for Rhino performs forward raytracing calculations, it delivers results in the form of visualisations, i.e., distribution of point interior illuminances (or luminances) on the reference plane in the form of a false-colour image. When clicking anywhere in the image, the respective point illuminance value appears. To calculate the average interior illuminance on the reference plane, 13-point illuminances were taken, representing the 13 sensors of the experimental setup. Figure 58 is a sample of the visualisations acquired from the simulations.

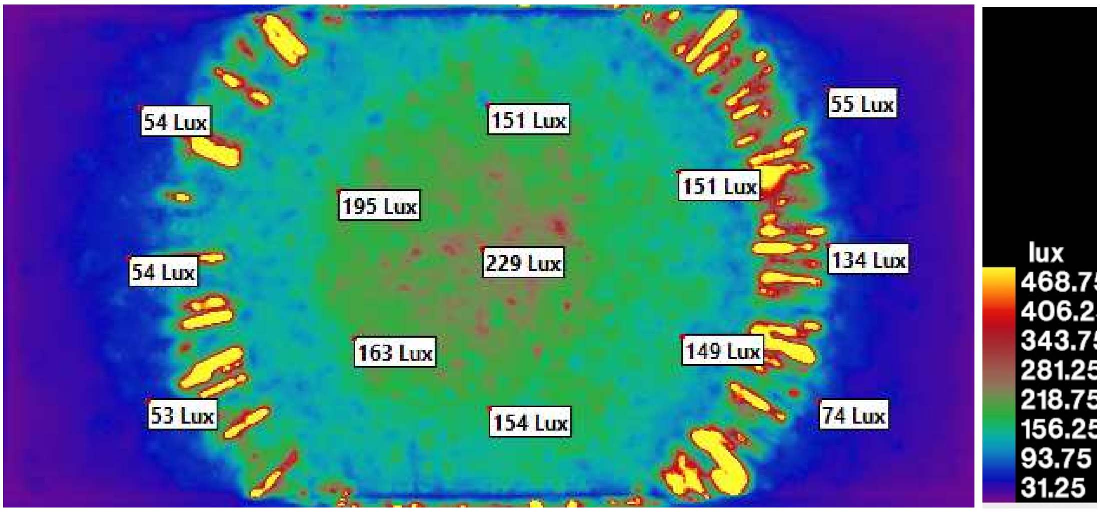


Figure 58. Simulated interior illuminance (lux) on the reference plane. Date: 27/03, 13:00pm, E_{ex}=90,200 lux.

Figure 59 includes the percentage of the average error for various groups of exterior illuminances. The minimum error is found to be 32% and is observed for exterior illuminances between 80 and 90 klux; the maximum error is approximately 62% and is found to occur for low exterior illuminances. Forward ray tracing is found to overestimate the light pipe performance for exterior illuminances lower than 50 klux and underestimate it for exterior illuminances above that value of exterior illuminance.

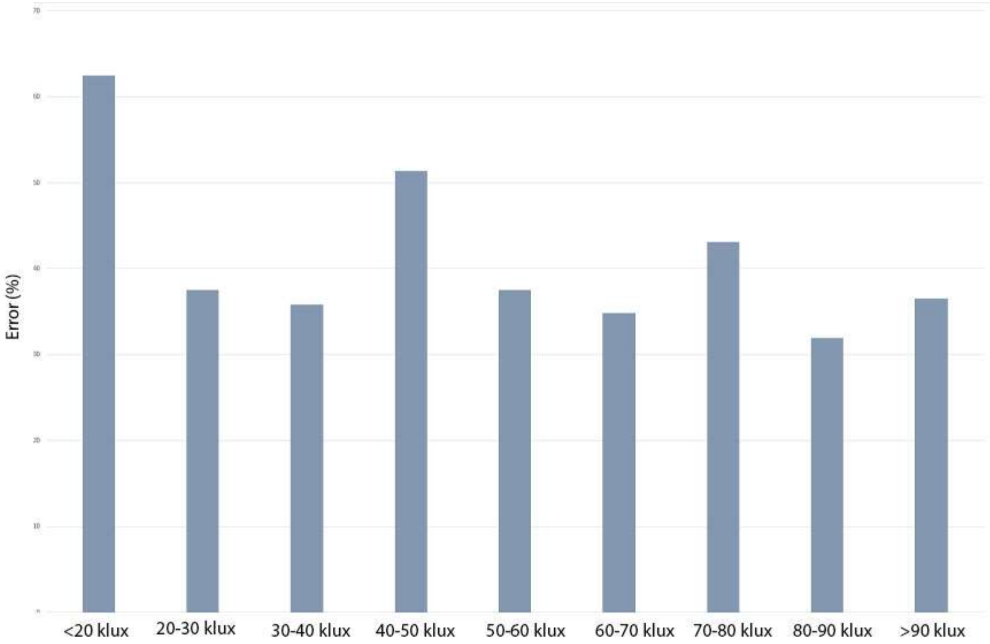


Figure 59. Percentage of error of the forward ray tracing simulations for various exterior illuminance groups

The distribution of light on the reference plane of the simulation model is symmetrical around the light pipe, regardless of the exterior conditions, unlike the experimental distribution, where the east-west axis had increased lighting levels during clear sky conditions.

Data values either retrieved from a sensor or from the simulated reference plane exceeding the values of corresponding sensors or points on the reference plane (diametrically positioned to the centre of the reference plane), by more than 1.5 times were excluded as outliers. This was required as bright patches or caustics can give much higher values to specific areas on the reference plane, that increase the average illuminance in the space but not the light availability.

Overall, the DIVA simulations using the forward ray tracing method provide results which can be considered representative of the real light conditions created by a light pipe if the error is considered.

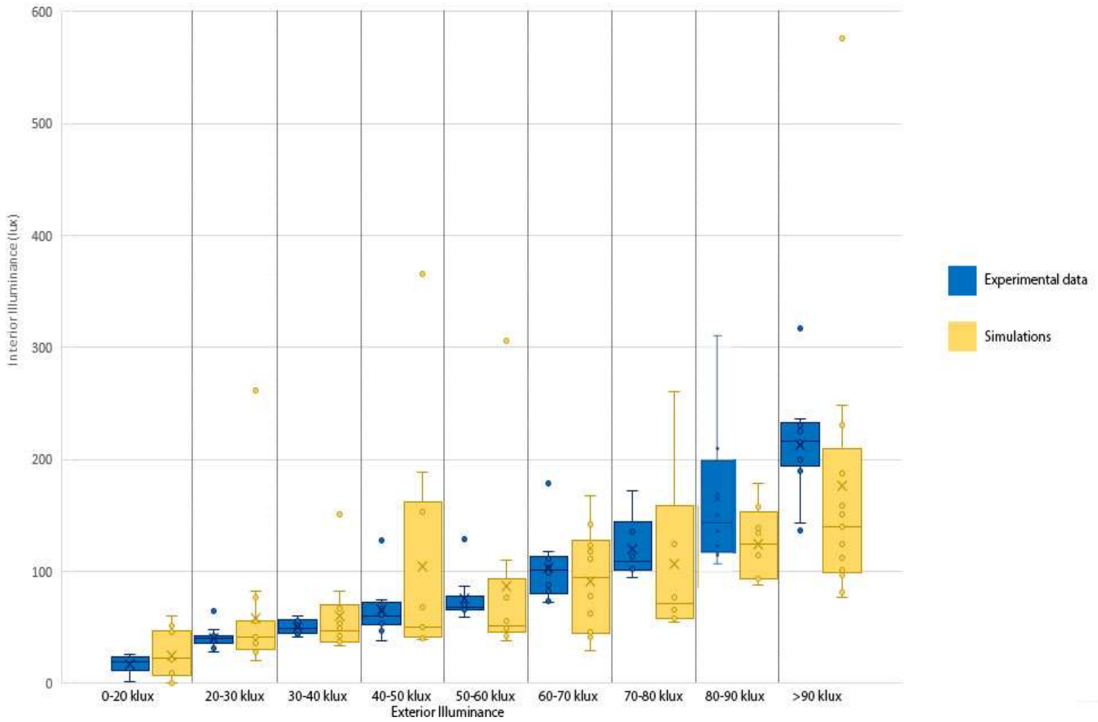


Figure 60. Boxplot of the average interior illuminance in the test cell, with data from the experiment and from simulations for exterior illuminance groups.

6.3 Comparison of experimental data to the mathematical algorithms for performance prediction

In Chapter 3: of this Thesis, some of the main light pipe performance prediction methods developed by scientific teams in the past were described and applied and equations for easier application were developed. Here, the experimental data are compared to the previously described performance prediction methods, to discover which methodology/ies provide comparable results.

The prediction methods that are compared to the experiment are the TTE method, the Luxplot method, the data provided by modelling the light pipe as a luminaire and simulating the indoor illuminance, as well as simulations with forward ray tracing methods. For simplicity, the equations used for the comparison are not the original ones, but the equations derived from the testing for various room and light pipe characteristics. The equations used are eq. (21), (23), (25), (39) and (41) (Chapter 3:) for the TTE, the Luxplot method and the simulations of the light pipe as a luminaire, respectively. The data from the forward ray tracing simulations are the average of the 13 points representing the sensors in the test cell. The size of the test cell and the exterior illuminance as recorded during the experiment were used, while the TTE for the experimental lighting system was 0.85 (calculated using Table 6 equations).

Figure 61 includes the indoor illuminance calculated with the four performance prediction methods for the whole range of exterior illuminance levels, as well as the experimental data. As expected, the TTE method gives results that overestimate the experimentally acquired indoor illuminances considerably. The methods that more precisely describe the experimental data are the simulations. The equations developed in Chapter 3: using the Luxplot method provide comparable error with the simulations. This fact provides adequate evidence that eq. (21), (23), (25), (39) and (41) can be used to acquire fast results on the prediction of performances of light pipes installed in Greek buildings.

The average error was 56% for the Luxplot method, 53% for the TTE method, 35% for simulating the light pipe as a luminaire, 40% for simulations the forward ray tracing technique and 9-36% for the equations developed using the experimental data. The average percentage of error does not change significantly in relation to the exterior illuminance values (Table 26).

The differences between the prediction methods and the experimental illuminance values are due to several reasons. All theoretical methods are semi-empirical, developed using data collected in Northern Europe (UK and possibly Italy). Even though the range of exterior illuminances may have been comparable with those of the present experiment, the solar radiation parameters might be considerably different. Another source of error is the assumptions made when eq. (21), (23), (25), (39) and (41) were formed. These are very general equations that enable quick performance prediction but do not necessarily guarantee high precision under all sky conditions.

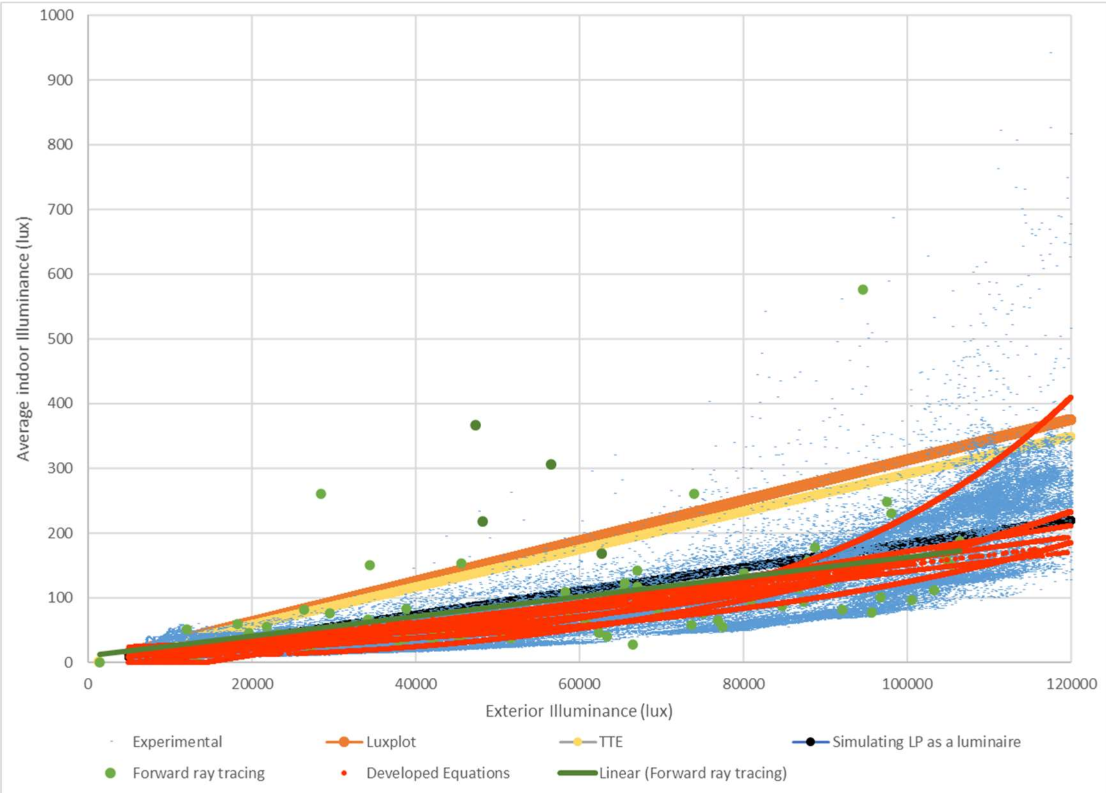


Figure 61. Average indoor illuminance as a function of the exterior illuminance

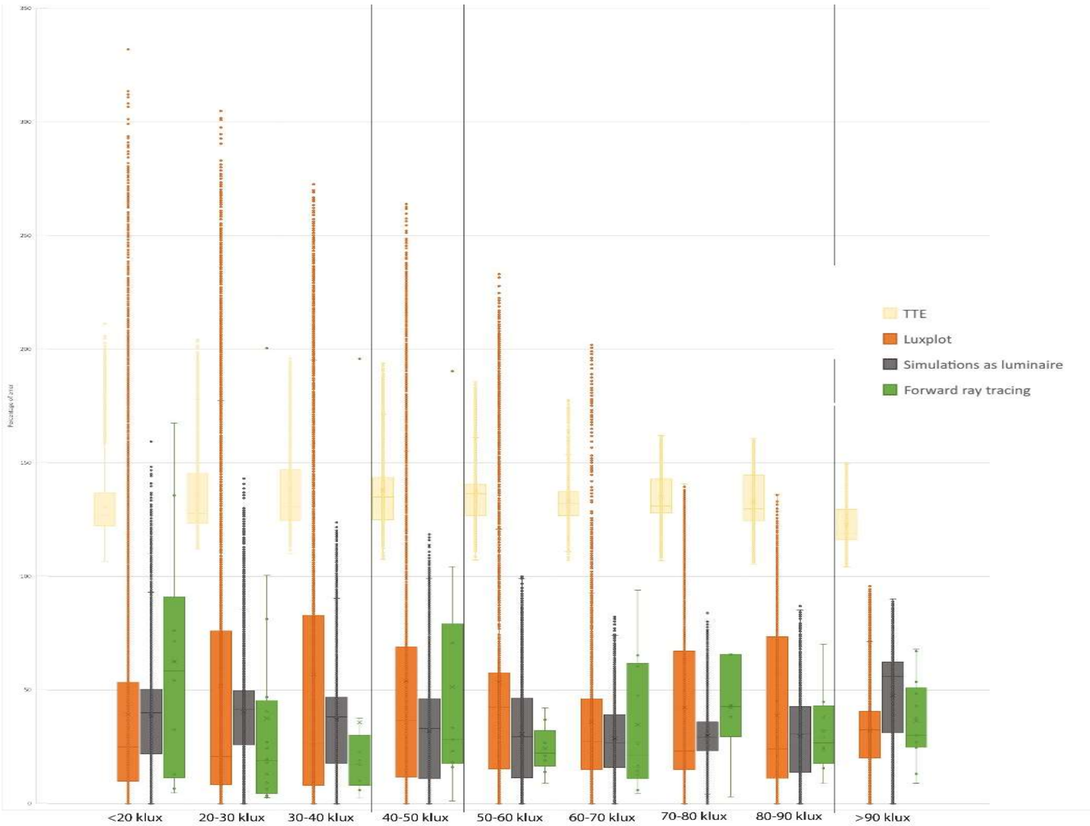


Figure 62. Boxplot of the percentage of error of the performance prediction methodologies (TTE, Luxplot, simulating the light pipe as a luminaire of cosine luminous distribution and simulations with forward raytracing) for exterior illuminance groups.

Table 26. Average percentage of error for different exterior illuminance groups

Exterior Illuminance (klux)	Average percentage of error (%)			
	TTE	Luxplot	Simulating LP as luminaire	Forward ray tracing
<20	130.60	39.37	38.58	62.49
20-30	136.22	51.86	40.33	37.54
30-40	138.55	57	37.00	35.81
40-50	137.88	54.10	31.93	51.39
50-60	137.67	39.38	38.59	37.49
60-70	133.02	35.95	28.76	34.80
70-80	134.96	42.41	30.01	43.13
80-90	133	38.83	29.76	31.91
>90	122.73	32.38	47.60	36.52

6.1 Conclusions

The comparison of the interior illuminance values calculated using the equations developed and described in Chapter 3 with the respective experimental data showed that the equations for the TTE method give results that are considerably different than the experimental data. On the other hand, the equations developed from the Luxplot method and the simulations emulating the light pipe as a luminaire of cosine luminous intensity, as well as the forward ray tracing simulations, provide comparable results with an error between 38 and 43%. The error for each methodology does not change significantly based on the exterior illumination.

Chapter 7: Electric lighting and controls

7.1 Synopsis

As described earlier in this Thesis, the experiment for the study of the performance of the lighting system which consists of a light pipe, LEDs and daylight linked controls, was designed, and set up to record the lighting due to both the natural and artificial lighting sources. A device was designed and constructed to host the lamps and the related equipment and sensors were installed to record energy consumption.

Unfortunately, due to technical issues that could not be predicted or overcome, the lighting provided by the LEDs or the combination of natural and artificial lighting could not be recorded. To perform the energy efficiency analysis, four methodological tasks, including different artificial lighting systems and/or required lighting levels were studied. The four tasks that were investigated aimed to provide methodologies for the calculation of the:

- Lighting power used to achieve minimum illuminances of 100, 200 and 300 lux using the experimental lighting system,
- Lighting power used to achieve average illuminances of 100, 200 and 300 lux using the experimental lighting system,
- Lighting power used to achieve minimum illuminances of 100, 200, 300 and 400 lux from an “office lighting system”,
- Lighting power used to achieve minimum illuminance of 300 lux from an “office lighting system” with luminaire dimming groups.

The office lighting system mentioned above includes LED luminaires commonly used in working environments, installed in an ortho-canonical grid, to achieve ambient lighting and uniformity levels recommended by European Standards. The procedure included simulations of the artificial lighting levels of the proposed systems in lighting software and utilisation of the experimental data to link the power used to achieve a desired interior illuminance with the environmental parameters during the experimental period. The results are case-specific; however, they showcase methodologies that can be applied in similar cases.

7.2 Energy consumption for lighting

Light pipes are lighting systems used to increase the levels of natural light in deep or windowless interior spaces, to provide time cues to the users and to reduce energy use for artificial lighting. The amount of energy savings depends on application, i.e., the characteristics of the space and of the light pipe, the geographic location and the artificial lighting system used. The artificial lighting system comprises the lamps and/or luminaires and the auxiliary equipment, as well as the lamps’ controls. The controls include sensors that measure natural lighting levels and dimmers that enable the provision of the supplementary artificial lighting, to achieve the required average or minimum illuminance on the reference plane.

There are not many studies that have attempted to estimate the energy savings from the use of light pipes. Canziani et al. (Canziani, Peron and Rossi, 2004) studied the performance of a horizontal system, with a glazing unit on one of the building’s facades and a reflective chamber. The energy savings that were recorded were on average 20% for artificial lighting using fluorescent lamps. However, this system cannot be compared to more conventional light pipes, where the position of the “light capturing” element is on the roof and not on a side exterior wall. Gorgulu and Ekren (Görgülü and Ekren, 2013) tested a system consisting of a light pipe and luminaires dimmed by fuzzy logic controllers. Even though the data recordings took place during autumn and winter months and the fact that other performance impeding factors were present, the authors describe a significant energy saving potential.

Estimating energy consumption for artificial lighting when light pipes are present is a difficult task, as natural light is constantly changing. For that estimation, it is assumed that when the minimum illuminance from daylight on the reference plane is 0 lux, the artificial lighting will provide all the necessary lighting and the energy used will be equal to the installed power times the time for which the system is used under these conditions. On the contrary, when the natural light coming from the light pipe provides the desired minimum value (i.e., 100, 200 or 300 lux), the electric lights will be switched off and no energy will be consumed. When only part of the necessary lighting levels is achieved by daylight, the remaining light should be provided by artificial lighting. The control system will dim the lamps to an appropriate level, so that the sum of natural and artificial lighting provides the required levels. However, the percentage of dimming or light output of the LEDs do not necessarily lead to an equal percentage of energy savings or consumption, respectively.

To estimate the relation between dimming levels and energy consumption Doulos et al. (2017) performed an experimental investigation of the relationship between light output and relative consumed power versus control signal and relative consumed power versus light output of LEDs and T5 fluorescent luminaires commonly used in office environments with daylight linked systems. The derived functions between the percentage of light output (κ, 0–1) and used power (λ, 0–1) using polynomial interpolation are given in Table 27. The range of used power of the four LED luminaires for a light output of 0-100% in 10% intervals, as derived by the functions in Table 27, is shown in Figure 63. The difference of the used power between the studied luminaires varies between 4.80% and 9.07% for the various light output levels, excluding the consumed power range for 0% light output. The difference between the various LED luminaires lies to the different dimming systems.

Table 27. Functions providing the used power (λ, 0-1) as a function of the light output (κ, 0-1) of four LED luminaires. Source: (Doulos *et al.*, 2017)

Light source	Derived functions	
A LED	$\lambda_1 = -0.257\,\kappa 4 + 0.658\,\kappa 3 - 0.357\,\kappa 2 + 0.914\kappa + 0.041$	(49)
B LED	$\lambda_2 = -0.335\,\kappa 4 + 0.836\,\kappa 3 - 0.542\,\kappa 2 + 0.968\kappa + 0.072$	(50)
C LED	$\lambda_3 = 0.733\,\kappa 4 - 1.065\,\kappa 3 + 0.519\,\kappa 2 + 0.742\kappa + 0.068$	(51)
D LED	$\lambda_4 = -0.949\,\kappa 4 + 2.467\,\kappa 3 - 2.205\,\kappa 2 + 1.650\kappa + 0.034$	(52)

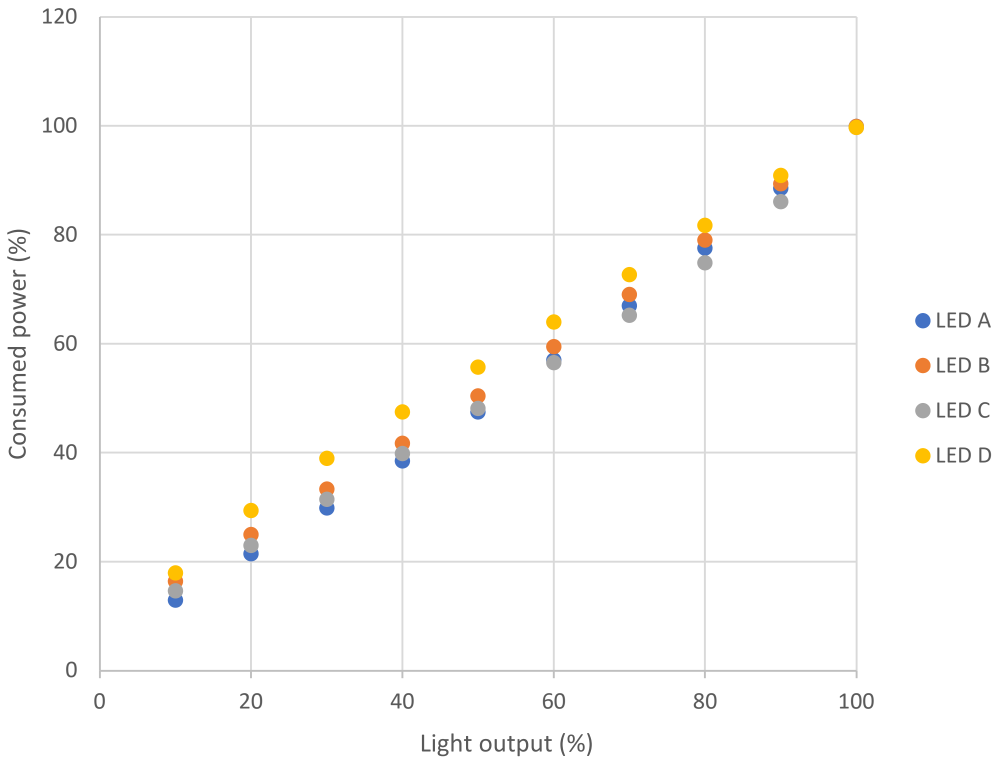


Figure 63. Used power for four LED luminaires for light output from 10-100% in 10% intervals, as provided by the functions in Table 27

The aim of this chapter is to develop a methodology with which to calculate how much energy for artificial lighting can be saved from the use of light pipes and daylight linked controls. To develop this methodology, four sub-tasks have been carried out, using the natural lighting data collected during the experiment and linking the required lighting levels and the used power with environmental parameters. These sub-tasks are described in the following paragraphs.

7.2.1 Lighting power used to achieve minimum illuminances of 100, 200 and 300 lux using the experimental lighting system

The first task of the methodology aims to provide an estimate of the power used for achieving a minimum of 100, 200 and 300 lux of illuminance on the reference plane. The steps that were followed for the estimation, are:

1. Selecting lamps: The lamps that were used for the calculations were the same in size (MR16 lamp size) with the ones installed in the experimental prototype. The wattage and the positioning of the lamps were set after performing simulations of the artificial lighting levels, without natural light, in the software DIVA for Rhino. The goal was to achieve 300 lux on the edges of the reference plane. The simulations showed that using this type of lamps, 300 lux could not be achieved at the edges of a reference plane with the same size of the experimental reference plane. Thus, the area of the reference plane was reduced, and the lighting levels were simulated in a space of dimensions 1.905 x 1.860 m. This space includes sensors 4-10 as shown in Figure 64 and has all the characteristics of the experimental layout (distance between ceiling

and reference plane=1.61m, interior surfaces of black matte fabric with reflectance of approximately 7%, etc).

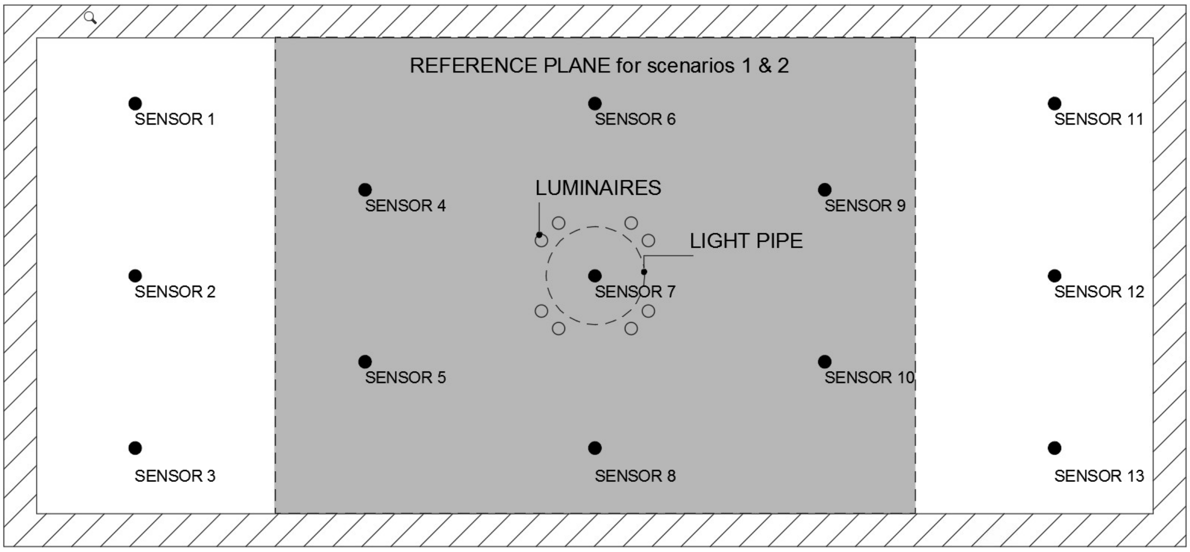


Figure 64. Positions of luminaires and reference plane for tasks 1 and 2

Table 28. Characteristics of the lamps used in the DIVA model (Source: Zumtobel)

Colour Code	4000 Kelvin	**Power**	11 W
Beam Angle (Nom)	30º	**Standby Power**	0.2 W
Luminous Flux (Nom)	800 lm	**Dimming**	LDO dimmable to 1% over DALI
Luminous Efficacy (rated) (Nom)	73 lm/W	**Article No**	Zumtobel 60818958

Eight lamps were arranged around the light pipe diffuser, as shown in Figure 64. The LED lamp characteristics are provided in Table 28. With the use of the specific lamps, a minimum illuminance of approximately 370 lux on the edges of the 1.905 m x 1.860 m space is achieved, while the average illuminance on the reference plane is 2,024.73 lux.

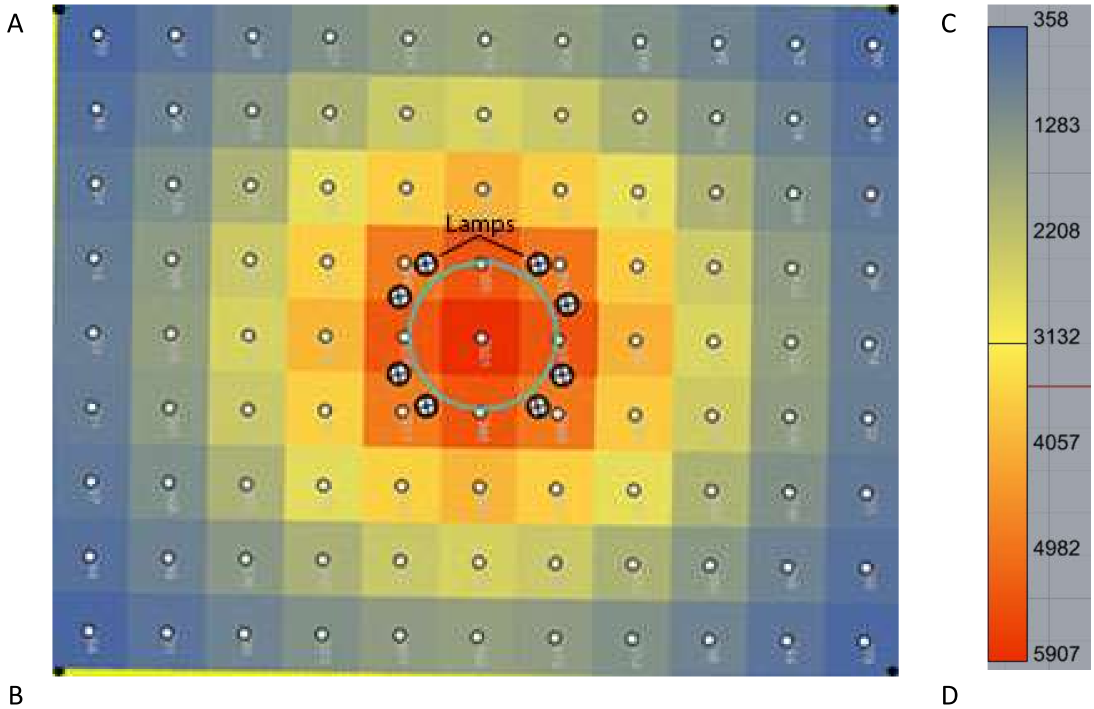


Figure 65. Illuminance distribution of artificial lighting for tasks 1 & 2. Eav=2,024.73 lux

2. Finding the minimum illuminance from daylight: The minimum illuminance from the daylight entering the space through the light pipe needed to be calculated. Sensors 4, 5, 9 and 10, which are the sensors further away from the projection of the light pipe on the reference plane, are not positioned at the edges of the reference plane, where the minimum illuminance was assumed to be. The illuminance at points A, B, C and D (Figure 65), i.e., the corners of the reference plane, was calculated using linear interpolation. As expected, in most of the cases, the minimum illuminance from the light pipe was recorded at one of these corner points, with a few only exceptions were all the sensors recordings were close to 0. For simplicity, the minimum illuminance on the reference plane was the minimum value of the illuminance at points A, B, C and D.
3. Calculating the required illuminance from the lamps: If the minimum illuminance from the incoming natural light on the reference plane of the space is E_{pm} and the required minimum illuminance on the reference plane is E_{min}, it is assumed that the illuminance required from the LEDs, E_{LED}, will be:

$$E_{LED}= E_{min}- E_{pm} \quad (53)$$

where for task 1, E_{min} is equal to 300, 200 or 100 lux.

4. Calculation of the relative LED light output (κ) required: The E_{LED} calculated by (**53**) can be expressed as a ratio or percentage of the maximum LED light output at the corners of the reference plane.

$$\kappa=\frac{E_{LED}}{370} \quad (54)$$

5. Calculation of the relative used LED power (λ): The relations proposed by Doulos et. al. (eq. (49(52) are employed to calculate the percentage of the total installed power that is used. The percentage of the used power for each E_{pm} is taken to be the

average of the four percentage values (λ_1-λ_4) resulting from the application of eq. ((49(52).

6. Calculation of the actual used LED power (P): The percentage of the used power (λ) multiplied by the total LED wattage, which in this task is 88 W (8 lamps of 11 W each) provides the actual used power (P). The additional wattage of the auxiliary equipment is not considered for this calculation.
7. Development of relations providing the used power (P) for the whole experimental period: In order to develop relations for the used power corresponding to each minimum required illuminance, regression analysis is carried out between the power to achieve the minimum required illuminance of 100, 200 and 300 lux on the reference plane of the 1.905 m x 1.860 m space and the independent parameters: the exterior illuminance (E_{ex}), the sun altitude (α) and azimuth (γ) and the sky diffuse coefficient (K_d). Table 29 includes the three relations providing the used power for each of the minimum required illuminances, using all the data acquired from the experiment.

Table 29. Equations providing the power of the artificial lighting system used as a function of the exterior illuminance, the position of the sun and the sky diffuse coefficient

Minimum required Illuminance (E_{min})	Relations giving power P		R-Squared
300 lux	$P= -0.0002\ E_{ex} - 0.193\ \alpha - 0.012\ \gamma - 0.899\ K_d + 76.77$	(55)	0.85
200 lux	$P= -0.00004\ E_{ex} - 0.037\ \alpha - 0.003\ \gamma - 0.198\ K_d + 15.03$	(56)	0.87
100 lux	$P= -0.00003\ E_{ex} - 0.020\ \alpha - 0.002\ \gamma + 0.049\ K_d + 9.66$	(57)	0.92

In the above eq. (55(57), P is the power used by the system (W), E_{ex} is the exterior illuminance (lux), α is the Solar Altitude angle (°), γ is the Solar Azimuth angle (°) and K_d is the sky diffuse coefficient.

8. Assessment of the impact of the independent variables on power: To investigate the strength of the effect of each independent variable (E_{ex}, α, γ and K_d) on the dependent variable (P), their beta coefficients were calculated. Beta coefficients are calculated as the product of the regression coefficients included in eq. (55(57), multiplied by the ratio of the standard deviation of the independent variables to the standard deviation of the power.

Table 30 includes the beta coefficients of each of the independent variables. It is evident that the exterior illuminance (E_{ex}) has the strongest effect on the power, followed by the sun altitude and the sun azimuth. The variable that seems to play the least important role is the sky diffuse coefficient. The reason why K_d is much less important than the other independent variables is not evident. However, this is mainly attributed to the high variability of the sky diffuse coefficient for an exterior illuminance value, under different environmental conditions (Figure 66). Unlike the monotone and increasing relationship between the exterior illuminance and the interior illuminance from the light pipe, where an increase of the exterior illuminance results in an increase in the interior illuminance, the association between K_d and the interior illuminance is fuzzy and not determined by a specific trend.

Table 30. Beta coefficients of each of the independent variables of (55(57)

Minimum required Illuminance	b-Coefficients of exterior Illuminance (E_{ex})	b-Coefficients of Altitude (α)	b-Coefficients of Azimuth (γ)	b-Coefficients of Sky Diffuse Coefficient (K_d)
300 lux	-0.67	-0.31	-0.06	-0.02
200 lux	-0.68	-0.31	-0.07	-0.02
100 lux	-0.75	-0.24	-0.09	0.01

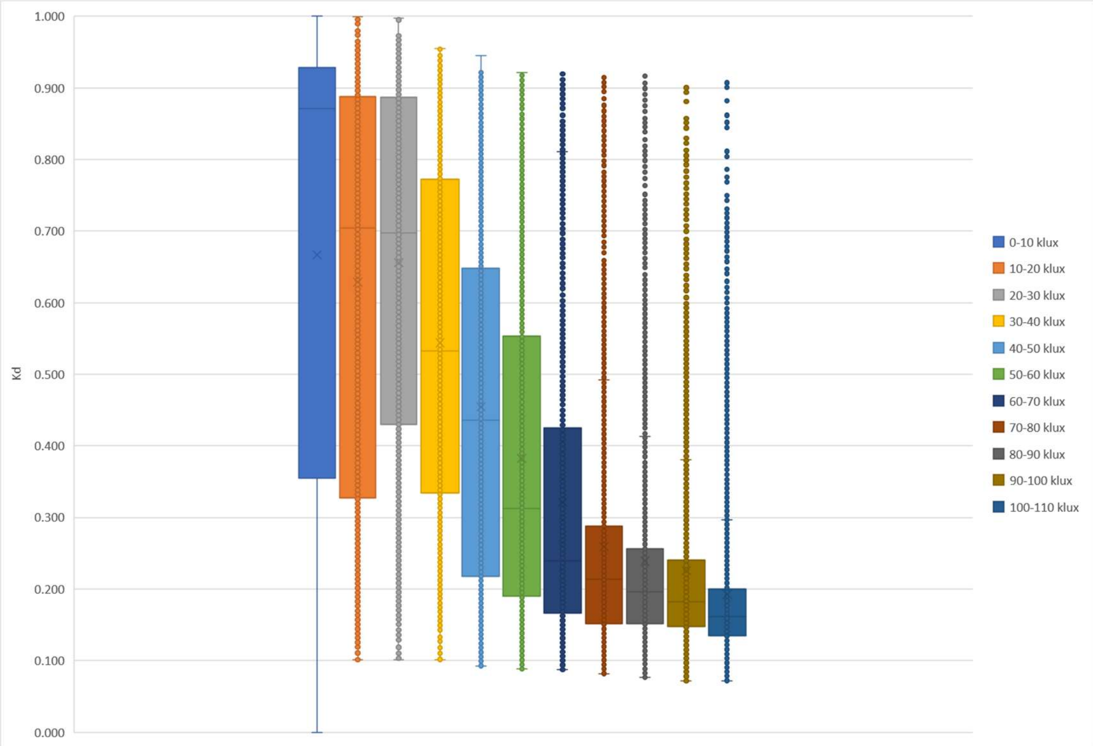


Figure 66. Boxplot of the sky diffuse coefficient (K_d) for groups of the exterior illuminance values

Given the low significance of K_d in the used power calculation, the equations in Table 31 which exclude K_d were developed and recommended for use. R-squares of eq. (58 -(60) are equal to those of eq. (55(57).

Table 31. Equations providing the power of the artificial lighting system used as a function of the exterior illuminance, and the position of the sun

Minimum required Illuminance (E_{min})	Relation giving power P		R-Squared
300 lux	$P= -0.0002\ E_{ex} - 0.195\ \alpha - 0.012\ \gamma + 76.14$	(58)	0.85
200 lux	$P= -0.00004\ E_{ex} - 0.038\ \alpha - 0.003\ \gamma + 14.89$	(59)	0.87
100 lux	$P= -0.00003\ E_{ex} - 0.020\ \alpha - 0.002\ \gamma + 9.70$	(60)	0.92

9. Development of relations providing the used power (P) for each month of the experimental period: The same analysis was repeated for each of the months when experimental measurements were carried out. The equations for each month are given in Table 32, while the beta-coefficients for the independent variables (E_{ex}, α, γ, K_d) are provided in Table 33. Functions for the months November and August have

not been developed, due to the limited amount of data (from 28th to 30th of November -1,319 observations, and from 1st to 7th of August - 3,455 observations).

The beta-coefficients for the independent variables of the monthly equations present the same effect on the power, as those for the generalised equations. The exterior illuminance has the strongest effect, while the sky diffuse coefficient the weakest effect on the used power of the artificial lighting. However, the beta-coefficients of E_{ex} decrease significantly for the equations of the months April-July.

The frequency histograms developed for each month show that even though the frequency of the low exterior illuminance values is high, and the range of recorded exterior illuminance values is low for the months December, February, and March, from April, the frequency of high illuminances increases, while the range of exterior illuminance values increases as well. This shows that the frequency of the exterior illuminance values has a great impact on the energy, but the desired interior illuminance levels set are also important. The dependence of the power on exterior illuminance increases during the "bright" months of the year for low interior illuminance levels, as the artificial lighting system is more often turned off. The frequency histograms for the exterior illuminance (Eex), the sun altitude (α), the sun azimuth (γ) and the sky diffuse coefficient (K_d) are provided in Appendix VIII.

Table 32. Equations providing the power of the artificial lighting system used as a function of the exterior illuminance, the position of the sun and the sky diffuse coefficient, for each month of experimental observations

	Month	Relations giving power P		R-Squared
Minimum required Illuminance = 300 lux	Dec	$P= -0.0001\ E_{ex} - 0.115\ \alpha - 0.010\ \gamma + 0.376\ K_d + 71.62$	(61)	0.85
	Feb	$P= -0.0002\ E_{ex} - 0.051\ \alpha - 0.017\ \gamma - 0.792\ K_d + 73.07$	(62)	0.91
	Mar	$P= -0.0002\ E_{ex} - 0.079\ \alpha - 0.004\ \gamma - 2.388\ K_d + 73.75$	(63)	0.92
	Apr	$P= -0.0003\ E_{ex} - 0.332\ \alpha - 0.010\ \gamma - 4.456\ K_d + 85.26$	(64)	0.69
	May	$P= -0.0002\ E_{ex} - 0.265\ \alpha - 0.004\ \gamma + 1.860\ K_d + 78.24$	(65)	0.82
	Jun	$P= -0.0002\ E_{ex} - 0.204\ \alpha - 0.008\ \gamma - 2.105\ K_d + 79.67$	(66)	0.81
	Jul	$P= -0.0001\ E_{ex} - 0.517\ \alpha + 0.007\ \gamma - 1.778\ K_d + 81.59$	(67)	0.81
Minimum required Illuminance = 200 lux	Dec	$P= -0.00002\ E_{ex} - 0.020\ \alpha - 0.002\ \gamma + 0.067\ K_d + 13.85$	(68)	0.85
	Feb	$P= -0.00004\ E_{ex} - 0.008\ \alpha - 0.003\ \gamma - 0.180\ K_d + 14.18$	(69)	0.91
	Mar	$P= -0.00004\ E_{ex} - 0.014\ \alpha - 0.0007\ \gamma - 0.488\ K_d + 14.34$	(70)	0.91
	Apr	$P= -0.00005\ E_{ex} - 0.059\ \alpha - 0.002\ \gamma - 0.576\ K_d + 16.17$	(71)	0.80
	May	$P= -0.00004\ E_{ex} - 0.053\ \alpha - 0.001\ \gamma + 0.316\ K_d + 15.46$	(72)	0.83
	Jun	$P= -0.00005\ E_{ex} - 0.040\ \alpha - 0.002\ \gamma - 0.549\ K_d + 15.78$	(73)	0.82
	Jul	$P= -0.00002\ E_{ex} - 0.102\ \alpha + 0.0005\ \gamma - 0.662\ K_d + 16.19$	(74)	0.85
Minimum required Illuminance = 100 lux	Dec	$P= -0.00003\ E_{ex} - 0.021\ \alpha - 0.002\ \gamma + 0.068\ K_d + 9.58$	(75)	0.87
	Feb	$P= -0.00004\ E_{ex} - 0.009\ \alpha - 0.003\ \gamma - 0.165\ K_d + 9.91$	(76)	0.91
	Mar	$P= -0.00004\ E_{ex} - 0.013\ \alpha - 0.001\ \gamma - 0.351\ K_d + 9.88$	(77)	0.93
	Apr	$P= -0.00003\ E_{ex} - 0.030\ \alpha - 0.003\ \gamma - 0.044\ K_d + 9.79$	(78)	0.85
	May	$P= -0.00003\ E_{ex} - 0.013\ \alpha - 0.003\ \gamma + 0.071\ K_d + 9.30$	(79)	0.86
	Jun	$P= -0.00003\ E_{ex} - 0.019\ \alpha - 0.002\ \gamma - 0.077\ K_d + 9.51$	(80)	0.85
	Jul	$P= -0.00002\ E_{ex} - 0.028\ \alpha - 0.003\ \gamma + 0.416 K_d + 9.30$	(81)	0.88

Table 33. Beta coefficients of each of the independent variables of Eq. (61(81)

	Month	Eex	α	γ	Kd
b-coefficient for minimum E_{int}=300 lux	Dec	-0.69	-0.27	-0.10	0.04
	Feb	-0.88	-0.11	-0.13	-0.04
	Mar	-0.92	-0.14	-0.03	-0.09
	Apr	-0.57	-0.37	-0.04	-0.08
	May	-0.63	-0.36	-0.02	0.04
	Jun	-0.74	-0.31	-0.05	-0.04
	Jul	-0.25	-0.71	0.04	-0.01
b-coefficient for minimum E_{int}=200 lux	Dec	-0.41	-0.16	-0.06	0.02
	Feb	-0.53	-0.05	-0.08	-0.03
	Mar	-0.58	-0.08	-0.01	-0.06
	Apr	-0.51	-0.32	-0.05	-0.05
	May	-0.50	-0.29	-0.02	0.02
	Jun	-0.57	-0.39	-0.06	-0.04
	Jul	-0.22	-0.60	0.01	-0.02
b-coefficient for minimum E_{int}=100 lux	Dec	-0.41	-0.16	-0.06	0.02
	Feb	-0.63	-0.07	-0.10	-0.03
	Mar	-0.79	-0.12	-0.04	-0.07
	Apr	-0.79	-0.43	-0.16	-0.01
	May	-0.91	-0.17	-0.18	0.01
	Jun	-0.92	-0.44	-0.15	-0.01
	Jul	-0.62	-0.46	-0.22	0.04

This paragraph provided a methodology for the calculation of the used artificial lighting power, for the whole experimental period and for each month of this period, for the following conditions:

- The space has dimensions 1.905 x 1.860 m and has black matte interior surfaces;
- A light pipe of diameter 0.30m and length 2.60 m is installed in the middle of the space;
- The height between the light pipe diffuser and the reference plane is 1.61m;
- The artificial lighting system consists 8 LED lamps of 11 W each (Table 28), which are positioned around the diffuser, as depicted in Figure 65;
- The lamps are dimmed by daylight linked controls;
- The desired minimum illuminance by both natural and artificial lighting is 100, 200 or 300 lux;
- The calculations are valid for the climatic conditions of Athens, Greece.

The R-squared ranges between 0.83 and 0.91 for the functions developed from all the experimental data, while the R-squared for the equations developed from the data of each month of the experimental period ranged between 0.85 and 0.92. By calculating the beta-coefficients for each of the independent variables, it is evident that the exterior illuminance is the independent variable that has the most significant impact on the power used, followed by the sun altitude, while the sky diffuse coefficient is usually the least important parameter.

7.2.2 Lighting power used to achieve average illuminances of 100, 200 and 300 lux using the experimental lighting system

The second task aims to provide an estimate of the power used for achieving an average of 100, 200 and 300 lux of illuminance on the reference plane. The steps that were followed for the estimation are:

1. Selecting lamps: The lamps, their layout, and the reference plane in task 2 are the same as in task 1. The reference plane has dimensions 1.905 x 1.860 m, and the lamp characteristics and layout are provided in Table 28 and Figure 65, respectively.
2. Finding the average illuminance from daylight: The average illuminance from the daylight entering the space through the light pipe was calculated by the values of sensors 4-10. The illuminance at points A, B, C and D (Figure 65), i.e., the corners of the reference plane, was calculated using linear interpolation and the values were also included in the calculation.
3. Calculating the required illuminance from the lamps: If the average illuminance from the incoming natural light on the reference plane of the space is E_{pav} and the required minimum illuminance on the reference plane is E_{av}, it is assumed that the illuminance required from the LEDs, E_{LED}, will be:

$$E_{LED}= E_{av}- E_{pav} \tag{82}$$

Where for task 2 E_{av} is equal to 300, 200 or 100 lux.

4. Calculation of the relative LED light output (κ) required: The E_{LED} calculated by Eq. 33 can be expressed as a ratio or percentage of the total LED light output on the reference plane, which provides an average illuminance of 2,025 lux on the reference plane.

$$\kappa=\frac{E_{LED}}{2025} \tag{83}$$

5. Calculation of the percentage of the used LED power (λ): The relations proposed by Doulos et. al. (eq. (49(52) are employed to calculate the percentage of the total installed power that is used. The percentage of the used power for each value of E_{pav} (300, 200, 100 lux) is taken to be the average of the four percentage values (λ1-λ4) resulting from the application of eq. (49(52).
6. Calculation of the actual used LED power (P): The percentage of the used power (λ) multiplied by the total LED wattage, which in this task is 88 W (8 lamps of 11 W each) provides the actual used power (P). The additional wattage of the auxiliary equipment is not considered for this calculation.

Development of relations providing the used power (P) for the whole experimental period: To develop relations for the used power, regression analysis is carried out between the power to achieve the average required illuminance of 100, 200 and 300 lux on the reference plane of the 1.905 m x 1.860 m space and the independent parameters: the exterior illuminance (E_{ex}), the sun altitude (α) and azimuth (γ) and the sky diffuse coefficient (K_d).

7. Table 34 includes the three relations providing the power used for each of the average required illuminances, using all the data acquired from the experiment.

Table 34. Equations providing the power of the artificial lighting system used as a function of the exterior illuminance, the position of the sun and the sky diffuse coefficient

Average required Illuminance (Eav)	Relations giving power P		R-Squared
300 lux	$P= -0.00007\ E_{ex} - 0.072\ \alpha - 0.005\ \gamma - 0.659\ K_d + 20.79$	(84)	0.82
200 lux	$P= -0.00006\ E_{ex} - 0.045\ \alpha - 0.005\ \gamma - 0.504\ K_d + 15.43$	(85)	0.90
100 lux	$P= -0.00003\ E_{ex} - 0.017\ \alpha - 0.003\ \gamma - 0.009\ K_d + 8.88$	(86)	0.81

In the above relations (Eq. (84(86), P is the power used by the system (W), E_{ex} is the exterior illuminance (lux), α is the Solar Altitude angle (°), γ is the Solar Azimuth angle (°) and K_d is the sky diffuse coefficient.

8. Assessment of the impact of the independent variables on power: As in task 1, the beta-coefficients of each independent variable (E_{ex}, α, γ and K_d) have been calculated to explore their effect on the dependent variable (P). Beta-coefficients are calculated as the product of the regression coefficients included in (Eq. (84(86), multiplied by the ratio of the standard deviation of the independent variables to the standard deviation of the power.

   Table 35 includes the beta-coefficients of each of the independent variables. As in task 1, the exterior illuminance (E_{ex}) has the strongest effect on the power, followed by the sun altitude and the sun azimuth, while the least important parameter is the sky diffuse coefficient. The reason why K_d is much less important than the other independent variables is not evident. Table 36 provides the equations for calculating the used power for artificial lighting for task 2, without including the sky diffuse coefficient. The R squared is the same as in the equations including K_d, which also validates its low importance.

Table 35. Beta coefficients of each of the independent variables of Eq. ((84(86)

Average required Illuminance	b-Coefficients of exterior illuminance (E_{ex})	b-Coefficients of Altitude (α)	b-Coefficients of Azimuth (γ)	b-Coefficients of sky diffuse coefficient (K_d)
300 lux	-0.63	-0.35	-0.07	-0.05
200 lux	-0.72	-0.29	-0.10	-0.05
100 lux	-0.70	-0.22	-0.13	0.00

Table 36. Equations providing the power of the artificial lighting system used as a function of the exterior illuminance, and the position of the sun

Average required Illuminance (E_{av})	Relation giving power P		R-Squared
300 lux	$P= -0.00006\ E_{ex} - 0.074\ \alpha - 0.005\ \gamma + 20.33$	(87)	0.82
200 lux	$P= -0.00005\ E_{ex} - 0.046\ \alpha - 0.005\ \gamma + 15.08$	(88)	0.90
100 lux	$P= -0.00003\ E_{ex} - 0.017\ \alpha - 0.003\ \gamma + 8.88$	(89)	0.81

9. Development of relations providing the used power (P) for each month of the experimental period: The same analysis was repeated for each of the months when experimental measurements were carried out. The equations for each month are given in Table 37, while the beta-coefficients for the independent variables (E_{ex}, α, γ, K_d) are provided in Table 38. Functions for the months November and August have not been developed, due to the limited amount of data.

Table 37. Equations providing the power of the artificial lighting system used as a function of the exterior illuminance, the position of the sun and the sky diffuse coefficient, for each month of experimental observations

	Month	Relations giving power P		R-Squared
Average required Illuminance = 300 lux	Dec	$P= -0.00004\ E_{ex} - 0.035\ \alpha - 0.003\ \gamma - 0.020\ K_d + 18.28$	(90)	0.83
	Feb	$P= -0.00006\ E_{ex} - 0.018\ \alpha - 0.006\ \gamma - 0.486 K_d + 18.90$	(91)	0.89
	Mar	$P= -0.00007\ E_{ex} - 0.029\ \alpha - 0.001\ \gamma - 0.922\ K_d + 19.07$	(92)	0.90
	Apr	$P= -0.\ 00007\ E_{ex} - 0.\ 121\ \alpha - 0.002\ \gamma - 1.088\ K_d + 22.55$	(93)	0.81
	May	$P= -0.00006\ E_{ex} - 0.131\ \alpha + 0.001\ \gamma + 1.588\ K_d + 22.15$	(94)	0.81
	Jun	$P= -0.00008\ E_{ex} - 0.101\ \alpha - 0.000003\ \gamma - 0.715\ K_d + 23.05$	(95)	0.80
	Jul	$P= -0.00002\ E_{ex} - 0.224\ \alpha + 0.005\ \gamma - 1.388\ K_d + 23.84$	(96)	0.87
Average required Illuminance = 200 lux	Dec	$P= -0.00004\ E_{ex} - 0.037\ \alpha - 0.004\ \gamma - 0.024\ K_d + 14.22$	(97)	0.85
	Feb	$P= -0.00006\ E_{ex} - 0.019\ \alpha - 0.006\ \gamma - 0.510\ K_d + 14.88$	(98)	0.89
	Mar	$P= -0.00007\ E_{ex} - 0.028\ \alpha - 0.002\ \gamma - 0.902\ K_d + 14.92$	(99)	0.92
	Apr	$P= -0.00005\ E_{ex} - 0.082\ \alpha - 0.004\ \gamma -0.684\ K_d + 16.16$	(100)	0.86
	May	$P= -0.00005\ E_{ex} - 0.067\ \alpha - 0.003\ \gamma + 0.518\ K_d + 15.84$	(101)	0.88
	Jun	$P= -0.00006\ E_{ex} - 0.063\ \alpha - 0.002\ \gamma - 0.563\ K_d + 16.41$	(102)	0.85
	Jul	$P= -0.00003\ E_{ex} - 0.116\ \alpha - 0.002\ \gamma - 0.553\ K_d + 16.49$	(103)	0.91
Average required Illuminance = 100 lux	Dec	$P= -0.00004\ E_{ex} - 0.039\ \alpha - 0.004\ \gamma - 0.024\ K_d + 9.97$	(104)	0.86
	Feb	$P= -0.00004\ E_{ex} - 0.033\ \alpha - 0.004\ \gamma - 0.034\ K_d + 9.84$	(105)	0.86
	Mar	$P= -0.00004\ E_{ex} - 0.028\ \alpha - 0.003\ \gamma - 0.266\ K_d + 9.55$	(106)	0.81
	Apr	$P= -0.00002\ E_{ex} - 0.028\ \alpha - 0.003\ \gamma - 0.158\ K_d + 8.35$	(107)	0.69
	May	$P= -0.00003\ E_{ex} - 0.004\alpha - 0.004\ \gamma - 0.064\ K_d + 8.27$	(108)	0.76
	Jun	$P= -0.00002\ E_{ex} - 0.018\ \alpha - 0.002\ \gamma +0.230\ K_d + 8.32$	(109)	0.74
	Jul	$P= -0.00002\ E_{ex} - 0.013\ \alpha - 0.004\ \gamma + 0.974\ K_d + 7.96$	(110)	0.80

Table 38. Beta coefficients of each of the independent variables of Eq. (90(110)

	Month	E_{ex}	α	γ	K_d
b-coefficient for average E_{av}=300 lux	Dec	-0.68	-0.28	-0.12	-0.01
	Feb	-0.88	-0.13	-0.15	-0.09
	Mar	-0.91	-0.16	-0.02	-0.11
	Apr	-0.55	-0.47	-0.03	-0.07
	May	-0.51	-0.47	0.02	0.08
	Jun	-0.67	-0.42	0.00	-0.03
	Jul	-0.17	-0.85	0.08	-0.03
b-coefficient for average E_{av}=200 lux	Dec	-0.69	-0.28	-0.12	-0.01
	Feb	-0.88	-0.13	-0.15	-0.09
	Mar	-0.91	-0.16	-0.03	-0.11
	Apr	-0.58	-0.45	-0.08	-0.06
	May	-0.64	-0.36	-0.06	0.04
	Jun	-0.73	-0.37	-0.04	-0.04
	Jul	-0.31	-0.68	-0.05	-0.02
b-coefficient for average E_{av}=100 lux	Dec	-0.69	-0.29	-0.12	-0.01
	Feb	-0.73	-0.25	-0.11	-0.01
	Mar	-0.73	-0.25	-0.09	-0.05
	Apr	-0.47	-0.39	-0.17	-0.04
	May	-0.80	-0.05	-0.20	-0.01
	Jun	-0.68	-0.26	-0.11	0.04
	Jul	-0.55	-0.20	-0.26	0.09

The beta-coefficients for the independent variables of the monthly equations present the same effect on the power, as those for the generalised equations. The exterior illuminance has the strongest effect, while the sky diffuse coefficient the weakest effect on the used power of the artificial lighting. During July, however, the sun elevation becomes more important, which could be attributed to the small range of exterior illuminance values.

This paragraph provided mathematical functions for the calculation of the artificial lighting power used, for the whole experimental period and for each month of this period, for the following conditions:

- The space has dimensions 1.905 x 1.860 m and has black matte interior surfaces;
- A light pipe of diameter 0.30m and length 2.60 m is installed in the middle of the space;
- The height between the light pipe diffuser and the reference plane is 1.61 m;
- The artificial lighting system consists 8 LED lamps of 11 W each (Table 28), which are positioned around the diffuser, as depicted in Figure 65;
- The lamps are dimmed by daylight linked controls;
- The desired average illuminance by both natural and artificial lighting is 100, 200 or 300 lux;
- The calculations are valid for the climatic conditions of Athens, Greece.

The R-squared ranges between 0.81 and 0.90 for the functions developed from all the experimental data, while the R-squared for the equations developed from the data of each month of the experimental period ranged between 0.74 and 0.92. By calculating the beta-coefficients for each of the independent variables, it is evident that the exterior illuminance is the independent variable that has the most significant impact on the power used, while the sky diffuse coefficient is the least important parameter.

7.2.3 Lighting power used to achieve minimum illuminances of 100, 200, 300 and 400 lux from an "office lighting system"

The third task aims to provide an estimate of the power used for achieving a minimum of 100, 200, 300 and 400 lux of illuminance on the reference plane. The steps that were followed for the calculations are:

1. Selecting lamps: The artificial lighting used for this task includes LED ceiling-recessed luminaires, widely used in working environments. The wattage and the positioning of the lamps were set after performing simulations of the artificial lighting levels, without natural light, in the software DIVA for Rhino. The goal was to achieve average (ambient) illuminance on the reference plane of at least 300 lux and uniformity (E_{min}/E_{av}) of 0.6 (recommendations for ambient lighting from EN 12464-1:2011. Light and lighting - Lighting of workplaces - Part 1: Indoor workplaces). The simulations showed that the average illuminance on the original reference plane of the test cell achieved by six of the selected lamps is 580 lux, while the minimum is 400 lux, resulting in a uniformity of 0.69. The space simulated had all the characteristics of the experimental layout (distance between ceiling and reference plane= 1.61 m, interior surfaces of black matte fabric with reflectance of approximately 7%, etc). The luminaire properties are provided in Table 39, while the positions of the luminaires and the artificial lighting levels (without natural lighting) are shown in Figure 67.

Table 39. Characteristics of the lamps used for calculating the used power

Colour Code	4000 Kelvin	**Power**	10 W
Beam Angle (Nom)	31°	**Standby Power**	0.19 W
Luminous Flux (Nom)	744 lm	**Dimming**	LDO dimmable to 1% over DALI
Luminous Efficacy (rated) (Nom)	74 lm/W	**Article No**	Zumtobel 62907111

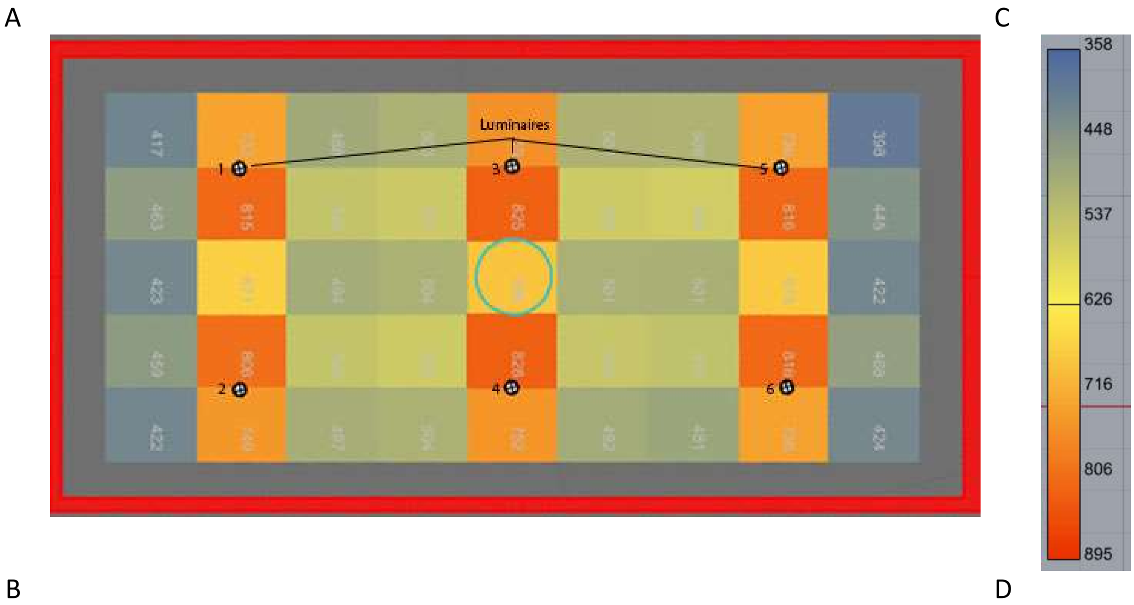


Figure 67. Illuminance distribution of artificial lighting for task 3. E_{av}=580 lux

2. Finding the minimum illuminance from daylight: The minimum illuminance from the daylight entering the space through the light pipe needed to be calculated. Sensors 1, 3, 11 and 13, which are the sensors with the maximum horizontal distance from the projection of the light pipe on the reference plane, are positioned at the four corners of the reference plane, where the minimum illuminance from artificial light is also recorded. For simplicity, the minimum illuminance on the reference plane was the minimum value recorded by sensors 1, 3, 11 and 13 and the minimum illuminance values from the artificial lighting was considered to be 400 lux, on every corner of the reference plane.
3. Calculating the required illuminance from the lamps: If the minimum illuminance from the incoming natural light on the reference plane of the space is E_{pm} and the required minimum illuminance on the reference plane is E_{min}, it is assumed that the illuminance required from the LEDs, E_{LED}, will be:

$$E_{LED} = E_{min} - E_{pm} \qquad (111)$$

where, for task 3, E_{min} is equal to 400, 300, 200 or 100 lux.

4. Calculation of the relative LED light output (κ) required: The E_{LED} calculated by Eq. (**111**) can be expressed as a ratio or percentage of the total LED light output at the corners of the reference plane, which provides a minimum illuminance of 400 lux on the reference plane.

$$\kappa=\frac{E_{LED}}{400} \tag{112}$$

5. Calculation of the percentage of the used LED power (λ): The relations proposed by Doulos et. al. Eq.(49(52) are employed to calculate the percentage of the total installed power that is actually used. The percentage of the used power for each E_{pm} is taken to be the average of the four percentage values (λ1-λ4) resulting from the application of Eq.(49(52).
6. Calculation of the actual used LED power (P): The percentage of the used power (λ) multiplied by the total LED wattage, which in this task is 60 W (6 lamps of 10 W each) provides the actual used power (P). The additional wattage of the auxiliary equipment is not considered for this calculation.
7. Development of relations providing the used power (P) for the whole experimental period: In order to develop relations for the used power corresponding to each minimum required illuminance, regression analysis is carried out between the power to achieve the minimum required illuminance of 100, 200, 300 and 400 lux on the reference plane and the independent parameters: the exterior illuminance (E_{ex}), the sun azimuth (α) and altitude (γ) and the sky diffuse coefficient (K_d). Table 40 includes the three relations providing the power used for each of the minimum required illuminances, using all the data acquired from the experiment.

Table 40. Equations providing the power of the artificial lighting system used as a function of the exterior illuminance, the position of the sun and the sky diffuse coefficient

Minimum required Illuminance (E_{min})	Relations giving power P		R-Squared
400 lux	$P= -0.00006\, E_{ex} - 0.035\, \alpha - 0.003\, \gamma + 0.430\, K_d + 61.12$	(113)	0.82
300 lux	$P= -0.00005\, E_{ex} - 0.030\, \alpha - 0.002\, \gamma + 0.369\, K_d + 45.06$	(114)	0.82
200 lux	$P= -0.00004\, E_{ex} - 0.027\, \alpha - 0.002\, \gamma + 0.323\, K_d + 31.27$	(115)	0.81
100 lux	$P= -0.00005\, E_{ex} - 0.028\, \alpha - 0.003\, \gamma + 0.318\, K_d + 18.61$	(116)	0.80

In the above relations (Eq. (113(116)), P is the power used by the system (W), E_{ex} is the exterior illuminance (lux), α is the Solar Altitude angle (°), γ is the Solar Azimuth angle (°) and K_d is the sky diffuse coefficient.

8. Assessment of the impact of the independent variables on power: To investigate the strength of the effect of each independent variable (E_{ex}, α, γ and K_d) on the dependent variable (P), their beta-coefficients were calculated. Beta-coefficients are calculated as the product of the regression coefficients included in Eq. (113(116), multiplied by the ratio of the standard deviation of the independent variables to the standard deviation of the power.

Table 41 includes the beta-coefficients of each of the independent variables. As expected, the exterior illuminance (E_{ex}) has the strongest effect on the power, followed by the sun altitude and the sun azimuth. The sky diffuse coefficient is again the least important parameter.

Given the low significance of K_d in the used power calculation, Eq. (117(120) (Table 42) which exclude K_d were developed and are recommended for use. R squares of Eq. (117(120) are equal to those of Eq. (113(116).

Table 41. Beta coefficients of each of the independent variables of Eq. (113(116)

Minimum required Illuminance	b-Coefficients of exterior illuminance (E_{ex})	b-Coefficients of Altitude (α)	b-Coefficients of Azimuth (γ)	b-Coefficients of sky diffuse coefficient (K_d)
400 lux	-0.70	-0.21	-0.05	0.04
300 lux	-0.70	-0.21	-0.05	0.04
200 lux	-0.70	-0.21	-0.05	0.04
100 lux	-0.69	-0.21	-0.06	0.04

Table 42. Equations providing the power of the artificial lighting system used as a function of the exterior illuminance, and the position of the sun

Minimum required Illuminance (E_{min})	Relations giving power P		R-Squared
400 lux	$P= -0.00006\ E_{ex} - 0.033\ \alpha - 0.003\ \gamma + 61.43$	(117)	0.82
300 lux	$P= -0.00005\ E_{ex} - 0.029\ \alpha - 0.003\ \gamma + 45.32$	(118)	0.82
200 lux	$P= -0.00005E_{ex} - 0.026\ \alpha - 0.002\ \gamma + 31.49$	(119)	0.81
100 lux	$P= -0.00005\ E_{ex} - 0.027\ \alpha - 0.003\ \gamma + 18.83$	(120)	0.80

9. Development of relations providing the used power (P) for each month of the experimental period: The same analysis was repeated for each of the months when experimental measurements were carried out. The equations for each month are given in Table 43, while the beta-coefficients for the independent variables (E_{ex}, α, γ, K_d) are provided in Table 44. Functions for the months November and August have not been developed, due to the limited amount of data (from 28th to 30th of November -1,319 observations, and from 1st to 7th of August - 3,455 observations). The beta coefficients for the independent variables of the monthly equations present the same effect on the power, as those for the generalised equations. The exterior illuminance has the strongest effect, while the sky diffuse coefficient the weakest effect on the used power of the artificial lighting. July remains an exception, where the exterior illuminance is almost as important as the sun altitude. Equations for the calculation of the used power in July have the lowest R-squared compared to the equations for the rest of the months. The reason for that differentiation is probably related to the weather conditions which do not present high variability.

Table 43. Equations providing the power of the artificial lighting system used as a function of the exterior illuminance, the position of the sun and the sky diffuse coefficient, for each month of experimental observations

	Month	Relations giving power P		R-Squared
Minimum required Illuminance = 400 lux	Dec	$P= -0.00003\ E_{ex} - 0.023\ \alpha - 0.0008\ \gamma + 0.217\ K_d + 60.16$	(121)	0.83
	Feb	$P= -0.00005\ E_{ex} - 0.003\ \alpha - 0.003\ \gamma + 0.137\ K_d + 60.44$	(122)	0.92
	Mar	$P= -0.00005\ E_{ex} - 0.010\ \alpha - 0.0003\ \gamma - 0.196\ K_d + 60.46$	(123)	0.92
	Apr	$P= -0.00006\ E_{ex} - 0.021\ \alpha - 0.003\ \gamma + 0.844\ K_d + 60.60$	(124)	0.69
	May	$P= -0.00006\ E_{ex} - 0.020\ \alpha - 0.007\ \gamma + 0.221\ K_d + 61.14$	(125)	0.67
	Jun	$P= -0.00006\ E_{ex} + 0.025\ \alpha - 0.005\ \gamma - 0.417\ K_d + 61.87$	(126)	0.76
	Jul	$P= -0.00004\ E_{ex} - 0.065\ \alpha - 0.004\ \gamma +0.425\ K_d + 61.41$	(127)	0.67
Minimum required Illuminance = 300 lux	Dec	$P= -0.00003\ E_{ex} - 0.019\ \alpha - 0.0007\ \gamma + 0.187\ K_d + 44.22$	(128)	0.83
	Feb	$P= -0.00004\ E_{ex} - 0.003\ \alpha - 0.003\ \gamma + 0.118\ K_d + 44.47$	(129)	0.92
	Mar	$P= -0.00004\ E_{ex} - 0.008\ \alpha - 0.0003\ \gamma - 0.168\ K_d + 44.48$	(130)	0.92
	Apr	$P= -0.00005\ E_{ex} - 0.018\ \alpha - 0.002\ \gamma + 0.726\ K_d + 44.60$	(131)	0.69
	May	$P= -0.00005\ E_{ex} - 0.018\ \alpha - 0.006\ \gamma + 0.190\ K_d + 45.08$	(132)	0.67
	Jun	$P= -0.00006\ E_{ex} - 0.022\ \alpha - 0.004\ \gamma - 0.360\ K_d + 45.70$	(133)	0.76
	Jul	$P= -0.00004\ E_{ex} - 0.056\ \alpha - 0.003\ \gamma + 0.365\ K_d + 45.30$	(134)	0.67
Minimum required Illuminance = 200 lux	Dec	$P= -0.00003\ E_{ex} - 0.017\ \alpha - 0.0006\ \gamma + 0.165\ K_d + 30.47$	(135)	0.83
	Feb	$P= -0.00004\ E_{ex} - 0.002\ \alpha - 0.003\ \gamma + 0.102\ K_d + 30.69$	(136)	0.92
	Mar	$P= -0.00004\ E_{ex} - 0.007\ \alpha - 0.0002\ \gamma - 0.154\ K_d + 30.70$	(137)	0.92
	Apr	$P= -0.00004\ E_{ex} - 0.016\ \alpha - 0.002\ \gamma + 0.660\ K_d + 30.85$	(138)	0.68
	May	$P= -0.00005\ E_{ex} - 0.016\ \alpha - 0.005\ \gamma + 0.169\ K_d + 31.31$	(139)	0.66
	Jun	$P= -0.00005\ E_{ex} - 0.020\ \alpha - 0.004\ \gamma - 0.347\ K_d + 31.88$	(140)	0.75
	Jul	$P= -0.00003\ E_{ex} - 0.051\ \alpha - 0.003\ \gamma + 0.310\ K_d + 31.52$	(141)	0.66
Minimum required Illuminance = 100 lux	Dec	$P= -0.00003\ E_{ex} - 0.017\ \alpha - 0.0006\ \gamma + 0.168\ K_d + 17.67$	(142)	0.82
	Feb	$P= -0.00004\ E_{ex} - 0.002\ \alpha - 0.002\ \gamma + 0.10\ K_d + 17.92$	(143)	0.92
	Mar	$P= -0.00004\ E_{ex} - 0.007\ \alpha - 0.0002\ \gamma - 0.165\ K_d + 17.93$	(144)	0.92
	Apr	$P= -0.00005\ E_{ex} - 0.017\ \alpha - 0.002\ \gamma + 0.705\ K_d + 18.15$	(145)	0.67
	May	$P= -0.00005\ E_{ex} - 0.017\ \alpha - 0.006\ \gamma + 0.17\ K_d + 18.71$	(146)	0.64
	Jun	$P= -0.00006\ E_{ex} - 0.021\ \alpha - 0.005\ \gamma -0.403\ K_d + 19.32$	(147)	0.73
	Jul	$P= -0.00004\ E_{ex} - 0.056\ \alpha - 0.003\ \gamma + 0.279\ K_d + 18.96$	(148)	0.64

Table 44. Beta-coefficients of each of the independent variables of Eq. (121(148)

	Month	E_{ex}	α	γ	K_d
b-coefficient for minimum E_{int}=400 lux	Dec	-0.71	-0.23	-0.04	0.09
	Feb	-0.90	-0.03	-0.11	0.03
	Mar	-0.93	-0.08	-0.01	-0.03
	Apr	-0.69	-0.12	-0.06	0.08
	May	-0.70	-0.11	-0.15	0.02
	Jun	-0.80	-0.24	-0.18	-0.03
	Jul	-0.45	-0.37	-0.09	0.01
b-coefficient for minimum E_{int}=300 lux	Dec	-0.71	-0.23	-0.04	0.09
	Feb	-0.90	-0.03	-0.11	0.03
	Mar	-0.93	-0.08	-0.01	-0.03
	Apr	-0.68	-0.12	-0.06	0.08
	May	-0.70	-0.11	-0.15	0.02
	Jun	-0.80	-0.15	-0.13	-0.03
	Jul	-0.45	-0.37	-0.09	0.01
b-coefficient for minimum E_{int}=200 lux	Dec	-0.71	-0.23	-0.04	0.09
	Feb	-0.91	-0.03	-0.11	0.03
	Mar	-0.93	-0.08	-0.01	-0.04
	Apr	-0.68	-0.12	-0.06	0.08
	May	-0.69	-0.11	-0.16	0.02
	Jun	-0.79	-0.24	-0.18	-0.03
	Jul	-0.44	-0.37	-0.09	0.01
b-coefficient for minimum E_{int}=100 lux	Dec	-0.71	-0.23	-0.04	0.09
	Feb	-0.91	-0.02	-0.11	0.03
	Mar	-0.94	-0.08	-0.01	-0.04
	Apr	-0.67	-0.12	-0.06	0.08
	May	-0.68	-0.11	-0.16	0.02
	Jun	-0.79	-0.23	-0.18	-0.03
	Jul	-0.43	-0.37	-0.09	0.01

This paragraph provided mathematical functions for the calculation of the artificial lighting power used, for the whole experimental period and for each month of this period, for the following conditions:

- The space and reference plane have the same dimensions as these of the experimental set-up (1.905 x 1.860 m); the interior surfaces have the sane properties as these of the test-cell (black matte);
- A light pipe of diameter 0.30m and length 2.60 m is installed in the middle of the space;
- The height between the light pipe diffuser and the reference plane is 1.61 m;
- The artificial lighting system consists 6 LED lamps of 10 W each (Table 39), which are positioned in an ortho-canonical grid, as depicted in Figure 67;
- The lamps are dimmed by daylight linked controls;

- The desired minimum illuminance by both natural and artificial lighting is 100, 200, 300 or 400 lux;
- The calculations are valid for the climatic conditions of Athens, Greece.

The R-squared ranges between 0.80 and 0.82 for the functions developed from all the experimental data, while the R-squared for the equations developed from the data of each month of the experimental period ranged between 0.64 and 0.92. By calculating the beta coefficients for each of the independent variables, it is evident that the exterior illuminance is the independent variable that has the most significant impact on the power used, while the sky diffuse coefficient is the least important parameter.

7.2.4 Lighting power used to achieve average illuminance of 300 lux from an "office lighting system" with luminaire dimming groups

The fourth task aims to provide an estimate of the power used for achieving an average illuminance value of 300 lux on the reference plane, with luminaire dimming groups. This task was expected to provide maximum energy savings and greater uniformity of illuminance on the reference plane. More specifically, the goals of the fourth task were to:

- Estimate the maximum energy savings or minimum used power due to the use of the light pipe and of daylight linked controls.
- Assess the uniformity achieved.
- Compare the results of the use of dimming groups with the previous tasks.

The steps that were followed for the calculations are:

1. Selecting lamps: The artificial lighting used for this task, including the luminaires and their positions in the space, is the same as in task 3. The luminaires are LED ceiling-recessed (Figure 68) and their properties are provided in Table 39. The space simulated had all the characteristics of the experimental layout.
2. Creating luminaire groups: To achieve maximum energy savings, the luminaires in a space with daylight linked controls need to be included in dimming (control) groups. The number and position of luminaires in these groups need to be associated with the daylight sources and the amount of daylight in the various areas of a space. In this task, two groups of luminaires were created, with the luminaires belonging to each group dimmed together, thus providing the same light output. One group includes the two central luminaires located on either side of the light pipe diffuser (luminaires 3 and 4), and the other group includes the four luminaires located further away from the diffuser (luminaires 1, 2, 5 and 6, Figure 68). Simulations carried out in the lighting software Relux provide the average illuminance on the original reference plane of the test cell achieved by the two groups of luminaires in full output or turned off, as shown in Figure 69, Figure 70 and Figure 71.
3. In a real application, the dimmers controlling the light output of a group of luminaires would receive input from a lighting sensor, which would sense the light already available on the reference plane corresponding to that group of luminaires. In the present study, to dim the two luminaire groups separately, the daylight entering the space through the light pipe needed to be calculated on reference planes that received artificial light from the respective luminaires. As a result, three reference planes were created, as shown in Figure 68. Reference plane A is mainly lit by luminaires 1 and 2, reference plane B is mainly lit by luminaires 3 and 4, and

reference plane C is mainly lit by luminaires 5 and 6. Reference planes A and C are considered identical, because of their position relevant to the light pipe.

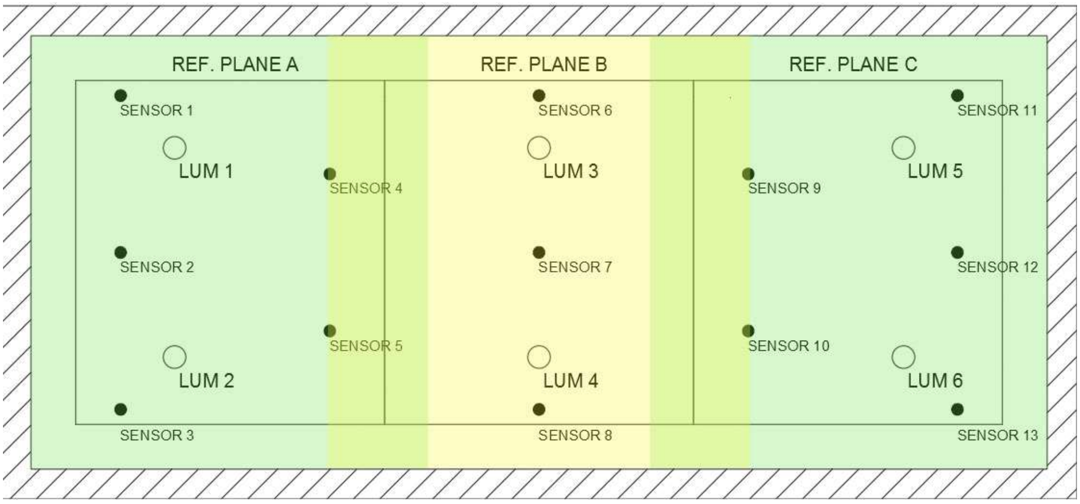


Figure 68. Image showing the positions of the luminaires, the respective reference planes and the experiment sensors 1-13.

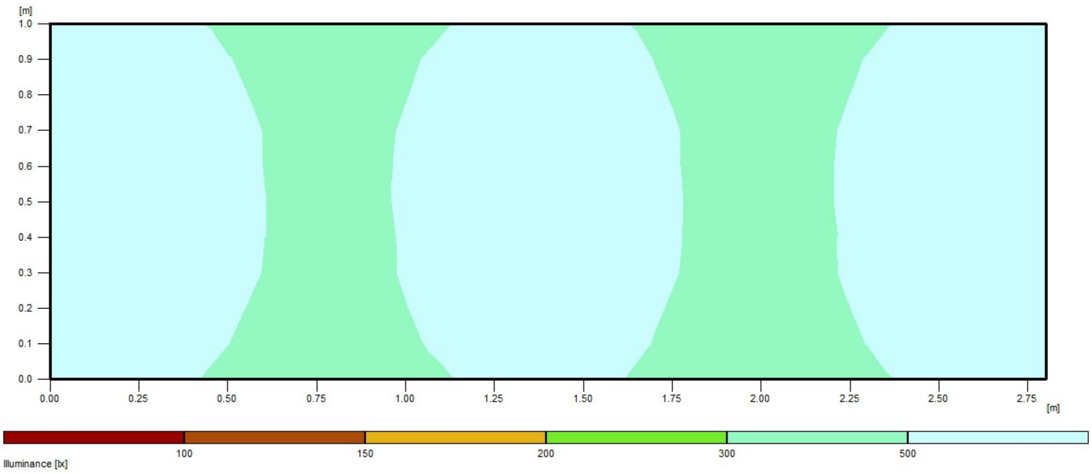


Figure 69. Illuminance distribution from all the luminaires. E_{av}=574 lux

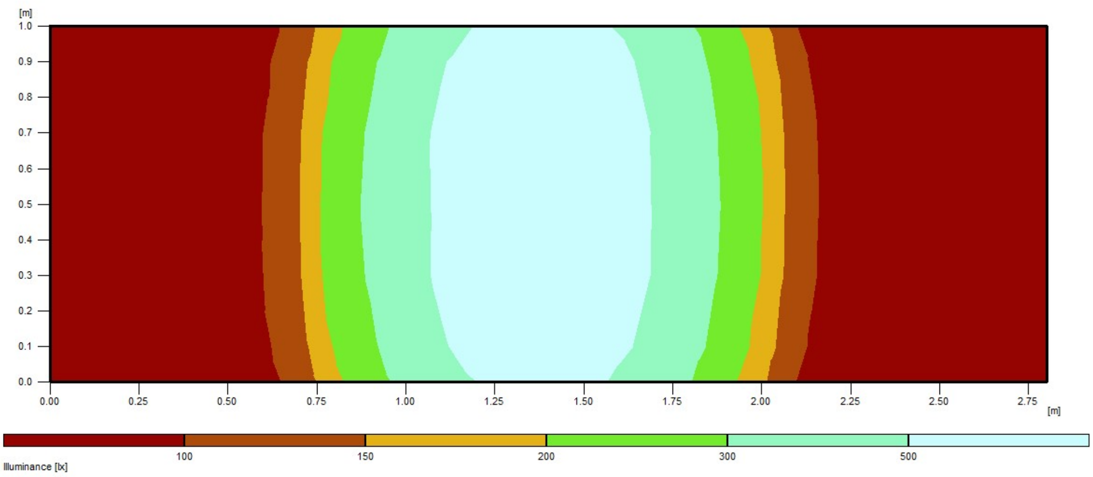


Figure 70. Illuminance distribution from the two luminaires 3 & 4 (close to the light pipe diffuser). E_{av}=238 lux

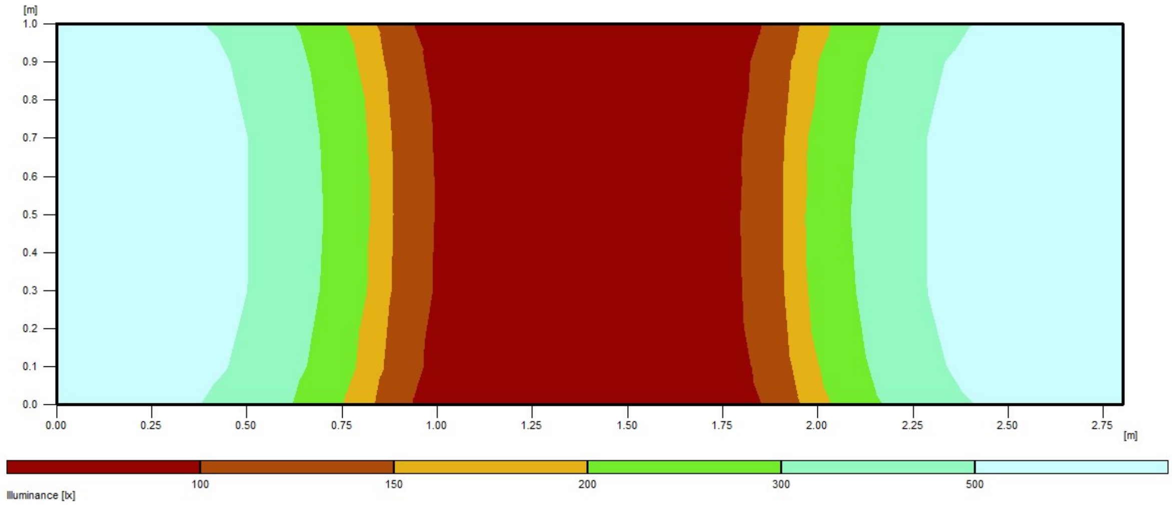


Figure 71. Illuminance distribution from luminaires 1, 2, 5 and 6. E_{av}=337 lux

4. Finding the daylight on each reference plane: To calculate how much will each luminaire group be dimmed, the daylight available on the respective reference planes is required. To select representative interior daylight values, the experimentally recorded data of exterior illuminance was grouped in eleven clusters: Cluster 1 included values from 0 to 10 klux, Cluster 2 included values from 10 to 20 klux, Cluster 3 included values from 20 to 30 klux, etc, ending in Cluster 11 which included values from 100 to 110 klux. For each Cluster, the median value of the average interior illuminance on reference plane B (under the light pipe) was calculated. The 13 interior sensor recordings for a point in time when the average illuminance on reference plane B was equal to the median illuminance on that reference plane, were selected and used for the calculation of the dimming levels. That way, 11 series of interior (daylight) illuminance values, as recorded during the experiment, each corresponding to a cluster of exterior illuminances, were used.

For calculation purposes, area A includes experiment sensors 1-5, area B includes sensors 4-10 and area C includes sensors 9-13 (Figure 68).

5. Calculating the required illuminance from the lamps: For each of the eleven series of sensor recordings, the average illuminance from daylight on each of the reference planes A, B and C was calculated. If the average illuminance from the incoming natural light is E_{pav} and the required average illuminance on the reference plane is E_{av}, it is assumed that the illuminance required from the LEDs, E_{LED}, for each of the reference planes, will be:

For reference plane A: $E_{LED\text{-}A} = E_{av\text{-}A} - E_{pav\text{-}A}$ (149)

For reference plane B: $E_{LED\text{-}B} = E_{av\_B} - E_{pav\_B}$ (150)

For reference plane C: $E_{LED\text{-}C} = E_{av\_C} - E_{pav\_C}$ (151)

where for task 4, each of the illuminances $E_{av\text{-}A}$, $E_{av\text{-}B}$ and $E_{av\text{-}C}$ is equal to 300 lux.

Since reference planes A and C have very similar daylight levels, the higher value between $E_{LED\text{-}A}$ and $E_{LED\text{-}C}$ is considered each time.

6. Finding dimming levels for each luminaire group: The previous step provided eleven couples of average illuminance values required from the luminaires to achieve the required average illuminance of 300 lux on the respective reference planes (A-C and B) and on the reference plane of the room. Using the software Relux, trials of dimming levels of the luminaires of groups A and C and of group B were conducted, without the presence of natural light. The aim was to achieve average illuminance values in each of the reference planes A, B and C as close to $E_{LED\text{-}A}$ or $E_{LED\text{-}C}$ and $E_{LED\text{-}B}$ as possible.

   Obviously, there are several possible combinations of dimming levels for the two groups of luminaires that can achieve the target illuminance. This is because the lighting output of one group of luminaires contributes to the increase of the lighting levels not only on its respective reference plane, but also of the levels on the neighbouring reference planes. However, since the goal of this study is to estimate the used power for artificial lighting in the room, the effect of the combination of dimming levels is not significant.

   To enable a consistent choice of dimming levels for the eleven cases, the following criteria were set:

   - The average illuminance from artificial lighting on each of the reference planes A, B and C should be equal or very close to the target illuminance of 300 lux.
   - The average illuminance of the reference plane of the room should be equal or greater than the target illuminance of 300 lux.
   - The uniformity of the lighting levels from both natural and artificial lighting on the room reference plane should be greater than 0.7.
   - When more than one dimming combination met the above criteria, the combination with the smaller average room illuminance (i.e., the one closer to 300 lux) was to be selected.

After the initial analysis, more trials were performed to increase the accuracy of the results. Table 45 includes the resulting dimming combinations.

Table 45. Decrease of the light output of the LEDs in each luminaire group for various exterior illuminances

Exterior illuminance range (lux)	Exterior illuminance value (lux)	Decrease of light output for luminaires 1, 2, 5 and 6 (%) (μ_1)	Decrease of light output for luminaires 3 and 4 (%)(μ_2)	Error (%) of Eq. (152)	Error (%) of Eq. (153)
0-10k	3,641	50	50	7.0	5.7
10-20k	12,104	50	55	3.3	6.7
20-30k	22,498	50	60	1.0	5.7
30-40k	32,790	50	55	4.9	11.1
40-50k	40,922	50	65	7.7	1.4
50-60k	50,004	55	65	1.8	7.8
60-70k	60,115	55	70	5.2	7.3
70-80k	79,896	55	75	11.3	12.2
80-90k	89,975	60	75	6.2	17.1
90-100k	97,458	65	90	0.7	4.5
100-110k	105,863	65	100	3.2	1.6
Additional trials					
0-10k	10,380	50	55	4.0	8.5
50-60k	55,683	50	70	12.5	4.5
70-80k	70,000	60	80	0	0.6
90-100k	93,000	60	100	7.1	8.7
90-100k	95,000	65	100	0	7.5
90-100k	99,943	70	100	6.1	4.7
100-110k	106,001	60	100	10.7	1.5
100-110k	110,000	70	100	2.9	0.5

Figure 72 shows the graphical representation of the relation between the decrease of the light output to achieve the target illuminance and the exterior illuminance. The respective equations describing this relation, are:

For luminaires 1, 2, 5 and 6 (reference planes A and C): $\mu_1 = 0.0002\, E_{ex} + 46$ (152)

For luminaires 3 and 4 (reference plane B): $\mu_2 = 0.0005\, E_{ex} + 45.49$ (153)

The percentage of error of the application of Eq. (152) and Eq. (153), as compared to the decrease of light output resulting from the trials is also provided in Table 45 and in Figure 73.

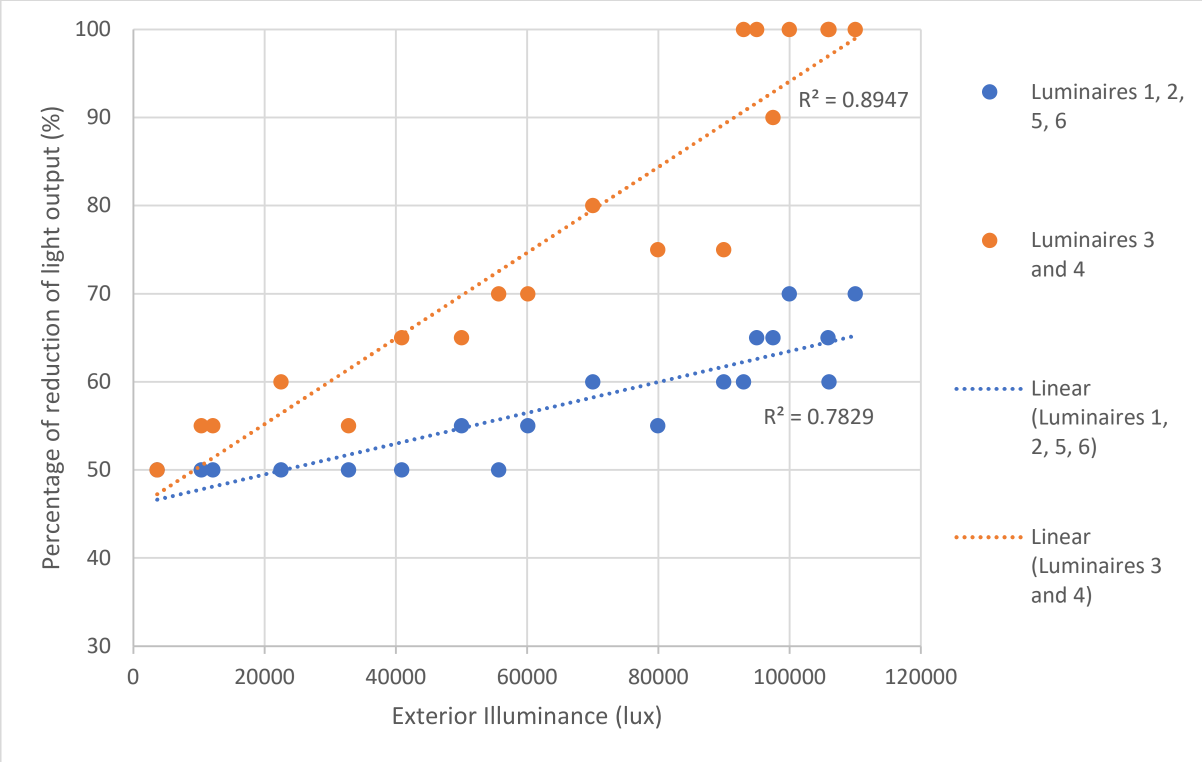


Figure 72. Percentage of the reduction in LED light output as a function of the exterior illuminance

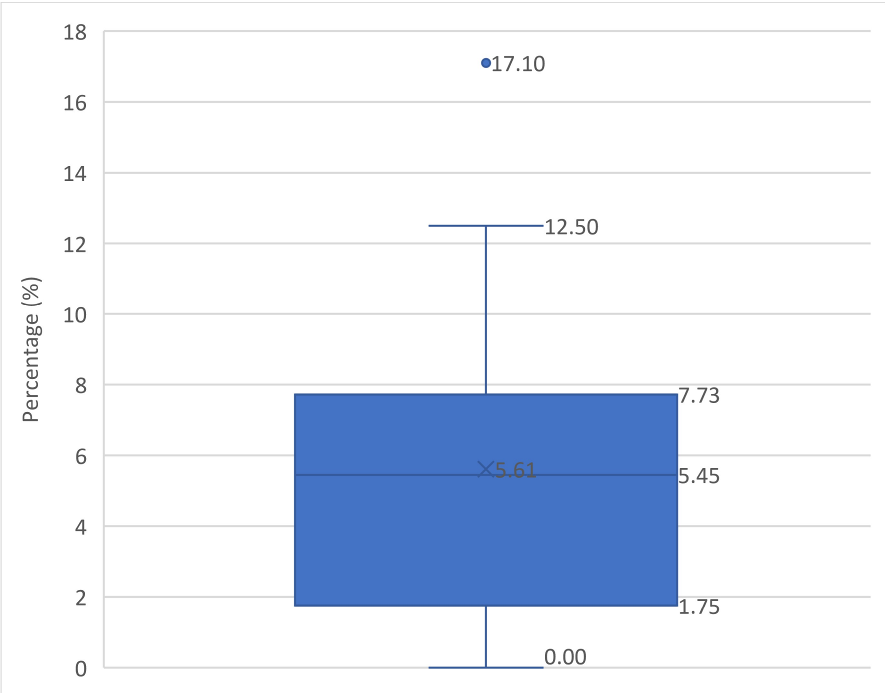


Figure 73. Boxplot of the error of both Eq. providing µ1 and µ2 (Eq. (152(153))

7. Calculation of the relative LED light output (κ) required: The previous step in the analysis provided the percentage of dimming, i.e., the decrease of the LEDs light output. The LEDs light output, i.e., the light provided by the luminaires, is needed to calculate the used power from Eq. (49(52). The percentage of the full light output of the luminaires required to reach the target illuminance (300 lux) is given by the following equations:

For reference planes A and C: $\kappa_1 = 100-\mu_1$ (154)

For reference plane B: $\kappa_2 = 100-\mu_2$ (155)

However, in the current task the error from the use of Eq. (152) and (153), needs to be considered. The percentage of the light output calculated from Eq. (152) and (153), was increased and decreased by a percentage equal to the 75th percentile of the error, which is 7.7%. So, a range of values of LEDs light output were acquired:

$\mu_{1max} = \mu_1-(0.077\ \mu_1)$ and $\mu_{1min} = \mu_1+(0.077\ \mu_1)$ (156)

$\mu_{2max} = \mu_2-(0.077\ \mu_2)$ and $\mu_{2min} = \mu_2+(0.077\ \mu_2)$ (157)

8. Calculation of the percentage of the used LED power (λ): The relations proposed by Doulos et. al. (Eq. (49(52) are employed to calculate the percentage of the total installed power that is actually used. The percentage of the used power for each E_{pm} is taken to be the average of the four percentage values (λ1-λ4) resulting from the application of Eq. ((49(52) The light output values used were three for each reference plane and group of luminaires:

   For luminaires 1, 2, 5 and 6: μ_{1max}, μ_1 and μ_{1min} and

   For luminaires 3 and 4: μ_{2max}, μ_2 and μ_{2min}.

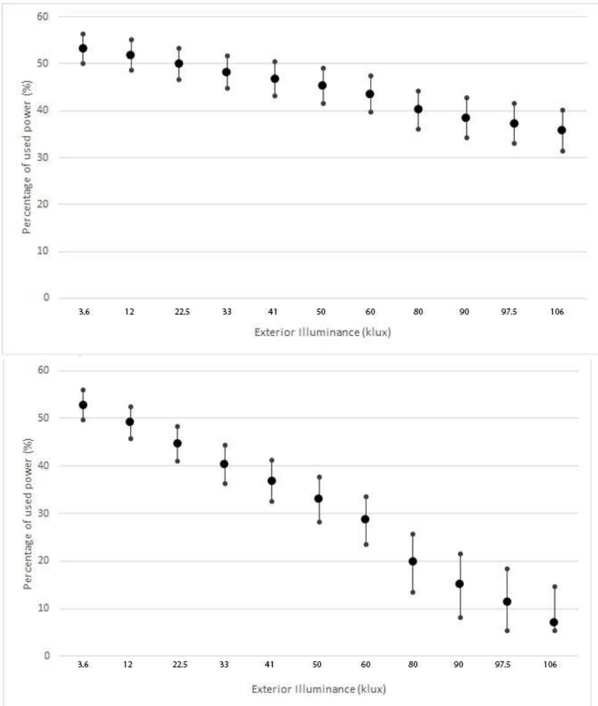


Figure 74. Left: Range of the power used for various exterior illuminances for reference planes A and C (luminaires 1, 2, 5, 6). Right: Range of the power used for various exterior illuminances for reference plane B (luminaires 3, 4).

9. Calculation of the actual used LED power (P): The minimum, maximum and the calculated percentage of the power (λ) multiplied by the total LED wattage, which in this task is 60 W (6 lamps of 10 W each) provides the actual used power (P). The additional wattage of the auxiliary equipment is not considered for this calculation.

This paragraph provided the methodology for calculating the decrease of the LEDs light output, to achieve the target illuminance combined with the natural light from the light pipe, as a function of the exterior illuminance and for estimating the used power for a daylight linked system with groups of luminaires. The equations developed are valid for the following conditions:

- The space and reference plane have the same dimensions as these of the experimental set-up (1.905 x 1.860 m); the interior surfaces have the same properties as these of the test-cell (black matte);
- A light pipe of diameter 0.30m and length 2.60 M is installed in the middle of the space;
- The height between the light pipe diffuser and the reference plane is 1.61m;
- The artificial lighting system consists 6 LED lamps of 10 W each (Table 39), which are positioned in an ortho-canonical grid, as depicted in Figure 67;
- The lamps are dimmed by daylight linked controls;
- The desired minimum illuminance by both natural and artificial lighting is 300 lux;
- The calculations are valid for the climatic conditions of Athens, Greece.

7.3 Conclusions

The sixth chapter of the thesis provided methodologies for estimating the used power for artificial lighting systems used in conjunction with light pipes. The used power can lead to an estimate of energy consumption and savings when combined with the time of use.

The four tasks that were investigated are:

- Lighting power used to achieve minimum illuminances of 100, 200 and 300 lux using the experimental lighting system,
- Lighting power used to achieve average illuminances of 100, 200 and 300 lux using the experimental lighting system,
- Lighting power used to achieve minimum illuminances of 100, 200, 300 and 400 lux from an "office lighting system",
- Lighting power used to achieve average illuminance of 300 lux from an "office lighting system" with luminaire dimming groups.

In tasks 1, 2 and 3, the methodologies developed provided equations for the calculation of the used power of the artificial lighting systems, for the whole experimental period and for each month within that period, with independent variables being the exterior illuminance (E_{ex}), the sun azimuth (α) and altitude (γ) and the sky diffuse coefficient (K_d). The analysis of the beta coefficients of each of the independent variables, showed that the exterior illuminance (E_{ex}) has the strongest effect on the power, followed by the sun altitude and the sun azimuth, while the variable that plays the least important role is the sky diffuse coefficient. These equations can be used under specific conditions which should be the same with these of the experiment, in terms of location, room and light pipe characteristics and lamps.

Task 4 showcases the methodology to estimate the used power for artificial lighting when the luminaires in the space are grouped and dimmed, depending on the daylight availability in the different areas of a space. This methodology included trials in a simple lighting software, where the contribution of the light emitted from luminaires of neighbouring groups could be considered. Combinations of dimming levels for various exterior illuminances provided relations between the decrease of the light output to achieve the target illuminance and the respective exterior illuminance. Finally, the percentage of the total installed power that is actually used was calculated.

To acquire the used power from the LED light output, mathematical relations from a previous study by Doulos et al. (2017) were used. Doulos et al. performed an experimental investigation of the relationship between light output and relative consumed power to estimate the relation between dimming levels and energy consumption.

To compare the energy savings resulting from the use of each of the four methodologies analysed in the previous paragraphs, a random day of April, the month in the middle of the experimental period, was selected to perform calculations.

Task 1

1. Calculation of the energy consumption of the base-case task: Initially, the energy consumption of the artificial lighting as the only light source was calculated. The light output that was required to achieve 300 lux of minimum illuminance on the reference plane required 81% of the total power of the installed lamps. The light output reduced by 19% was used with Eq. ((49(52) to calculate the required power. The average of the results of applying Eq. ((49(52) was then multiplied by the system wattage (88 Watts) and then by 9 hours, as the measurements were carried out from 7 am to 4 pm. The total energy consumed by the used lamps for the base-case task and for a random day in April is 628.74 Wh.
2. Calculation of the energy consumption for task 1: Eq. (55) was used to calculate the used power of the lighting system and the result was multiplied by 1/60, as the experimental measurements were carried out every minute. The energy consumption values for every minute were then added. The total energy consumed by the used lamps for task 1, for a random day in April is 446.23 Wh, 29% lower than the energy consumed for the base-case task.

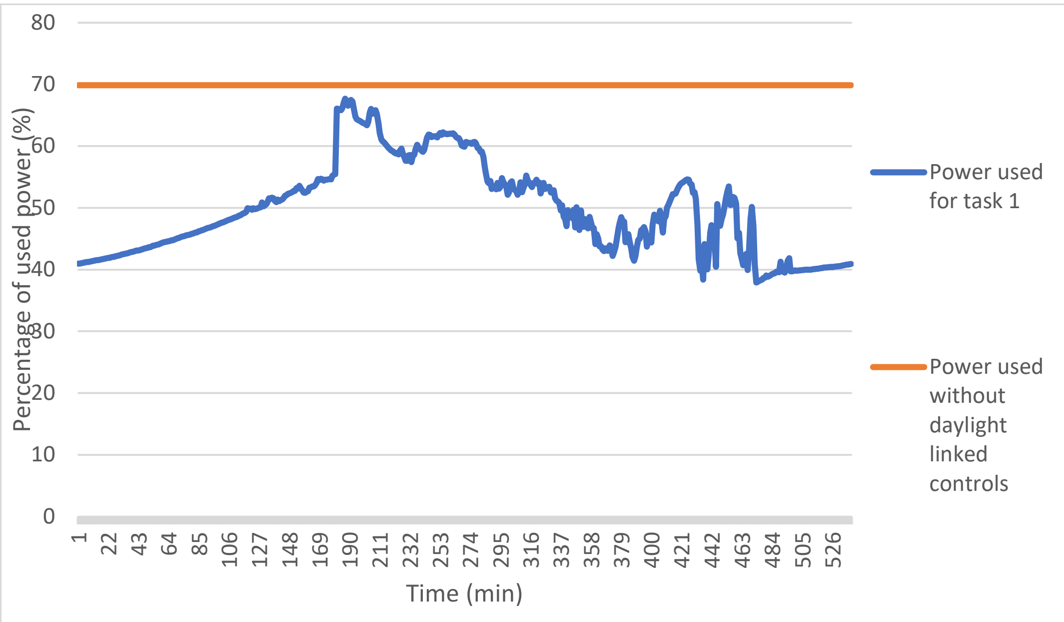


Figure 75. Distribution of the power used for every minute of a 9-hour period (7 am- 4pm) on April 28

Task 2

1. Calculation of the energy consumption of the base-case task: Initially, the energy consumption of the artificial lighting as the only light source was calculated. The light output that was required to achieve 300 lux of average illuminance on the reference plane required 14.81% of the total power of the installed lamps. The light output reduced by 85.19% was used with Eq. ((49(52) to calculate the required power. The average of the results of applying Eq. ((49(52) was then multiplied by the system wattage (88 Watts) and then by 9 hours, as the measurements were carried out from 7 am to 4 pm. The total energy consumed by the used lamps for the base-case task and for a random day in April is 158.49 Wh.
2. Calculation of the energy consumption for task 2: Eq. (84) was used to calculate the used power of the lighting system and the result was multiplied by 1/60, as the experimental measurements were carried out every minute. The energy consumption values for every minute were then added. The total energy consumed by the used lamps for task 2, for a random day in April is 97.30 Wh, 38.61% lower than the energy consumed for the base-case task.

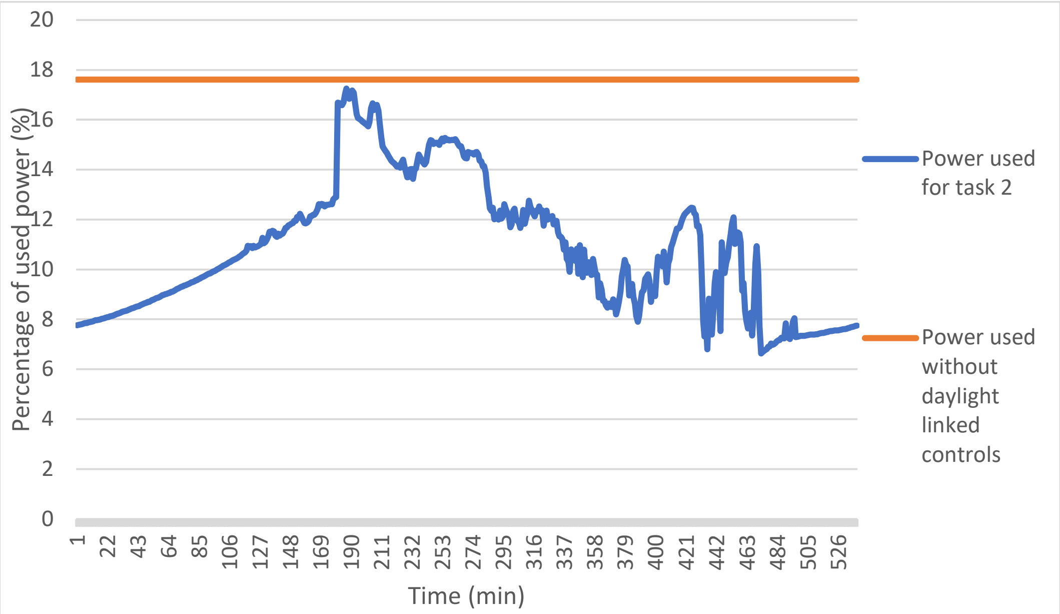


Figure 76. Distribution of the power used for every minute of a 9-hour period (7 am- 4pm) on April 28

Task 3

1. Calculation of the energy consumption of the base-case task: Initially, the energy consumption of the artificial lighting as the only light source was calculated. The light output that was required to achieve 300 lux of minimum illuminance on the reference plane required 75% of the total power of the installed lamps. The light output reduced by 25% was used with Eq. ((49(52) to calculate the required power. The average of the results of applying Eq. ((49(52) was then multiplied by the system wattage (60 Watts) and then by 9 hours, as the measurements were carried out from 7 am to 4 pm. The total energy consumed by the used lamps for the base-case task and for a random day in April is 395.89 Wh.

2. Calculation of the energy consumption for task 3: Eq. (114) was used to calculate the used power of the lighting system and the result was multiplied by 1/60, as the experimental measurements were carried out every minute. The energy by the used lamps for task 3, for a random day in April is 355.39 Wh, 10.23% lower than the energy consumed for the base-case task.

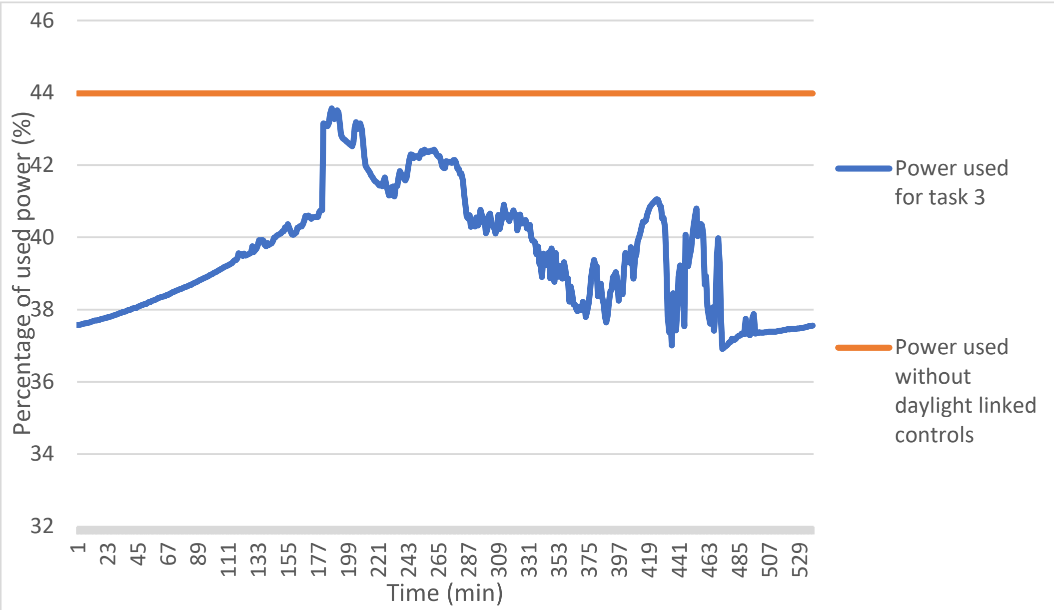


Figure 77. Distribution of the power used for every minute of a 9-hour period (7 am- 4pm) on April 28

Task 4

1. Calculation of the energy consumption of the base-case task: Initially, the energy consumption of the artificial lighting as the only light source was calculated. The light output that was required to achieve 300 lux of average illuminance on the reference plane required 51.72% of the total power of the installed lamps. The light output reduced by 48.28% was used with Eq. ((49(52) to calculate the required power. The average of the results of applying Eq. ((49(52) was then multiplied by the system wattage (60 Watts) and then by 9 hours, as the measurements were carried out from 7 am to 4 pm. The total energy consumed by the used lamps for the base-case task and for a random day in April is 280.40 Wh.
2. Calculation of the energy consumption for task 4: Eq. (152(**155**)were used to calculate the relative light output required from the LEDs to achieve an average interior illuminance of 300 lux. Eq. ((49(52) were then employed to calculate the required power for each minute. The average of the results of applying Eq. ((49(52) was then multiplied by the system wattage (60 Watts) and the result was multiplied by 1/60, as the experimental measurements were carried out every minute. The energy consumption values for every minute were then added. The total energy consumed by the used lamps for task 4, for a random day in April is 185.11 Wh, 33.98% lower than the energy consumed for the base-case task.

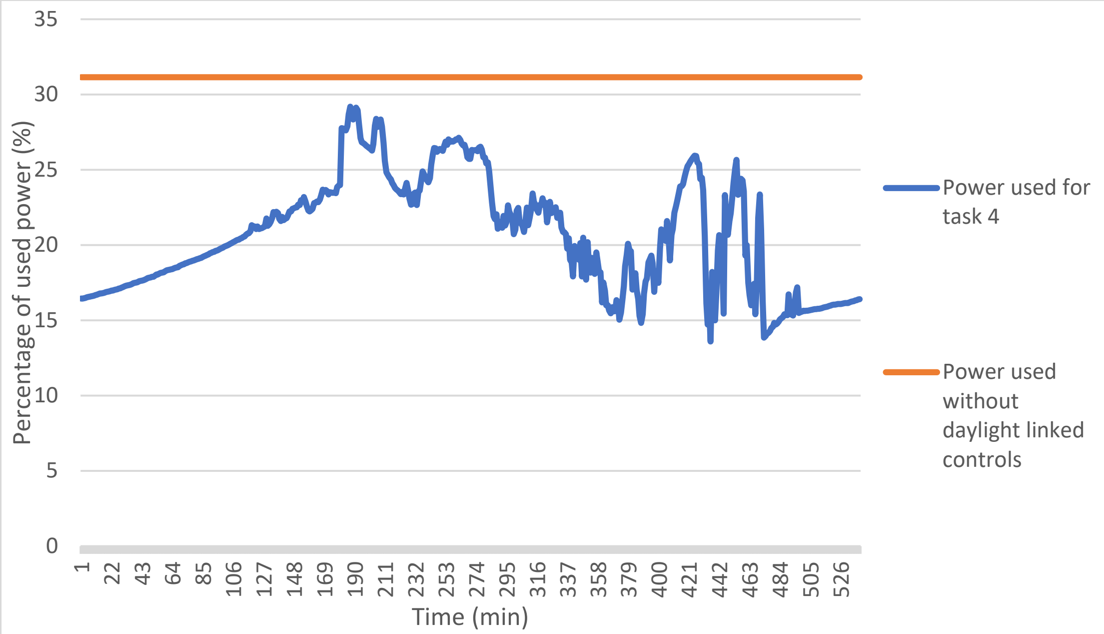


Figure 78. Distribution of the power used for every minute of a 9-hour period (7 am- 4pm) on April 28

As expected, the tasks that required an average illuminance value to be achieved provided greater savings than the ones where the same illuminance value was required as a minimum on the reference plane. Task 4, where the luminaires were grouped depending on their distance from the source of daylight, presented approximately 14% lower energy consumption from task 2, where all the luminaires were in the same dimming group and positioned around the light pipe diffuser. As a general note, the layout of luminaires in an ortho-canonical grid provides greater energy savings and better uniformity levels and should be preferred for environments with increased lighting quality requirements. The resulting savings in CO_2 emissions and cost are provided in Table 46.

The results presented in this chapter apply to the specific environment and lighting systems used and simulated and are intended to showcase a methodology, rather than provide formulas for universal use. It should be mentioned however, that the effect of various interior surface reflectances would only be significant for environments like the one in tasks 3 and 4, where the light sources are positioned relatively close to the walls, and for luminaires with more widespread light emissions. For light sources with narrow downward light emission, like the light pipe, the reflectances of the ceiling and of the side walls do not affect the illuminance distribution on a horizontal reference plane significantly. User intervention that can significantly change the energy consumption is also not considered.

Table 46. Parameters for the calculation of costs and CO_2 emissions associated with the use of the light pipe

Cost and CO_2 Emissions related information		
Design average illuminance for electrical lighting	300	lux
Measured average illuminance from natural lighting	100	lux
Capital cost of electric luminaires and controls	620	€
Capital cost of daylight guidance system	1,200	€
Lamp life	15,000	hours
Price of electricity (Commercial use - Γ21)	0.12	€/kWh
Working hours per year	3,000	h
CO_2 emissions (According to the electricity generation mix in Greece for 2019)	547.11	gCO2/kWh
Annual capital cost of combined electrical and daylight guidance installation	1820	€
Annual running cost of electricity (no light pipe)	55.44	€
Max Annual running cost of electricity (with light pipe)	49.896	€
Min Annual running cost of electricity (with light pipe) max	29.9376	€
CO2 emissions (no light pipe)	252,764.82	gCO2/kWh
Max CO2 emissions (with light pipe)	227,488.338	gCO2/kWh
Min CO2 emissions (with light pipe)	151,658.892	gCO2/kWh

Chapter 8: Conclusions

Light is one of the basic elements necessary for maintaining life on earth. Light enables vision, affects our circadian rhythms, gives form to our buildings and spaces, and provides time cues and view. Daylight helps in the formation of vitamin D, provides energy to almost all the ecosystems in earth, but also provides light, warmth, and energy for use in our modern buildings (Gessler *et al.*, 2017). Daylight should be present in every interior space where people spend a significant period of their day, however, the need for taller buildings and often deeper floor plans in modern cities often do not permit daylight to penetrate in the core of spaces.

Light pipes are innovative daylight systems that can guide daylight and sunlight in the deepest parts of buildings. They can guide daylight from the roof or the facades for long distances through very reflective tubes and provide natural light to spaces that would not otherwise have access to it. Light pipes are considered efficient systems as they present relatively low losses of performance (approximately 6% less efficient per additional metre of tube, (CIE, 2012), they do not increase the heat load of the space if appropriately installed (Šikula, Mohelníková and Plášek, 2014) and can be combined with artificial lighting when required. They contribute to reducing the energy consumed for lighting and provide time cues to building occupants.

Based on the existing literature as reviewed in Chapter 2:, the present Thesis aimed to contribute to the knowledge on the technology of light pipes by experimentally investigating the performance of light pipes in the Mediterranean - Greek environment and sky conditions; study the already available theoretical tools and/or simulation methods and whether they are able to predict the light pipe performance in the Greek environment and sky conditions; develop methodology/ies for the prediction of the light pipe lighting performance in the specific context; explore how light pipes can be efficiently combined with artificial lighting and controls and what is the magnitude of the energy savings achieved.

Predicting the performance of light pipes is not a straightforward task. Comparison of two theoretical methodologies, the Luxplot method developed by Jenkins et. al. (Jenkins, Muneer and Kubie, 2005) and the TTE method described in CIE Technical Report 173:2012 with permission of Solar Project SRL (Solarspot International, 2008; CIE, 2012a) and of simulations, showed that the results may differ significantly. The theoretical methodologies studied were based on field studies of light pipe systems that could differ considerably.

Using a computer program to simulate the performance of a light pipe modelled accurately, showed that backward raytracing cannot be used. For tube lengths greater than 0.5m the software would fail to give any light distribution in the interior.

The methods that provided comparable results were the Luxplot method and the TTE method, using in both cases, the Flux from the TTE method. The magnitude of difference between the illuminance results of the Luxplot and simulations of the light pipe as a cosine luminous intensity distribution luminaire, can reach 80%, with the Luxplot method giving higher values. Equations providing the average illuminance from one light pipe in a rectangular space were developed for all the tested methodologies, for easier and faster application. The inconsistency of the results from the application of the existing methodologies and algorithms leads to the conclusion that data from measurements under laboratory conditions needs to be acquired and compared to the theoretical results. The comparison would hopefully provide information about which the described methodologies is more accurate for the sky conditions of Athens, Greece.

An experiment was set up to test the performance of a light pipe in the weather/sky conditions of Athens, Greece. A lighting system, consisting of a light pipe, LED lamps and daylight linked controls was designed and constructed in a test cell, located at the Kapodistrian University of Athens, Greece, campus. The parameters initially monitored were the exterior and interior illuminance, the luminance, and the energy consumption of the designed system. The testing period lasted for approximately 7 months, from November 28th, 2014 until the beginning of August 2015 (no data was recorded in January 2015). Unfortunately, after August 2015, the collection of data for the artificial lighting, the combination of natural and artificial lighting, as well as the consumed energy was impossible, due to technical problems. Consequently, the analysis of the light pipe performance, i.e., the interior illuminance achieved by the light pipe, was based on the experimental data, while the analysis of the artificial lighting and energy savings was based on calculations.

The data acquired from the experiment show that the light pipe installed in the test cell offers 100 lux of interior illuminance on average, while the average DPF is around 0.15%. The maximum indoor illuminance recorded by a sensor throughout the testing period was 8.4 klux (sensor 4), on 26/04/2015, 12:15 pm. At the same moment, the minimum illuminance was 38 lux (sensor 11), the average illuminance in the space was 1,043 lux, while the exterior illuminance 120 klux (Table 22). The bright patches of light on the reference plane during clear sky days, decrease the uniformity, which on average is 0.26. Uniformity is higher when the sky is relatively clear and when the reference plane is limited to the area under the light pipe diffuser. This shows that light pipes are downward emitting lighting systems and explains why the environment, i.e., the reflectance of the walls, has a small effect on the distribution of the light on the reference plane.

The indoor illuminance values were found to present a strong temporal and spatial variability. The analysis showed that the average indoor illuminance varies strongly as a function of the sky clearness and of the exterior illuminance levels. A significant reduction of the average indoor illuminance is observed for increasing K_d values, i.e., for cloudy skies. As measured, under clear sky conditions ($0.07 < K_d < 0.14$), the average indoor illuminance was about five times higher than during the almost fully cloudy period ($0.84 < K_d < 0.93$). It was also found that the relation between the average indoor and outdoor illuminance is almost exponential.

The distribution of the natural light levels on the reference plane during cloudy sky conditions was symmetrical, with the levels falling as the distance from the centre (under the diffuser) was increasing. Under clear sky conditions the distribution loses its symmetry as the sun altitude increases. The transmitted beam radiation was reflected towards the east-west axis of the room.

The illuminance delivered by the light pipe on the reference plane was expressed as formulae, with the independent variable being the exterior illuminance. The sky clearness was also considered, as each of the 10 developed formulae corresponds to one of 10 K_d clusters. The developed equations can be used for light pipes installed in Athens, Greece, under any sky conditions. The effect of the light pipe geometry can be accounted for by incorporating the efficiency values of guides of various diameters, lengths and reflectance properties provided by the CIE Technical Report: Tubular daylight guidance systems (CIE, 2012) in the calculations. The effect of the space characteristics on the lighting levels, except from the distance between the diffuser and the reference plane, is ignored, as light pipes are mainly downward emitting systems. The R-squared for the developed equations ranges between 0.90 and 0.99.

The experimental data was then compared to the results of forward ray tracing simulations. The minimum error of the average interior illuminance that resulted from the simulations was 32% and was observed for exterior illuminances between 80 and 90 klux; the maximum error was approximately 62% and was found to occur for low exterior illuminances. Forward ray tracing is found to overestimate the light pipe performance for exterior illuminances lower than 50 klux and underestimate it for exterior illuminances above that value of exterior illuminance. The distribution of light on the reference plane of the simulation model was symmetrical around the light pipe, regardless of the exterior conditions, unlike the experimental distribution, where the east-west axis had increased lighting levels during clear sky conditions.

The comparison of the interior illuminance values calculated using the equations developed and described in Chapter 3: with the respective experimental data showed that the equations for the TTE and Luxplot methods give results that are considerably different than the experimental data. The average error was 56% for the Luxplot method, 53% for the TTE method, 35% for simulating the light pipe as a luminaire, 40% for simulations the forward ray tracing technique and 9-36% for the equations developed using the experimental data.

Since it was not possible to use experimental data for the lighting or energy consumption of the artificial lights installed in the test cell, simulations were used for estimating the used power for artificial lighting systems used in conjunction with light pipes. The artificial lighting systems that were simulated were two: a system like the one installed in the test cell and an "office system", i.e., LED lamps, commonly used in office spaces, installed in an ortho-canonical grid, while the room modelled had the characteristics of the test cell (size, reflectance values). All the systems were dimmed according to the available daylight levels in the space. However, only one system (Task 4) had two dimming groups, depending on the proximity to the natural lighting source. More specifically, the tasks investigated were:

- Task 1: Lighting power used to achieve minimum illuminances of 100, 200 and 300 lux using the experimental lighting system,
- Task 2: Lighting power used to achieve average illuminances of 100, 200 and 300 lux using the experimental lighting system,
- Task 3: Lighting power used to achieve minimum illuminances of 100, 200, 300 and 400 lux from an "office lighting system",
- Task 4: Lighting power used to achieve minimum illuminance of 300 lux from an "office lighting system" with luminaire dimming groups.

Equations for the calculation of the used power of the artificial lighting systems of Tasks 1-3 were developed, for the whole experimental period and for each month within that period, with independent variables being the exterior illuminance (E_{ex}), the sun azimuth (α) and altitude (γ) and the sky diffuse coefficient (K_d). The analysis of the beta coefficients of each of the independent variables, showed that the exterior illuminance (E_{ex}) has the strongest effect on the power, followed by the sun altitude and the sun azimuth, while the variable that plays the least important role is the sky diffuse coefficient. These equations can be used under specific conditions which should be the same with these of the experiment, in terms of location, room and light pipe characteristics and lamps.

The four examples consume 10 to 38% less energy than if the respective artificial lighting system was the only light source in the space. Comparison of the results for the used power for the four tasks show that the tasks that required an average illuminance value to be achieved provided greater savings than the ones where the same illuminance value was required as a minimum on the reference plane. Task 4, where the luminaires were grouped depending on their distance from the source of daylight, presented approximately 14% lower energy consumption from task 2, where all the luminaires were in the same dimming group and positioned around the light pipe diffuser. As a general note, the layout of luminaires in an ortho-canonical grid provides greater energy savings and better uniformity levels and should be preferred for environments with increased lighting quality requirements.

The results presented in this Thesis apply to the specific environment and lighting systems used and simulated and are intended to showcase methodologies, rather than provide formulas for universal use. It should be mentioned however, that the effect of various interior surface reflectances would only be significant for environments where the light sources are positioned relatively close to the walls, and for luminaires with widespread light emissions. For light sources with narrow downward light emission, like the light pipe, the reflectances of the ceiling and of the side walls do not affect the illuminance distribution on a horizontal reference plane significantly. User intervention that can significantly change the energy consumption is also not considered.

Light pipes are lighting systems that can provide natural light to spaces and areas with no openings, where vertical illuminance is of small importance. Domestic corridors, basements and storage rooms would be adequately lit by a few only units. Working environments can also benefit from the use of light pipes, especially in environments with high exterior illumination, like Greece. The experiment carried out in this study showed that one light pipe, of 0.30 m diameter and 2.60 m length, can provide 100 lux of light on average to a space with an area of 5 m^2, approximately. This illuminance can provide one third to half of the necessary illuminance levels for general lighting in an office space, leading to substantial energy savings. At the same time, light pipes provide time cues, even though they cannot provide view.

The cost of light pipes, which has not been examined in this Thesis, as well as the poor incorporation of artificial lighting in the same device, are probably the main obstacles in the widespread use of this technology. Future research that would enable the resolution of these issues is required for this system to gain functionality and applicability.

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Appendix I

Results of the application of the TTE method and of the algorithm produced by the TTE method (**21**) for the calculation of the average illuminance E_{pipe} on the reference plane. Each table of results is followed by the respective graph giving the correlation of the illuminance calculated with the two methods.

Room surface reflectances (%): Walls/Ceiling/Floor-Reference Plane=50/70/30

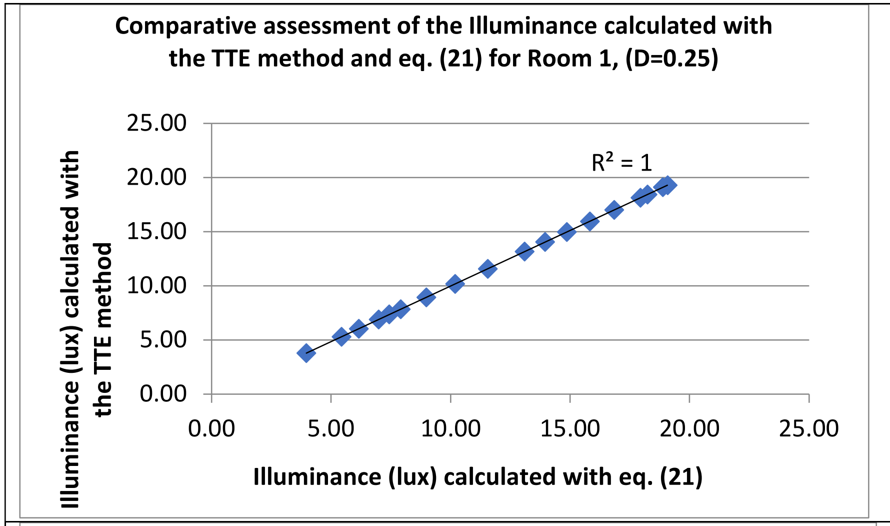
Reference plane: 0.85m above the floor and 0.50m offset from the walls

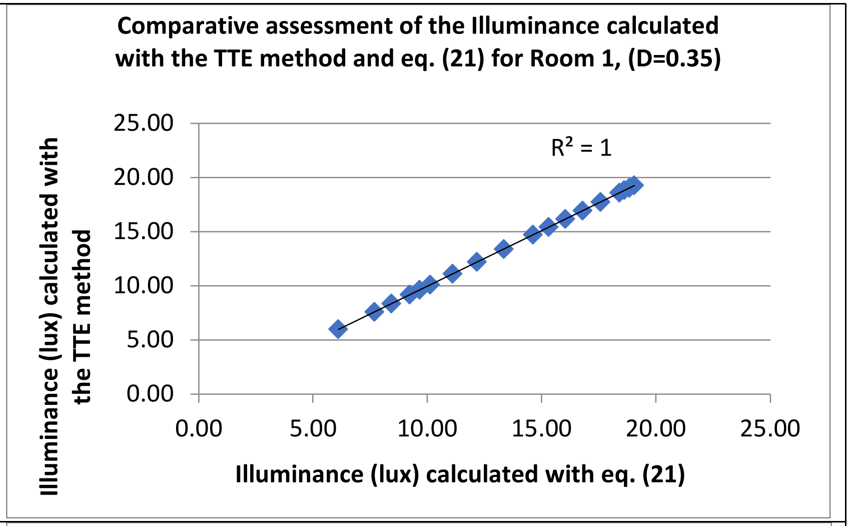
τ_{dome} x τ_{dif}=0.82. ρ=0.98. MF=0.9

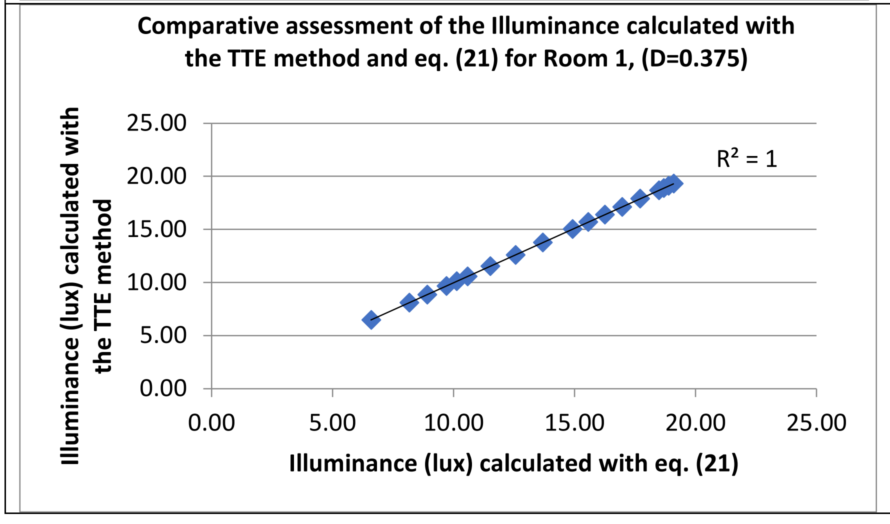
E_{ex}=5,000 lux

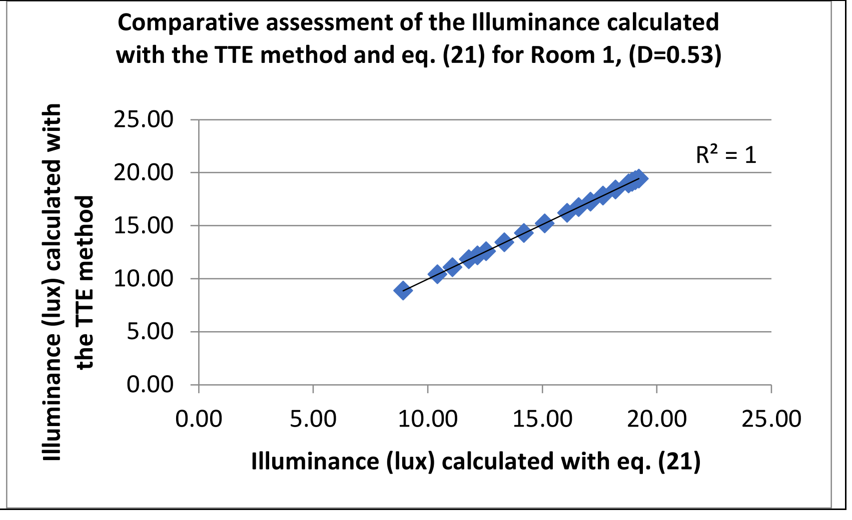
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
4.00	4.00	3.00	0.25	0.25	0.98	177.42	0.38	19.07	19.30
				0.50	0.97	175.61	0.38	18.88	19.10
				0.75	0.94	169.53	0.36	18.22	18.42
				1.00	0.92	166.88	0.36	17.94	18.13
				2.00	0.87	156.69	0.34	16.84	17.01
				3.00	0.81	147.12	0.32	15.82	15.95
				4.00	0.76	138.14	0.30	14.85	14.96
				5.00	0.72	129.70	0.28	13.94	14.03
				6.00	0.67	121.78	0.26	13.09	13.16
				8.00	0.59	107.37	0.23	11.54	11.57
				10.00	0.52	94.66	0.20	10.18	10.17
				12.00	0.46	83.45	0.18	8.97	8.93
				14.00	0.41	73.57	0.16	7.91	7.84
				15.00	0.38	69.08	0.15	7.43	7.35
				16.00	0.36	64.86	0.14	6.97	6.88
				18.00	0.32	57.18	0.12	6.15	6.03
				20.00	0.28	50.41	0.11	5.42	5.29
				25.00	0.20	36.79	0.08	3.96	3.78
4.00	4.00	3.00	0.35	0.25	0.98	347.31	0.38	19.05	19.27
				0.50	0.97	343.34	0.38	18.83	19.05
				0.75	0.96	339.41	0.37	18.62	18.83
				1.00	0.95	335.53	0.37	18.40	18.61
				2.00	0.90	320.45	0.35	17.58	17.76
				3.00	0.86	306.04	0.34	16.79	16.95
				4.00	0.82	292.28	0.32	16.03	16.17
				5.00	0.79	279.14	0.31	15.31	15.44
				6.00	0.75	266.59	0.29	14.62	14.73
				8.00	0.69	243.16	0.27	13.34	13.41
				10.00	0.63	221.79	0.24	12.16	12.21
				12.00	0.57	202.29	0.22	11.10	11.11
				14.00	0.52	184.51	0.20	10.12	10.11
				15.00	0.50	176.22	0.19	9.67	9.64
				16.00	0.47	168.29	0.18	9.23	9.20
				18.00	0.43	153.50	0.17	8.42	8.36
				20.00	0.39	140.01	0.15	7.68	7.61
				25.00	0.31	111.24	0.12	6.10	5.99

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
4.00	4.00	3.00	0.38	0.25	0.98	399.48	0.38	19.09	19.31
				0.50	0.97	395.21	0.38	18.88	19.10
				0.75	0.96	390.98	0.37	18.68	18.89
				1.00	0.95	386.80	0.37	18.48	18.69
				2.00	0.91	370.52	0.35	17.70	17.89
				3.00	0.87	354.93	0.34	16.96	17.13
				4.00	0.83	339.99	0.32	16.24	16.39
				5.00	0.80	325.68	0.31	15.56	15.69
				6.00	0.77	311.97	0.30	14.91	15.02
				8.00	0.70	286.26	0.27	13.68	13.76
				10.00	0.64	262.67	0.25	12.55	12.60
				12.00	0.59	241.03	0.23	11.52	11.54
				14.00	0.54	221.17	0.21	10.57	10.57
				15.00	0.52	211.86	0.20	10.12	10.11
				16.00	0.50	202.94	0.19	9.70	9.68
				18.00	0.46	186.22	0.18	8.90	8.86
				20.00	0.42	170.87	0.16	8.16	8.10
				25.00	0.34	137.82	0.13	6.58	6.48
4.00	4.00	3.00	0.53	0.25	0.99	803.27	0.84	41.77	19.35
				0.50	0.98	797.07	0.83	41.45	19.19
				0.75	0.97	790.92	0.82	41.13	19.04
				1.00	0.96	784.81	0.82	40.81	18.89
				2.00	0.94	760.85	0.79	39.56	18.30
				3.00	0.91	737.63	0.77	38.36	17.73
				4.00	0.88	715.11	0.74	37.19	17.18
				5.00	0.85	693.28	0.72	36.05	16.65
				6.00	0.83	672.12	0.70	34.95	16.13
				8.00	0.78	631.72	0.66	32.85	15.14
				10.00	0.73	593.74	0.62	30.87	14.20
				12.00	0.69	558.05	0.58	29.02	13.33
				14.00	0.64	524.50	0.55	27.27	12.50
				15.00	0.62	508.49	0.53	26.44	12.11
				16.00	0.61	492.97	0.51	25.63	11.73
				18.00	0.57	463.33	0.48	24.09	11.00
				20.00	0.54	435.48	0.45	22.64	10.32
				25.00	0.46	372.95	0.39	19.39	8.79


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 1, (D=0.25)
R² = 1
25.00
20.00
15.00
10.00
5.00
0.00
0.00
5.00
10.00
15.00
20.00
25.00
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)

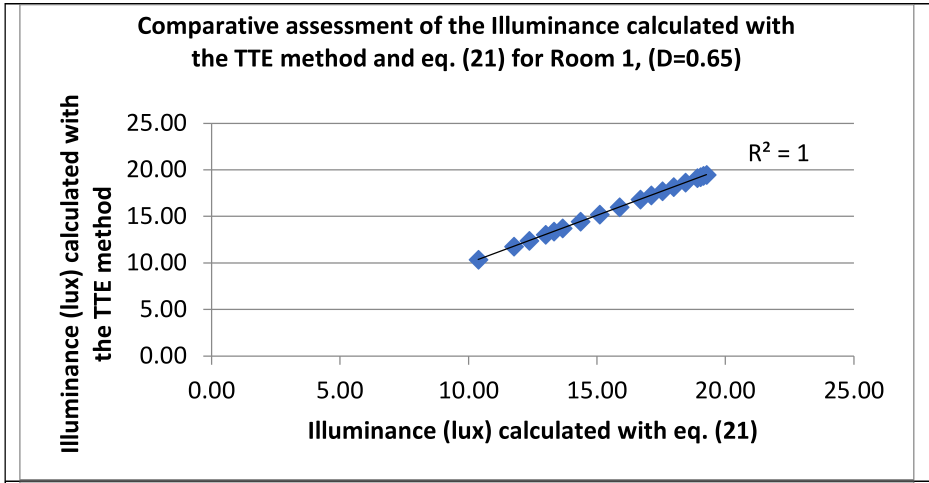

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 1, (D=0.35)
R² = 1
25.00
20.00
15.00
10.00
5.00
0.00
0.00
5.00
10.00
15.00
20.00
25.00
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)

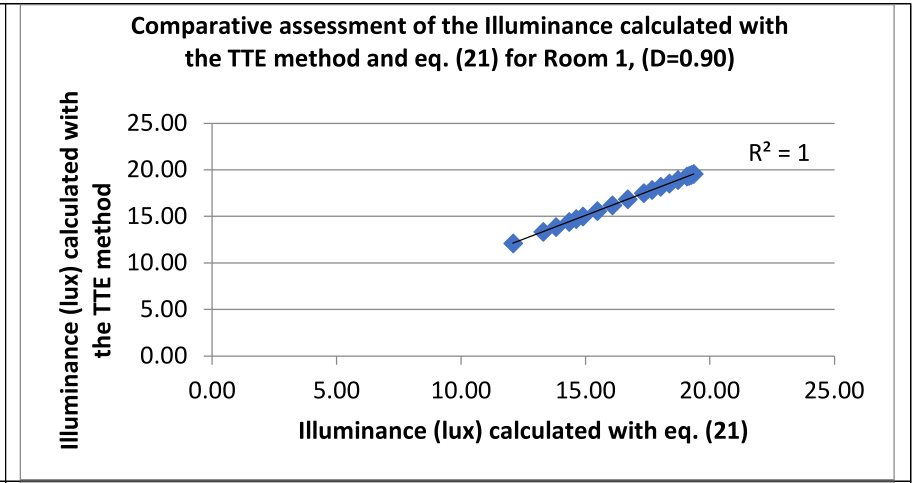

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 1, (D=0.375)
R² = 1
25.00
20.00
15.00
10.00
5.00
0.00
0.00
5.00
10.00
15.00
20.00
25.00
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)

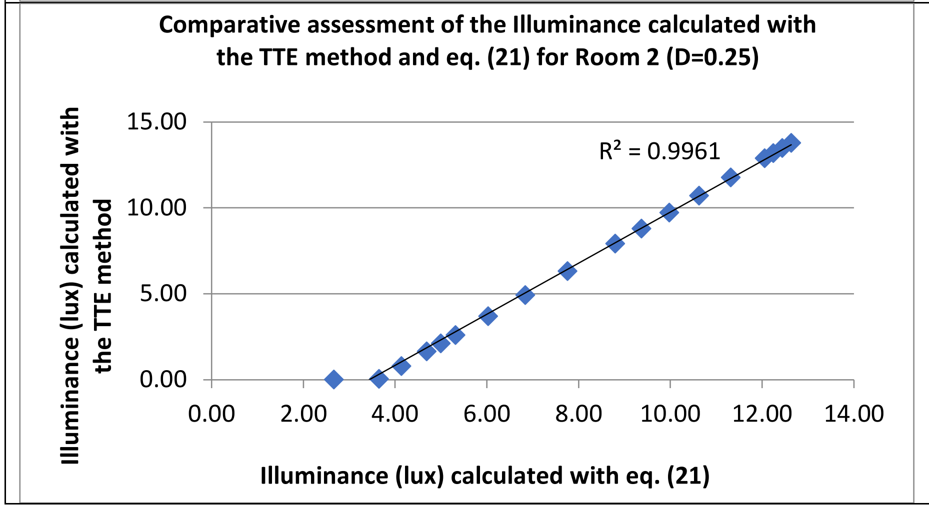

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 1, (D=0.53)
R² = 1
25.00
20.00
15.00
10.00
5.00
0.00
0.00
5.00
10.00
15.00
20.00
25.00
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)

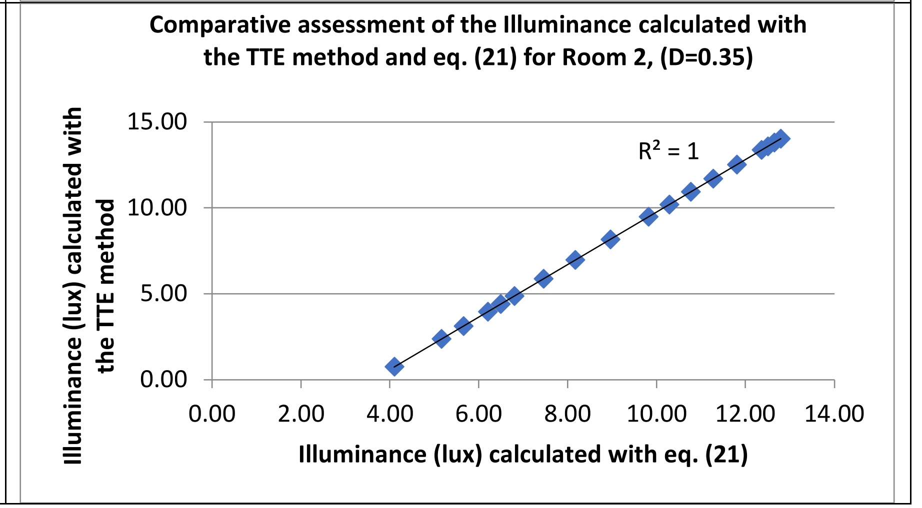
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
4.00	4.00	3.00	0.65	0.25	0.99	1211.10	0.39	19.26	19.49
				0.50	0.98	1203.56	0.38	19.14	19.36
				0.75	0.98	1196.06	0.38	19.02	19.24
				1.00	0.97	1188.60	0.38	18.90	19.12
				2.00	0.95	1159.26	0.37	18.44	18.64
				3.00	0.92	1130.64	0.36	17.98	18.17
				4.00	0.90	1102.72	0.35	17.54	17.72
				5.00	0.88	1075.49	0.34	17.10	17.27
				6.00	0.86	1048.94	0.33	16.68	16.84
				8.00	0.82	997.78	0.32	15.87	16.01
				10.00	0.78	949.12	0.30	15.09	15.21
				12.00	0.74	902.83	0.29	14.36	14.46
				14.00	0.70	858.80	0.27	13.66	13.74
				15.00	0.68	837.60	0.27	13.32	13.39
				16.00	0.67	816.92	0.26	12.99	13.06
				18.00	0.63	777.07	0.25	12.36	12.41
				20.00	0.60	739.18	0.24	11.76	11.79
				25.00	0.53	652.32	0.21	10.37	10.37
4.00	4.00	3.00	0.90	0.25	0.99	2331.67	0.39	19.34	19.57
				0.50	0.99	2320.62	0.38	19.25	19.48
				0.75	0.98	2309.62	0.38	19.16	19.38
				1.00	0.98	2298.67	0.38	19.07	19.29
				2.00	0.96	2255.41	0.37	18.71	18.92
				3.00	0.94	2212.96	0.37	18.36	18.56
				4.00	0.93	2171.31	0.36	18.01	18.21
				5.00	0.91	2130.45	0.35	17.67	17.86
				6.00	0.89	2090.35	0.35	17.34	17.52
				8.00	0.86	2012.41	0.33	16.69	16.85
				10.00	0.83	1937.37	0.32	16.07	16.21
				12.00	0.79	1865.13	0.31	15.47	15.60
				14.00	0.77	1795.59	0.30	14.89	15.01
				15.00	0.75	1761.79	0.29	14.61	14.72
				16.00	0.74	1728.64	0.29	14.34	14.44
				18.00	0.71	1664.18	0.28	13.80	13.89
				20.00	0.68	1602.13	0.27	13.29	13.36
				25.00	0.62	1456.93	0.24	12.09	12.13

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
4.00	4.00	5.00	0.25	0.25	0.97	174.95	0.25	12.63	13.78
				0.50	0.95	172.22	0.25	12.43	13.48
				0.75	0.94	169.53	0.24	12.24	13.18
				1.00	0.92	166.88	0.24	12.05	12.89
				2.00	0.87	156.69	0.23	11.31	11.77
				3.00	0.81	147.12	0.21	10.62	10.71
				4.00	0.76	138.14	0.20	9.97	9.72
				5.00	0.72	129.70	0.19	9.36	8.79
				6.00	0.67	121.78	0.18	8.79	7.92
				8.00	0.59	107.37	0.16	7.75	6.33
				10.00	0.52	94.66	0.14	6.83	4.93
				12.00	0.46	83.45	0.12	6.02	3.69
				14.00	0.41	73.57	0.11	5.31	2.60
				15.00	0.38	69.08	0.10	4.99	2.11
				16.00	0.36	64.86	0.09	4.68	1.64
				18.00	0.32	57.18	0.08	4.13	0.79
				20.00	0.28	50.41	0.07	3.64	0.05
				25.00	0.20	36.79	0.05	2.66	0.00
4.00	4.00	5.00	0.35	0.25	0.98	347.31	0.26	12.79	14.03
				0.50	0.97	343.34	0.25	12.64	13.81
				0.75	0.96	339.41	0.25	12.50	13.59
				1.00	0.95	335.53	0.25	12.36	13.37
				2.00	0.90	320.45	0.24	11.80	12.52
				3.00	0.86	306.04	0.23	11.27	11.71
				4.00	0.82	292.28	0.22	10.76	10.93
				5.00	0.79	279.14	0.21	10.28	10.19
				6.00	0.75	266.59	0.20	9.82	9.49
				8.00	0.69	243.16	0.18	8.96	8.17
				10.00	0.63	221.79	0.16	8.17	6.97
				12.00	0.57	202.29	0.15	7.45	5.87
				14.00	0.52	184.51	0.14	6.80	4.87
				15.00	0.50	176.22	0.13	6.49	4.40
				16.00	0.47	168.29	0.12	6.20	3.96
				18.00	0.43	153.50	0.11	5.65	3.12
				20.00	0.39	140.01	0.10	5.16	2.37
				25.00	0.31	111.24	0.08	4.10	0.75


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 1, (D=0.65)
Illuminance (lux) calculated with the TTE method
25.00
20.00
15.00
10.00
5.00
0.00
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00
Illuminance (lux) calculated with eq. (21)

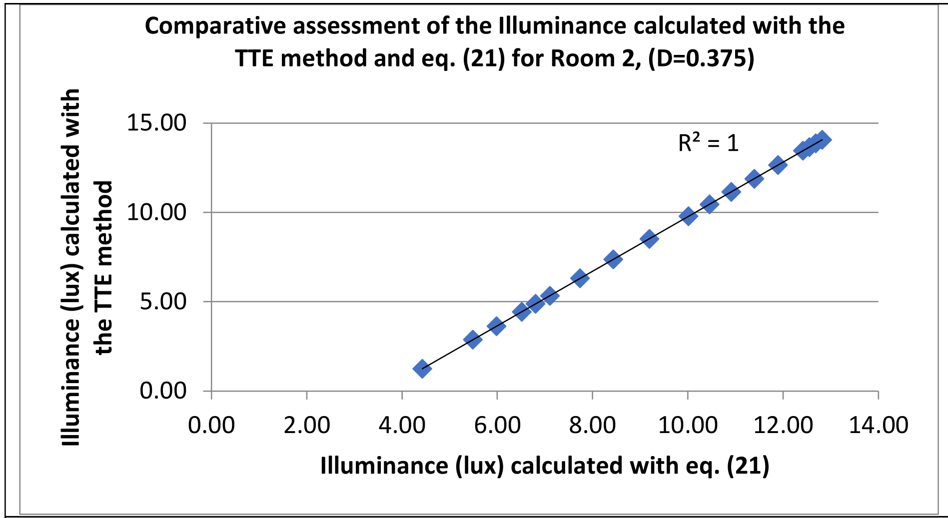

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 1, (D=0.90)
Illuminance (lux) calculated with the TTE method
25.00
20.00
15.00
10.00
5.00
0.00
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00
Illuminance (lux) calculated with eq. (21)

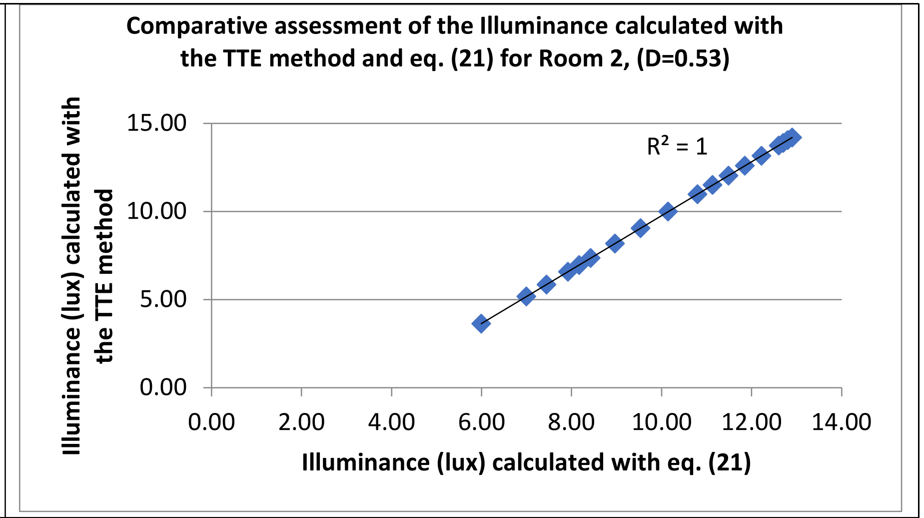

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 2 (D=0.25)
Illuminance (lux) calculated with the TTE method
15.00
10.00
5.00
0.00
R² = 0.9961
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
Illuminance (lux) calculated with eq. (21)

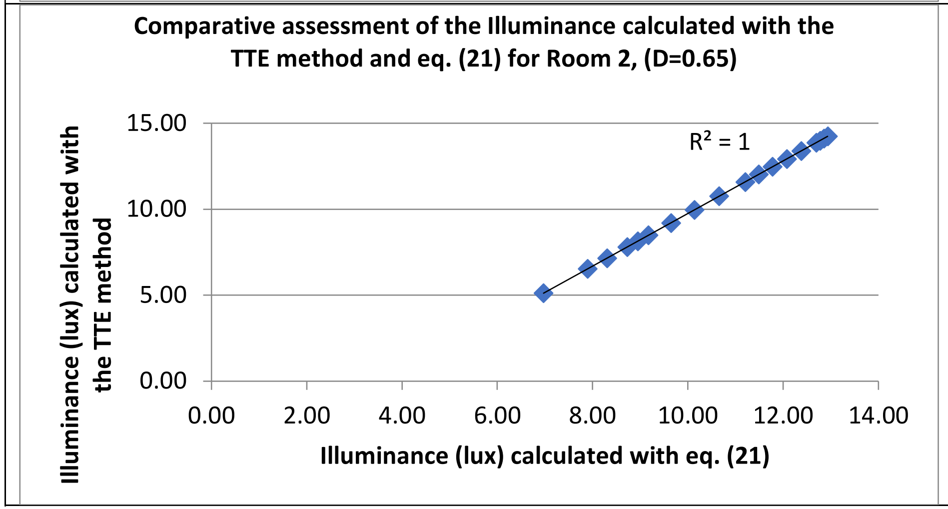

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 2, (D=0.35)
Illuminance (lux) calculated with the TTE method
15.00
10.00
5.00
0.00
R² = 1
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
Illuminance (lux) calculated with eq. (21)

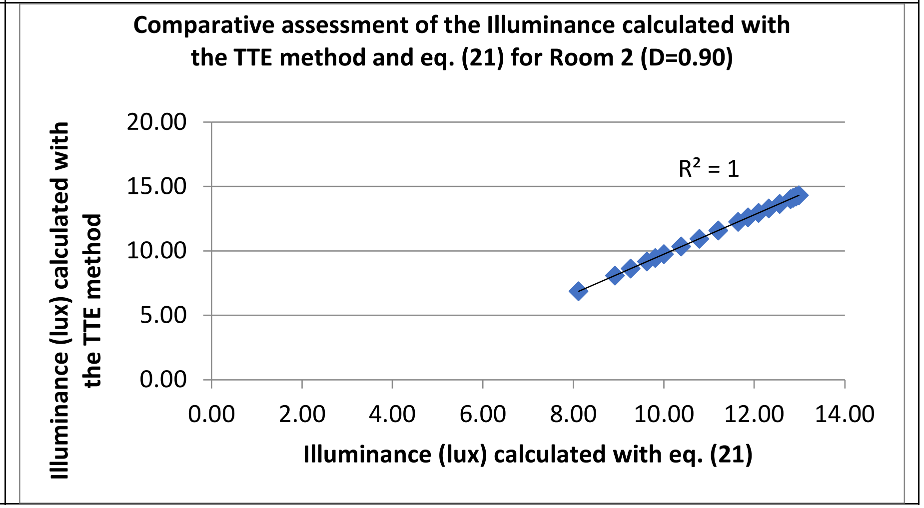
oom Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
4.00	4.00	5.00	0.375	0.25	0.98	399.48	0.26	12.82	14.07
				0.50	0.97	395.21	0.25	12.68	13.86
				0.75	0.96	390.98	0.25	12.54	13.65
				1.00	0.95	386.80	0.25	12.41	13.45
				2.00	0.91	370.52	0.24	11.89	12.65
				3.00	0.87	354.93	0.23	11.39	11.89
				4.00	0.83	339.99	0.22	10.91	11.15
				5.00	0.80	325.68	0.21	10.45	10.45
				6.00	0.77	311.97	0.20	10.01	9.78
				8.00	0.70	286.26	0.18	9.18	8.52
				10.00	0.64	262.67	0.17	8.43	7.36
				12.00	0.59	241.03	0.15	7.73	6.30
				14.00	0.54	221.17	0.14	7.10	5.33
				15.00	0.52	211.86	0.14	6.80	4.87
				16.00	0.50	202.94	0.13	6.51	4.43
				18.00	0.46	186.22	0.12	5.97	3.61
				20.00	0.42	170.87	0.11	5.48	2.86
				25.00	0.34	137.82	0.09	4.42	1.24
4.00	4.00	5.00	0.53	0.25	0.99	803.27	0.26	12.90	14.20
				0.50	0.98	797.07	0.26	12.80	14.05
				0.75	0.97	790.92	0.25	12.70	13.90
				1.00	0.96	784.81	0.25	12.60	13.75
				2.00	0.94	760.85	0.24	12.22	13.16
				3.00	0.91	737.63	0.24	11.85	12.59
				4.00	0.88	715.11	0.23	11.49	12.04
				5.00	0.85	693.28	0.22	11.13	11.50
				6.00	0.83	672.12	0.22	10.79	10.98
				8.00	0.78	631.72	0.20	10.15	9.99
				10.00	0.73	593.74	0.19	9.54	9.06
				12.00	0.69	558.05	0.18	8.96	8.18
				14.00	0.64	524.50	0.17	8.42	7.36
				15.00	0.62	508.49	0.16	8.17	6.97
				16.00	0.61	492.97	0.16	7.92	6.58
				18.00	0.57	463.33	0.15	7.44	5.86
				20.00	0.54	435.48	0.14	6.99	5.17
				25.00	0.46	372.95	0.12	5.99	3.64

oom Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
4.00	4.00	5.00	0.65	0.25	0.99	1211.10	0.26	12.93	14.25
				0.50	0.98	1203.56	0.26	12.85	14.12
				0.75	0.98	1196.06	0.26	12.77	14.00
				1.00	0.97	1188.60	0.25	12.69	13.88
				2.00	0.95	1159.26	0.25	12.38	13.40
				3.00	0.92	1130.64	0.24	12.07	12.93
				4.00	0.90	1102.72	0.24	11.77	12.48
				5.00	0.88	1075.49	0.23	11.48	12.03
				6.00	0.86	1048.94	0.22	11.20	11.60
				8.00	0.82	997.78	0.21	10.65	10.77
				10.00	0.78	949.12	0.20	10.13	9.97
				12.00	0.74	902.83	0.19	9.64	9.22
				14.00	0.70	858.80	0.18	9.17	8.50
				15.00	0.68	837.60	0.18	8.94	8.15
				16.00	0.67	816.92	0.17	8.72	7.82
				18.00	0.63	777.07	0.17	8.30	7.17
				20.00	0.60	739.18	0.16	7.89	6.55
				25.00	0.53	652.32	0.14	6.97	5.13
4.00	4.00	5.00	0.90	0.25	0.99	2331.67	0.26	12.99	14.33
				0.50	0.99	2320.62	0.26	12.93	14.24
				0.75	0.98	2309.62	0.26	12.86	14.14
				1.00	0.98	2298.67	0.26	12.80	14.05
				2.00	0.96	2255.41	0.25	12.56	13.68
				3.00	0.94	2212.96	0.25	12.33	13.32
				4.00	0.93	2171.31	0.24	12.09	12.97
				5.00	0.91	2130.45	0.24	11.87	12.62
				6.00	0.89	2090.35	0.23	11.64	12.28
				8.00	0.86	2012.41	0.22	11.21	11.61
				10.00	0.83	1937.37	0.22	10.79	10.97
				12.00	0.79	1865.13	0.21	10.39	10.36
				14.00	0.77	1795.59	0.20	10.00	9.77
				15.00	0.75	1761.79	0.20	9.81	9.48
				16.00	0.74	1728.64	0.19	9.63	9.20
				18.00	0.71	1664.18	0.19	9.27	8.65
				20.00	0.68	1602.13	0.18	8.92	8.12
				25.00	0.62	1456.93	0.16	8.11	6.89


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 2, (D=0.375)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00

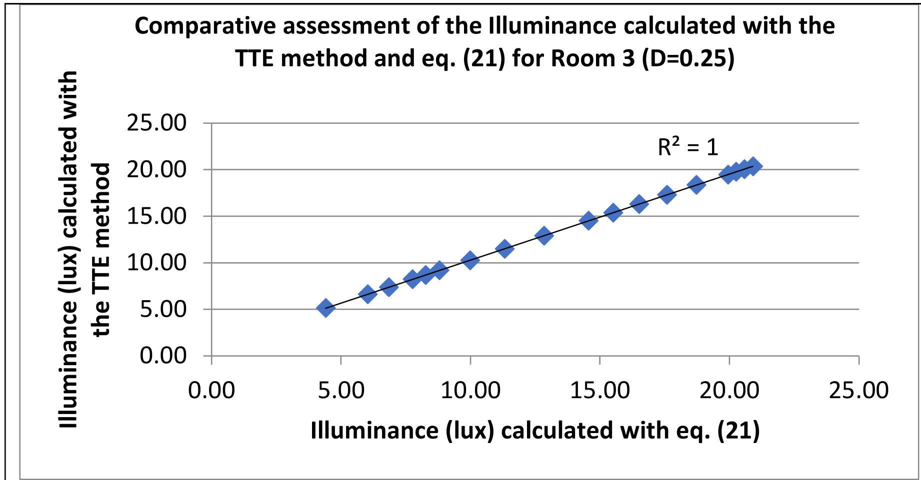

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 2, (D=0.53)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00

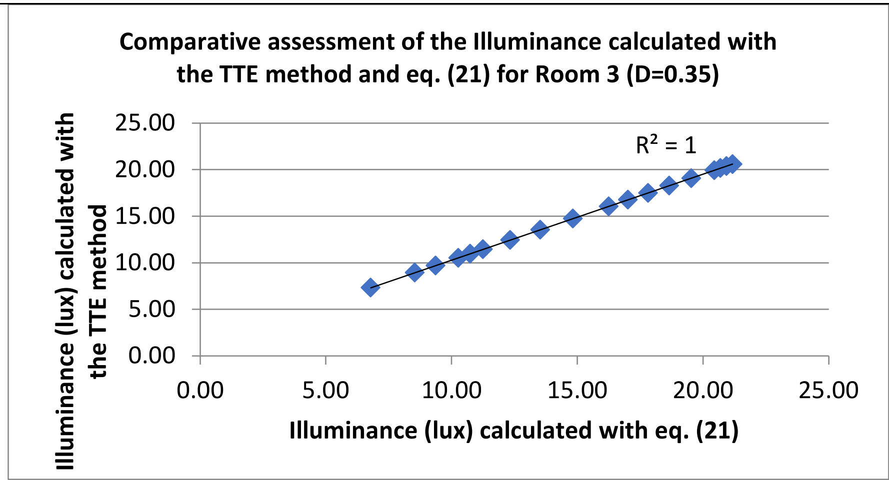

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 2, (D=0.65)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00

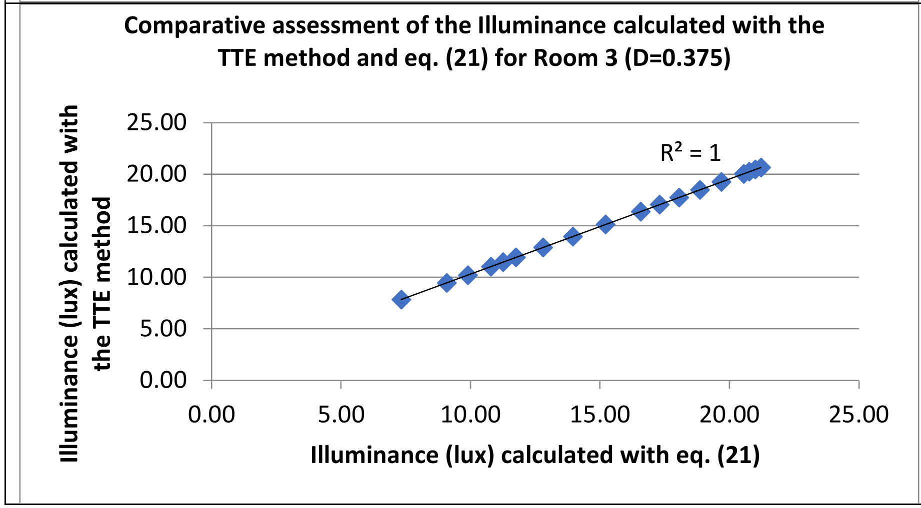

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 2 (D=0.90)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00

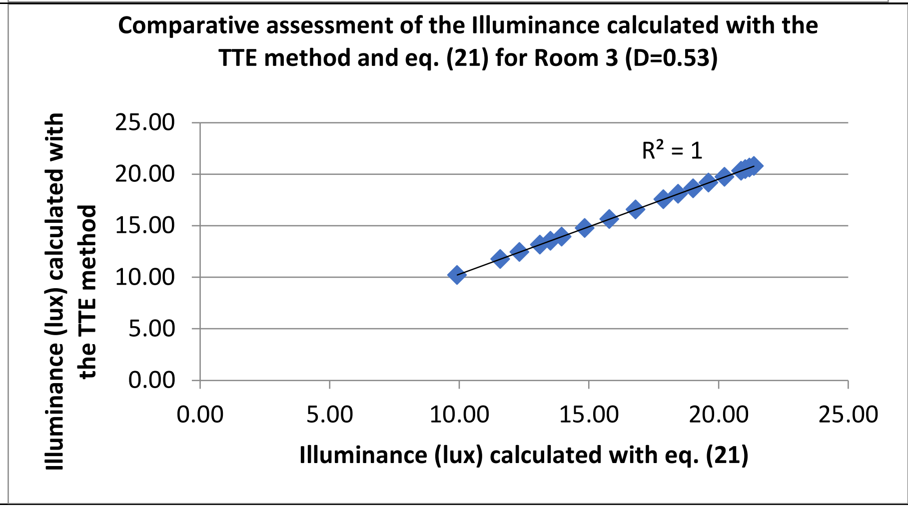
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
6.00	4.00	3.00	0.25	0.25	0.97	174.95	0.42	20.90	20.37
				0.50	0.95	172.22	0.41	20.58	20.06
				0.75	0.94	169.53	0.41	20.26	19.77
				1.00	0.92	166.88	0.40	19.94	19.48
				2.00	0.87	156.69	0.37	18.72	18.35
				3.00	0.81	147.12	0.35	17.58	17.30
				4.00	0.76	138.14	0.33	16.51	16.31
				5.00	0.72	129.70	0.31	15.50	15.38
				6.00	0.67	121.78	0.29	14.55	14.50
				8.00	0.59	107.37	0.26	12.83	12.91
				10.00	0.52	94.66	0.23	11.31	11.51
				12.00	0.46	83.45	0.20	9.97	10.27
				14.00	0.41	73.57	0.18	8.79	9.18
				15.00	0.38	69.08	0.17	8.25	8.69
				16.00	0.36	64.86	0.16	7.75	8.22
				18.00	0.32	57.18	0.14	6.83	7.38
				20.00	0.28	50.41	0.12	6.02	6.63
				25.00	0.20	36.79	0.09	4.40	5.13
6.00	4.00	3.00	0.35	0.25	0.98	347.31	0.42	21.17	20.61
				0.50	0.97	343.34	0.42	20.93	20.39
				0.75	0.96	339.41	0.41	20.69	20.17
				1.00	0.95	335.53	0.41	20.46	19.95
				2.00	0.90	320.45	0.39	19.54	19.10
				3.00	0.86	306.04	0.37	18.66	18.29
				4.00	0.82	292.28	0.36	17.82	17.52
				5.00	0.79	279.14	0.34	17.02	16.78
				6.00	0.75	266.59	0.33	16.25	16.07
				8.00	0.69	243.16	0.30	14.82	14.75
				10.00	0.63	221.79	0.27	13.52	13.55
				12.00	0.57	202.29	0.25	12.33	12.45
				14.00	0.52	184.51	0.22	11.25	11.45
				15.00	0.50	176.22	0.21	10.74	10.99
				16.00	0.47	168.29	0.21	10.26	10.54
				18.00	0.43	153.50	0.19	9.36	9.71
				20.00	0.39	140.01	0.17	8.54	8.95
				25.00	0.31	111.24	0.14	6.78	7.33

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
6.00	4.00	3.00	0.375	0.25	0.98	399.48	0.42	21.21	20.65
				0.50	0.97	395.21	0.42	20.99	20.44
				0.75	0.96	390.98	0.42	20.76	20.24
				1.00	0.95	386.80	0.41	20.54	20.03
				2.00	0.91	370.52	0.39	19.68	19.23
				3.00	0.87	354.93	0.38	18.85	18.47
				4.00	0.83	339.99	0.36	18.06	17.74
				5.00	0.80	325.68	0.35	17.30	17.03
				6.00	0.77	311.97	0.33	16.57	16.36
				8.00	0.70	286.26	0.30	15.20	15.10
				10.00	0.64	262.67	0.28	13.95	13.95
				12.00	0.59	241.03	0.26	12.80	12.88
				14.00	0.54	221.17	0.23	11.75	11.91
				15.00	0.52	211.86	0.23	11.25	11.45
				16.00	0.50	202.94	0.22	10.78	11.02
				18.00	0.46	186.22	0.20	9.89	10.20
				20.00	0.42	170.87	0.18	9.07	9.45
				25.00	0.34	137.82	0.15	7.32	7.83
6.00	4.00	3.00	0.53	0.25	0.99	803.27	0.43	21.36	20.78
				0.50	0.98	797.07	0.42	21.19	20.63
				0.75	0.97	790.92	0.42	21.03	20.48
				1.00	0.96	784.81	0.42	20.86	20.33
				2.00	0.94	760.85	0.40	20.23	19.74
				3.00	0.91	737.63	0.39	19.61	19.17
				4.00	0.88	715.11	0.38	19.01	18.62
				5.00	0.85	693.28	0.37	18.43	18.08
				6.00	0.83	672.12	0.36	17.87	17.56
				8.00	0.78	631.72	0.34	16.79	16.57
				10.00	0.73	593.74	0.32	15.79	15.64
				12.00	0.69	558.05	0.30	14.84	14.76
				14.00	0.64	524.50	0.28	13.94	13.94
				15.00	0.62	508.49	0.27	13.52	13.55
				16.00	0.61	492.97	0.26	13.11	13.17
				18.00	0.57	463.33	0.25	12.32	12.44
				20.00	0.54	435.48	0.23	11.58	11.76
				25.00	0.46	372.95	0.20	9.92	10.22


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 3 (D=0.25)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
25.00
20.00
15.00
10.00
5.00
0.00

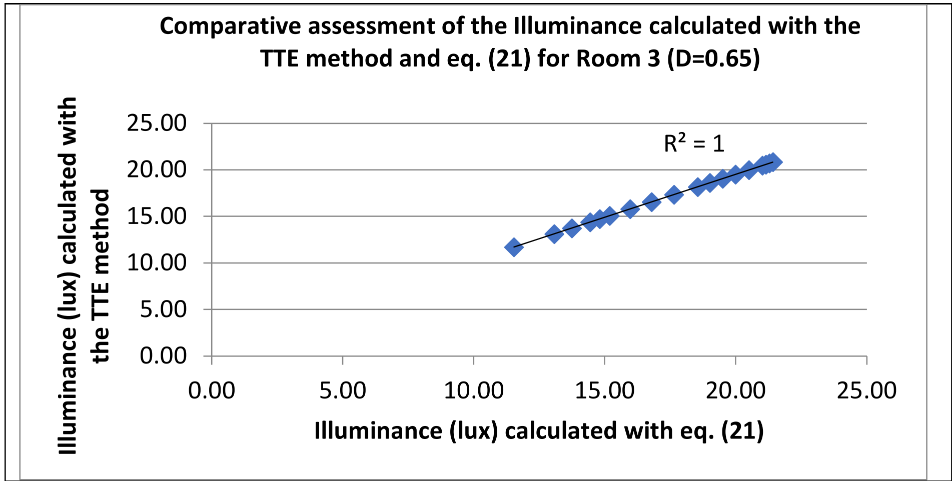

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 3 (D=0.35)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)

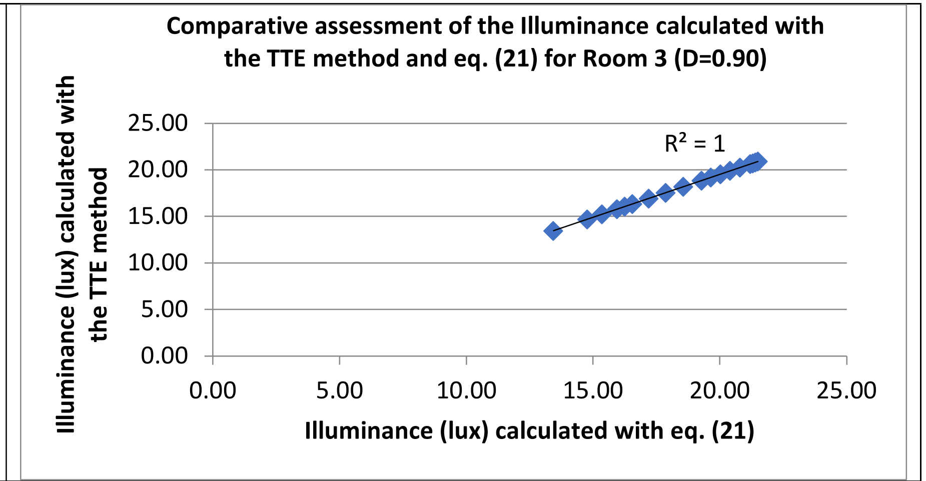

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 3 (D=0.375)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)

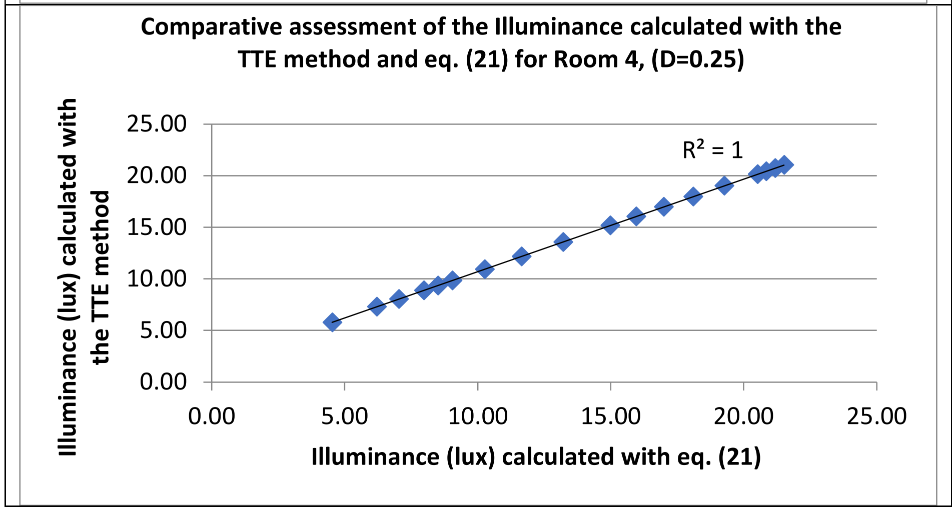

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 3 (D=0.53)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)

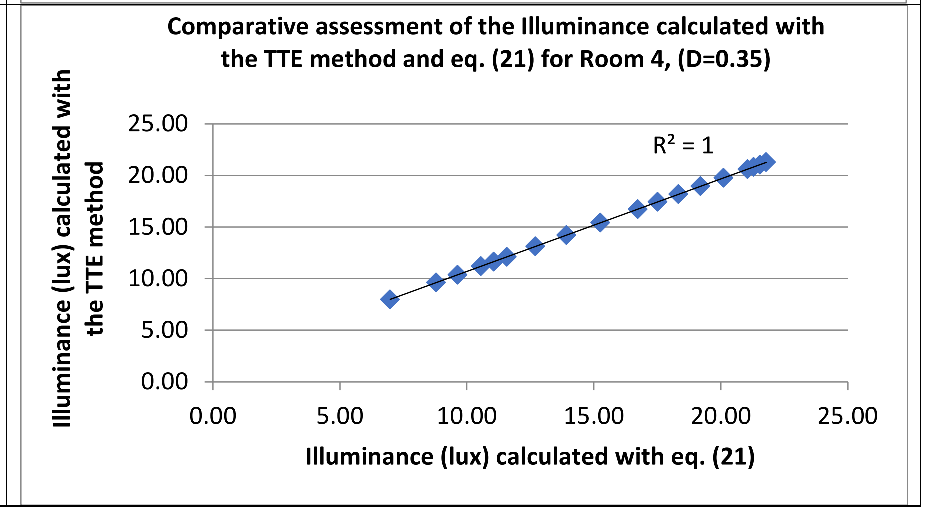
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
6.00	4.00	3.00	0.65	0.25	0.99	1211.10	0.43	21.41	20.83
				0.50	0.98	1203.56	0.43	21.27	20.71
				0.75	0.98	1196.06	0.42	21.14	20.58
				1.00	0.97	1188.60	0.42	21.01	20.46
				2.00	0.95	1159.26	0.41	20.49	19.98
				3.00	0.92	1130.64	0.40	19.98	19.52
				4.00	0.90	1102.72	0.39	19.49	19.06
				5.00	0.88	1075.49	0.38	19.01	18.62
				6.00	0.86	1048.94	0.37	18.54	18.18
				8.00	0.82	997.78	0.35	17.64	17.35
				10.00	0.78	949.12	0.34	16.78	16.56
				12.00	0.74	902.83	0.32	15.96	15.80
				14.00	0.70	858.80	0.30	15.18	15.08
				15.00	0.68	837.60	0.30	14.81	14.74
				16.00	0.67	816.92	0.29	14.44	14.40
				18.00	0.63	777.07	0.27	13.74	13.75
				20.00	0.60	739.18	0.26	13.07	13.13
				25.00	0.53	652.32	0.23	11.53	11.71
6.00	4.00	3.00	0.90	0.25	0.99	2331.67	0.43	21.50	20.91
				0.50	0.99	2320.62	0.43	21.40	20.82
				0.75	0.98	2309.62	0.43	21.29	20.73
				1.00	0.98	2298.67	0.42	21.19	20.63
				2.00	0.96	2255.41	0.42	20.79	20.26
				3.00	0.94	2212.96	0.41	20.40	19.90
				4.00	0.93	2171.31	0.40	20.02	19.55
				5.00	0.91	2130.45	0.39	19.64	19.20
				6.00	0.89	2090.35	0.39	19.27	18.86
				8.00	0.86	2012.41	0.37	18.55	18.20
				10.00	0.83	1937.37	0.36	17.86	17.56
				12.00	0.79	1865.13	0.34	17.20	16.94
				14.00	0.77	1795.59	0.33	16.55	16.35
				15.00	0.75	1761.79	0.32	16.24	16.06
				16.00	0.74	1728.64	0.32	15.94	15.78
				18.00	0.71	1664.18	0.31	15.34	15.23
				20.00	0.68	1602.13	0.30	14.77	14.70
				25.00	0.62	1456.93	0.27	13.43	13.47

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
7.00	4.00	3.00	0.25	0.25	0.97	174.95	0.43	21.51	21.04
				0.50	0.95	172.22	0.42	21.17	20.74
				0.75	0.94	169.53	0.42	20.84	20.44
				1.00	0.92	166.88	0.41	20.52	20.15
				2.00	0.87	156.69	0.39	19.27	19.02
				3.00	0.81	147.12	0.36	18.09	17.97
				4.00	0.76	138.14	0.34	16.98	16.98
				5.00	0.72	129.70	0.32	15.95	16.05
				6.00	0.67	121.78	0.30	14.97	15.17
				8.00	0.59	107.37	0.26	13.20	13.58
				10.00	0.52	94.66	0.23	11.64	12.18
				12.00	0.46	83.45	0.21	10.26	10.95
				14.00	0.41	73.57	0.18	9.05	9.86
				15.00	0.38	69.08	0.17	8.49	9.36
				16.00	0.36	64.86	0.16	7.97	8.89
				18.00	0.32	57.18	0.14	7.03	8.05
				20.00	0.28	50.41	0.12	6.20	7.30
				25.00	0.20	36.79	0.09	4.52	5.80
7.00	4.00	3.00	0.35	0.25	0.98	347.31	0.44	21.79	21.29
				0.50	0.97	343.34	0.43	21.54	21.06
				0.75	0.96	339.41	0.43	21.29	20.84
				1.00	0.95	335.53	0.42	21.05	20.62
				2.00	0.90	320.45	0.40	20.10	19.77
				3.00	0.86	306.04	0.38	19.20	18.96
				4.00	0.82	292.28	0.37	18.34	18.19
				5.00	0.79	279.14	0.35	17.51	17.45
				6.00	0.75	266.59	0.33	16.72	16.74
				8.00	0.69	243.16	0.31	15.25	15.42
				10.00	0.63	221.79	0.28	13.91	14.22
				12.00	0.57	202.29	0.25	12.69	13.12
				14.00	0.52	184.51	0.23	11.57	12.12
				15.00	0.50	176.22	0.22	11.05	11.66
				16.00	0.47	168.29	0.21	10.56	11.21
				18.00	0.43	153.50	0.19	9.63	10.38
				20.00	0.39	140.01	0.18	8.78	9.62
				25.00	0.31	111.24	0.14	6.98	8.00


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 3 (D=0.65)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00

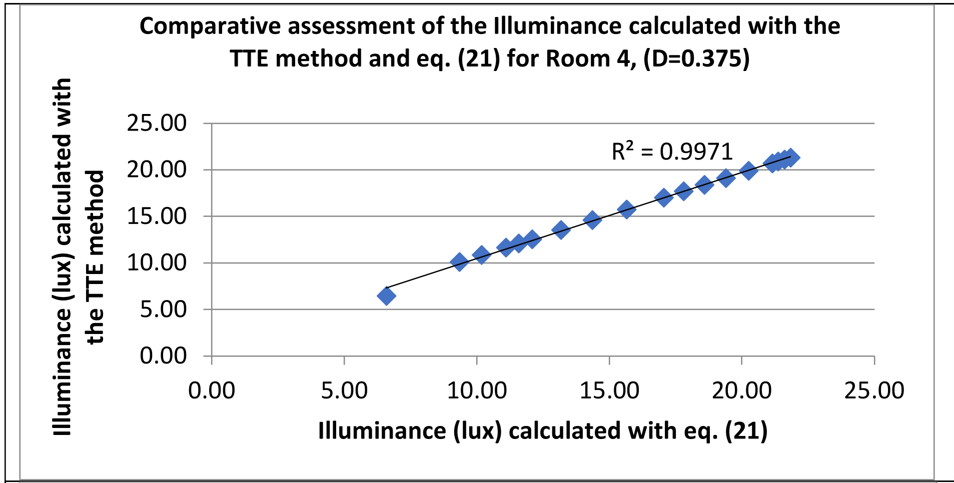

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 3 (D=0.90)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00

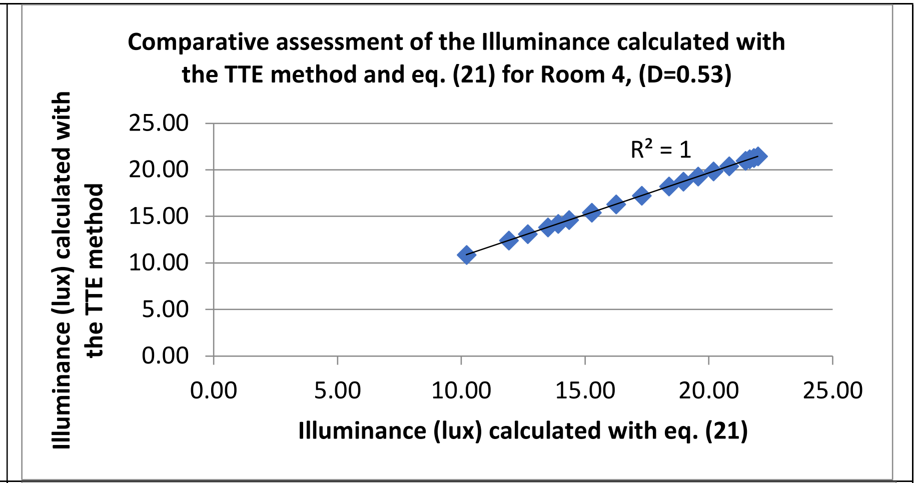

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 4, (D=0.25)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00

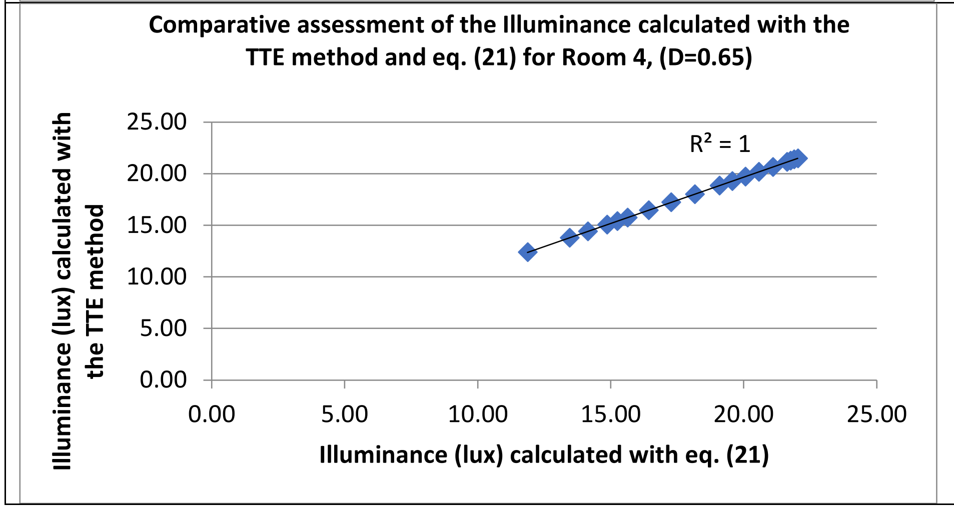

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 4, (D=0.35)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00

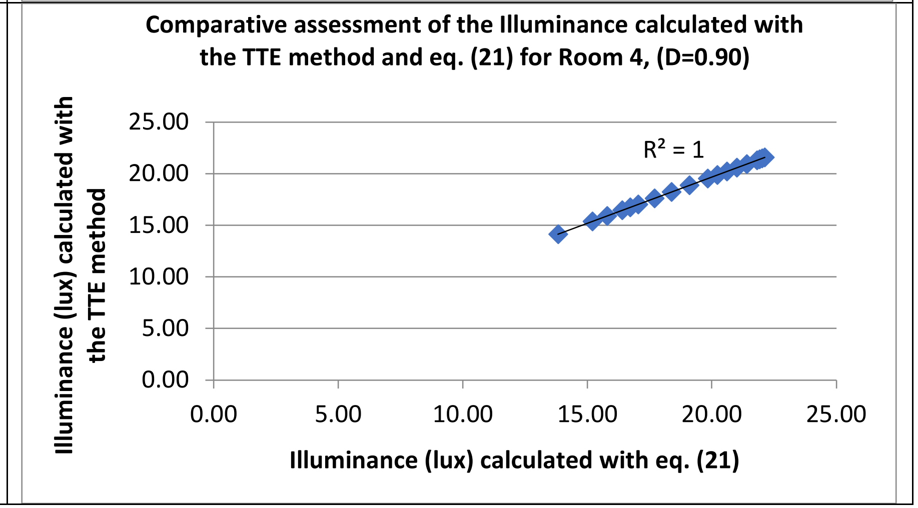
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
7.00	4.00	3.00	0.375	0.25	0.98	399.48	0.44	21.83	21.32
				0.50	0.97	395.21	0.43	21.60	21.11
				0.75	0.96	390.98	0.43	21.37	20.91
				1.00	0.95	386.80	0.42	21.14	20.70
				2.00	0.91	370.52	0.40	20.25	19.90
				3.00	0.87	354.93	0.39	19.40	19.14
				4.00	0.83	339.99	0.37	18.58	18.41
				5.00	0.80	325.68	0.36	17.80	17.71
				6.00	0.77	311.97	0.34	17.05	17.03
				8.00	0.70	286.26	0.31	15.64	15.77
				10.00	0.64	262.67	0.29	14.35	14.62
				12.00	0.59	241.03	0.26	13.17	13.56
				14.00	0.54	221.17	0.24	12.09	12.58
				15.00	0.52	211.86	0.23	11.58	12.13
				16.00	0.50	202.94	0.22	11.09	11.69
				18.00	0.46	186.22	0.20	10.18	10.87
				20.00	0.42	170.87	0.19	9.34	10.12
				25.00	0.34	137.82	0.13	6.58	6.48
7.00	4.00	3.00	0.53	0.25	0.99	803.27	0.44	21.98	21.45
				0.50	0.98	797.07	0.44	21.81	21.30
				0.75	0.97	790.92	0.43	21.64	21.15
				1.00	0.96	784.81	0.43	21.47	21.00
				2.00	0.94	760.85	0.42	20.81	20.41
				3.00	0.91	737.63	0.40	20.18	19.84
				4.00	0.88	715.11	0.39	19.56	19.29
				5.00	0.85	693.28	0.38	18.97	18.75
				6.00	0.83	672.12	0.37	18.39	18.24
				8.00	0.78	631.72	0.35	17.28	17.24
				10.00	0.73	593.74	0.32	16.24	16.31
				12.00	0.69	558.05	0.31	15.27	15.44
				14.00	0.64	524.50	0.29	14.35	14.61
				15.00	0.62	508.49	0.28	13.91	14.22
				16.00	0.61	492.97	0.27	13.49	13.84
				18.00	0.57	463.33	0.25	12.68	13.11
				20.00	0.54	435.48	0.24	11.91	12.43
				25.00	0.46	372.95	0.20	10.20	10.89

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
7.00	4.00	3.00	0.65	0.25	0.99	1211.10	0.44	22.03	21.50
				0.50	0.98	1203.56	0.44	21.89	21.38
				0.75	0.98	1196.06	0.44	21.75	21.26
				1.00	0.97	1188.60	0.43	21.62	21.13
				2.00	0.95	1159.26	0.42	21.09	20.66
				3.00	0.92	1130.64	0.41	20.56	20.19
				4.00	0.90	1102.72	0.40	20.06	19.73
				5.00	0.88	1075.49	0.39	19.56	19.29
				6.00	0.86	1048.94	0.38	19.08	18.86
				8.00	0.82	997.78	0.36	18.15	18.02
				10.00	0.78	949.12	0.35	17.26	17.23
				12.00	0.74	902.83	0.33	16.42	16.47
				14.00	0.70	858.80	0.31	15.62	15.75
				15.00	0.68	837.60	0.30	15.23	15.41
				16.00	0.67	816.92	0.30	14.86	15.07
				18.00	0.63	777.07	0.28	14.13	14.42
				20.00	0.60	739.18	0.27	13.44	13.80
				25.00	0.53	652.32	0.24	11.86	12.38
7.00	4.00	3.00	0.90	0.25	0.99	2331.67	0.44	22.12	21.58
				0.50	0.99	2320.62	0.44	22.02	21.49
				0.75	0.98	2309.62	0.44	21.91	21.40
				1.00	0.98	2298.67	0.44	21.81	21.30
				2.00	0.96	2255.41	0.43	21.40	20.94
				3.00	0.94	2212.96	0.42	20.99	20.57
				4.00	0.93	2171.31	0.41	20.60	20.22
				5.00	0.91	2130.45	0.40	20.21	19.87
				6.00	0.89	2090.35	0.40	19.83	19.53
				8.00	0.86	2012.41	0.38	19.09	18.87
				10.00	0.83	1937.37	0.37	18.38	18.23
				12.00	0.79	1865.13	0.35	17.69	17.61
				14.00	0.77	1795.59	0.34	17.04	17.02
				15.00	0.75	1761.79	0.33	16.71	16.73
				16.00	0.74	1728.64	0.33	16.40	16.45
				18.00	0.71	1664.18	0.32	15.79	15.90
				20.00	0.68	1602.13	0.30	15.20	15.38
				25.00	0.62	1456.93	0.28	13.82	14.14


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 4, (D=0.375)
R² = 0.9971
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00

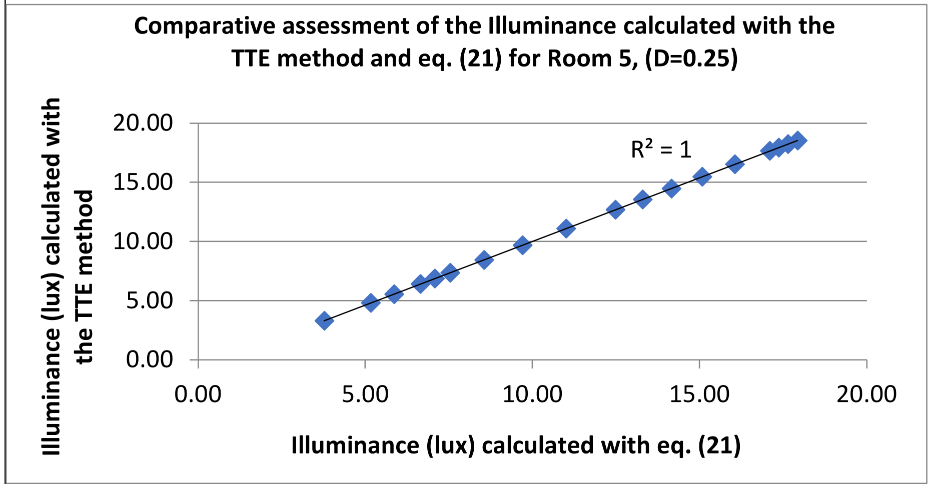

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 4, (D=0.53)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00

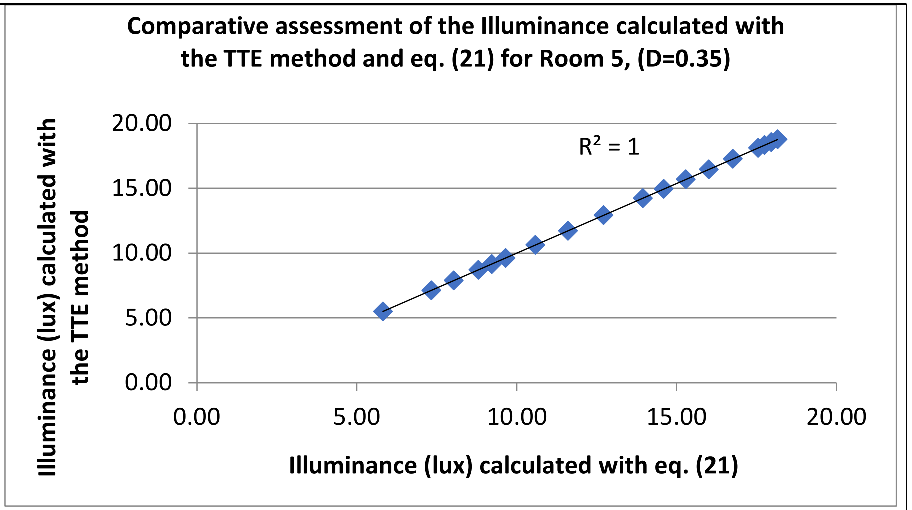

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 4, (D=0.65)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00

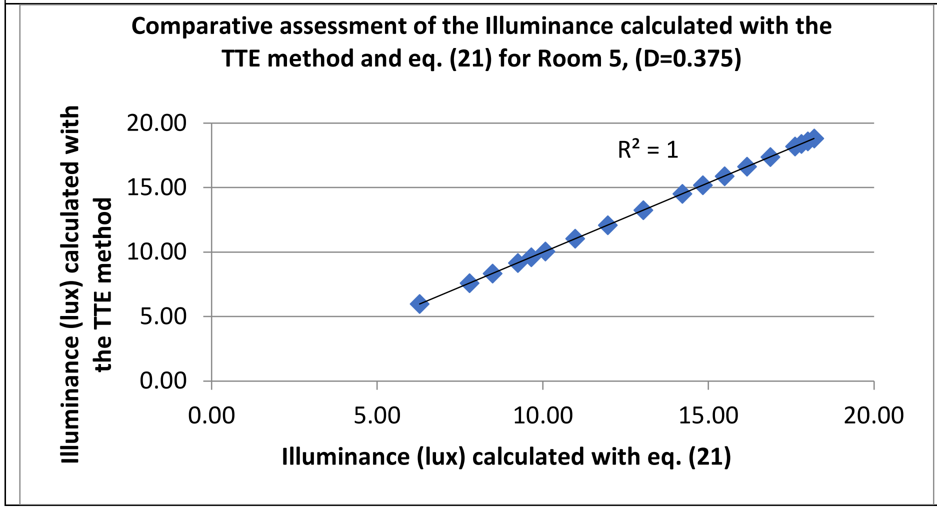

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 4, (D=0.90)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00

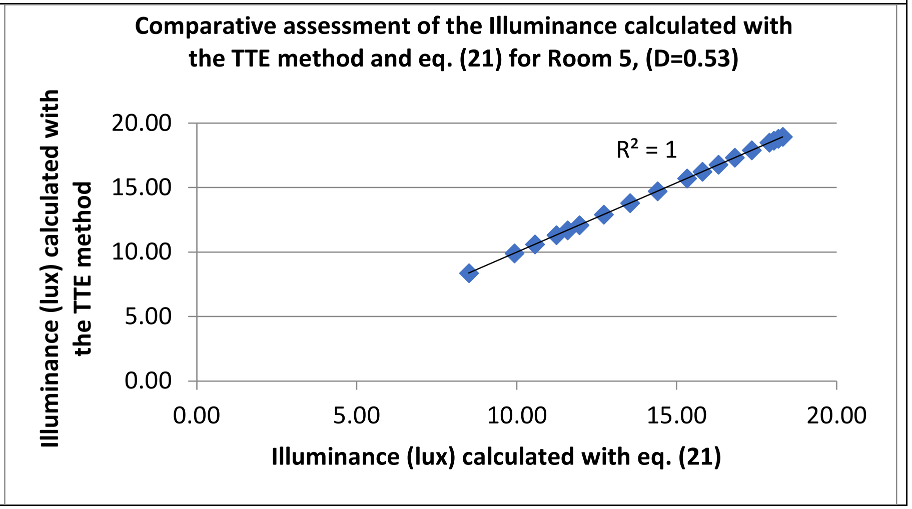
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
5.00	5.00	4.00	0.25	0.25	0.97	174.95	0.36	17.92	18.54
				0.50	0.95	172.22	0.35	17.64	18.23
				0.75	0.94	169.53	0.35	17.37	17.94
				1.00	0.92	166.88	0.34	17.10	17.65
				2.00	0.87	156.69	0.32	16.05	16.52
				3.00	0.81	147.12	0.30	15.07	15.47
				4.00	0.76	138.14	0.28	14.15	14.48
				5.00	0.72	129.70	0.27	13.29	13.55
				6.00	0.67	121.78	0.25	12.48	12.67
				8.00	0.59	107.37	0.22	11.00	11.08
				10.00	0.52	94.66	0.19	9.70	9.68
				12.00	0.46	83.45	0.17	8.55	8.44
				14.00	0.41	73.57	0.15	7.54	7.35
				15.00	0.38	69.08	0.14	7.08	6.86
				16.00	0.36	64.86	0.13	6.64	6.39
				18.00	0.32	57.18	0.12	5.86	5.55
				20.00	0.28	50.41	0.10	5.16	4.80
				25.00	0.20	36.79	0.08	3.77	3.30
5.00	5.00	4.00	0.35	0.25	0.98	347.31	0.36	18.15	18.78
				0.50	0.97	343.34	0.36	17.94	18.56
				0.75	0.96	339.41	0.35	17.74	18.34
				1.00	0.95	335.53	0.35	17.54	18.12
				2.00	0.90	320.45	0.33	16.75	17.27
				3.00	0.86	306.04	0.32	16.00	16.46
				4.00	0.82	292.28	0.31	15.28	15.69
				5.00	0.79	279.14	0.29	14.59	14.95
				6.00	0.75	266.59	0.28	13.93	14.24
				8.00	0.69	243.16	0.25	12.71	12.92
				10.00	0.63	221.79	0.23	11.59	11.72
				12.00	0.57	202.29	0.21	10.57	10.62
				14.00	0.52	184.51	0.19	9.64	9.62
				15.00	0.50	176.22	0.18	9.21	9.16
				16.00	0.47	168.29	0.18	8.80	8.71
				18.00	0.43	153.50	0.16	8.02	7.88
				20.00	0.39	140.01	0.15	7.32	7.12
				25.00	0.31	111.24	0.12	5.81	5.50

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
5.00	5.00	4.00	0.375	0.25	0.98	399.48	0.36	18.19	18.82
				0.50	0.97	395.21	0.36	17.99	18.61
				0.75	0.96	390.98	0.36	17.80	18.41
				1.00	0.95	386.80	0.35	17.61	18.20
				2.00	0.91	370.52	0.34	16.87	17.40
				3.00	0.87	354.93	0.32	16.16	16.64
				4.00	0.83	339.99	0.31	15.48	15.91
				5.00	0.80	325.68	0.30	14.83	15.20
				6.00	0.77	311.97	0.28	14.20	14.53
				8.00	0.70	286.26	0.26	13.03	13.27
				10.00	0.64	262.67	0.24	11.96	12.12
				12.00	0.59	241.03	0.22	10.97	11.06
				14.00	0.54	221.17	0.20	10.07	10.08
				15.00	0.52	211.86	0.19	9.65	9.63
				16.00	0.50	202.94	0.18	9.24	9.19
				18.00	0.46	186.22	0.17	8.48	8.37
				20.00	0.42	170.87	0.16	7.78	7.62
				25.00	0.34	137.82	0.13	6.27	6.00
5.00	5.00	4.00	**0.53**	0.25	0.99	803.27	0.37	18.31	18.95
				0.50	0.98	797.07	0.36	18.17	18.80
				0.75	0.97	790.92	0.36	18.03	18.65
				1.00	0.96	784.81	0.36	17.89	18.50
				2.00	0.94	760.85	0.35	17.34	17.91
				3.00	0.91	737.63	0.34	16.81	17.34
				4.00	0.88	715.11	0.33	16.30	16.79
				5.00	0.85	693.28	0.32	15.80	16.25
				6.00	0.83	672.12	0.31	15.32	15.73
				8.00	0.78	631.72	0.29	14.40	14.74
				10.00	0.73	593.74	0.27	13.53	13.81
				12.00	0.69	558.05	0.25	12.72	12.93
				14.00	0.64	524.50	0.24	11.95	12.11
				15.00	0.62	508.49	0.23	11.59	11.72
				16.00	0.61	492.97	0.22	11.24	11.34
				18.00	0.57	463.33	0.21	10.56	10.61
				20.00	0.54	435.48	0.20	9.93	9.93
				25.00	0.46	372.95	0.17	8.50	8.39


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 5, (D=0.25)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00

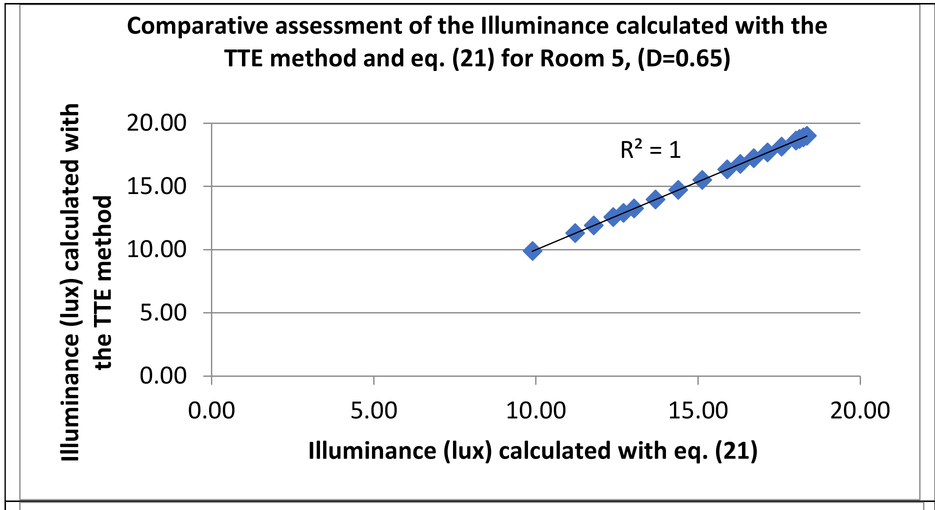

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 5, (D=0.35)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00

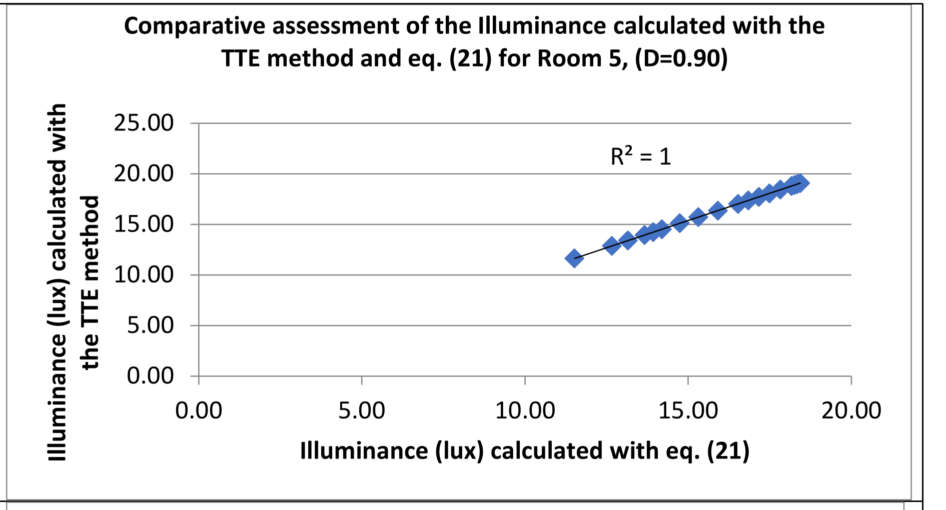

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 5, (D=0.375)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00

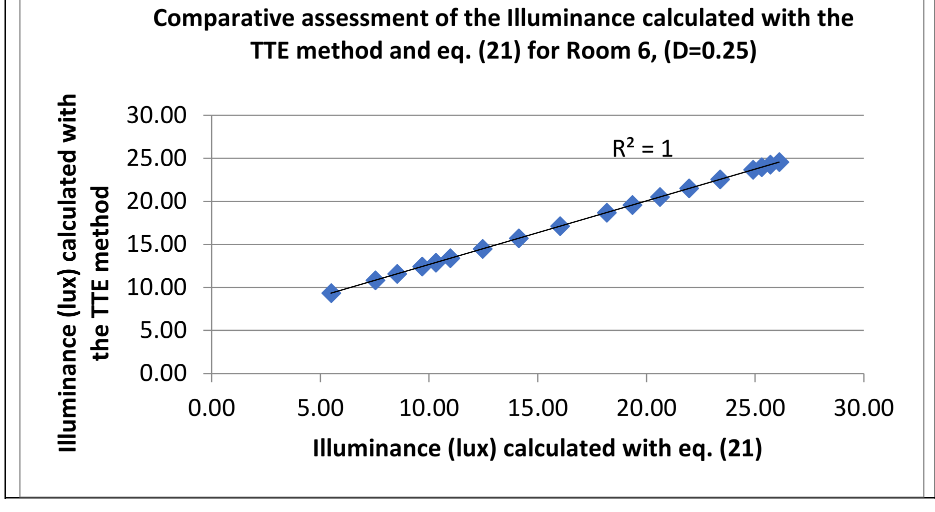

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 5, (D=0.53)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00

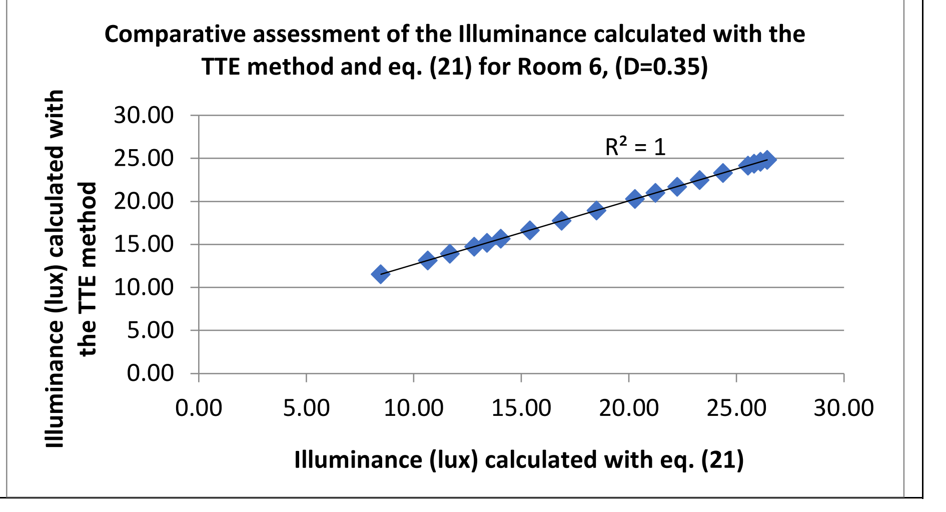
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
5.00	5.00	4.00	0.65	0.25	0.99	1211.10	0.37	18.35	19.00
				0.50	0.98	1203.56	0.36	18.24	18.88
				0.75	0.98	1196.06	0.36	18.13	18.75
				1.00	0.97	1188.60	0.36	18.01	18.63
				2.00	0.95	1159.26	0.35	17.57	18.15
				3.00	0.92	1130.64	0.34	17.13	17.69
				4.00	0.90	1102.72	0.33	16.71	17.23
				5.00	0.88	1075.49	0.33	16.30	16.79
				6.00	0.86	1048.94	0.32	15.90	16.35
				8.00	0.82	997.78	0.30	15.12	15.52
				10.00	0.78	949.12	0.29	14.38	14.73
				12.00	0.74	902.83	0.27	13.68	13.97
				14.00	0.70	858.80	0.26	13.01	13.25
				15.00	0.68	837.60	0.25	12.69	12.91
				16.00	0.67	816.92	0.25	12.38	12.57
				18.00	0.63	777.07	0.24	11.78	11.92
				20.00	0.60	739.18	0.22	11.20	11.30
				25.00	0.53	652.32	0.20	9.89	9.88
5.00	5.00	4.00	0.90	0.25	0.99	2331.67	0.37	18.43	19.08
				0.50	0.99	2320.62	0.37	18.34	18.99
				0.75	0.98	2309.62	0.37	18.26	18.90
				1.00	0.98	2298.67	0.36	18.17	18.80
				2.00	0.96	2255.41	0.36	17.83	18.43
				3.00	0.94	2212.96	0.35	17.49	18.07
				4.00	0.93	2171.31	0.34	17.16	17.72
				5.00	0.91	2130.45	0.34	16.84	17.37
				6.00	0.89	2090.35	0.33	16.52	17.03
				8.00	0.86	2012.41	0.32	15.91	16.37
				10.00	0.83	1937.37	0.31	15.31	15.73
				12.00	0.79	1865.13	0.29	14.74	15.11
				14.00	0.77	1795.59	0.28	14.19	14.52
				15.00	0.75	1761.79	0.28	13.93	14.23
				16.00	0.74	1728.64	0.27	13.66	13.95
				18.00	0.71	1664.18	0.26	13.15	13.40
				20.00	0.68	1602.13	0.25	12.66	12.87
				25.00	0.62	1456.93	0.23	11.52	11.64

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
6.00	6.00	2.50	0.25	0.25	0.97	174.95	0.52	26.09	24.60
6.00	6.00	2.50	0.25	0.50	0.95	172.22	0.51	25.69	24.30
6.00	6.00	2.50	0.25	0.75	0.94	169.53	0.51	25.29	24.00
6.00	6.00	2.50	0.25	1.00	0.92	166.88	0.50	24.89	23.71
6.00	6.00	2.50	0.25	2.00	0.87	156.69	0.47	23.37	22.59
6.00	6.00	2.50	0.25	3.00	0.81	147.12	0.44	21.94	21.53
6.00	6.00	2.50	0.25	4.00	0.76	138.14	0.41	20.60	20.54
6.00	6.00	2.50	0.25	5.00	0.72	129.70	0.39	19.35	19.61
6.00	6.00	2.50	0.25	6.00	0.67	121.78	0.36	18.16	18.74
6.00	6.00	2.50	0.25	8.00	0.59	107.37	0.32	16.01	17.15
6.00	6.00	2.50	0.25	10.00	0.52	94.66	0.28	14.12	15.74
6.00	6.00	2.50	0.25	12.00	0.46	83.45	0.25	12.45	14.51
6.00	6.00	2.50	0.25	14.00	0.41	73.57	0.22	10.97	13.42
6.00	6.00	2.50	0.25	15.00	0.38	69.08	0.21	10.30	12.92
6.00	6.00	2.50	0.25	16.00	0.36	64.86	0.19	9.67	12.46
6.00	6.00	2.50	0.25	18.00	0.32	57.18	0.17	8.53	11.61
6.00	6.00	2.50	0.25	20.00	0.28	50.41	0.15	7.52	10.86
6.00	6.00	2.50	0.25	25.00	0.20	36.79	0.11	5.49	9.36
6.00	6.00	2.50	0.35	0.25	0.98	347.31	0.53	26.43	24.85
6.00	6.00	2.50	0.35	0.50	0.97	343.34	0.52	26.13	24.62
6.00	6.00	2.50	0.35	0.75	0.96	339.41	0.52	25.83	24.40
6.00	6.00	2.50	0.35	1.00	0.95	335.53	0.51	25.53	24.18
6.00	6.00	2.50	0.35	2.00	0.90	320.45	0.49	24.39	23.34
6.00	6.00	2.50	0.35	3.00	0.86	306.04	0.47	23.29	22.53
6.00	6.00	2.50	0.35	4.00	0.82	292.28	0.44	22.24	21.75
6.00	6.00	2.50	0.35	5.00	0.79	279.14	0.42	21.24	21.01
6.00	6.00	2.50	0.35	6.00	0.75	266.59	0.41	20.29	20.31
6.00	6.00	2.50	0.35	8.00	0.69	243.16	0.37	18.50	18.99
6.00	6.00	2.50	0.35	10.00	0.63	221.79	0.34	16.88	17.78
6.00	6.00	2.50	0.35	12.00	0.57	202.29	0.31	15.39	16.69
6.00	6.00	2.50	0.35	14.00	0.52	184.51	0.28	14.04	15.69
6.00	6.00	2.50	0.35	15.00	0.50	176.22	0.27	13.41	15.22
6.00	6.00	2.50	0.35	16.00	0.47	168.29	0.26	12.81	14.77
6.00	6.00	2.50	0.35	18.00	0.43	153.50	0.23	11.68	13.94
6.00	6.00	2.50	0.35	20.00	0.39	140.01	0.21	10.65	13.18
6.00	6.00	2.50	0.35	25.00	0.31	111.24	0.17	8.47	11.56


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 5, (D=0.65)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R^2 = 1

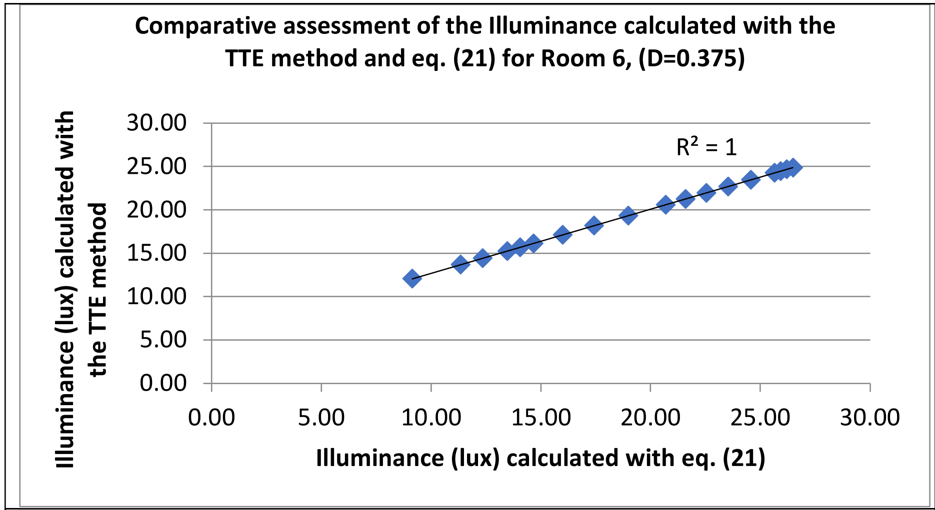

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 5, (D=0.90)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R^2 = 1

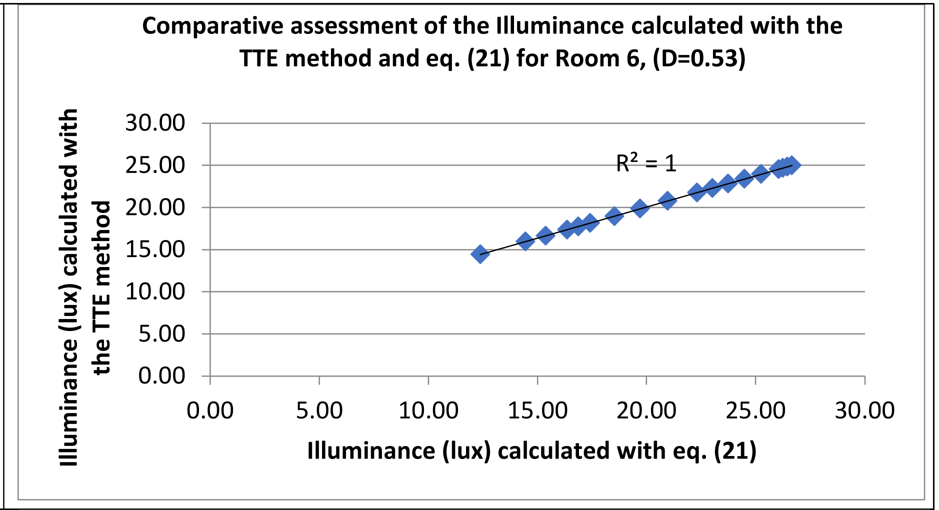

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 6, (D=0.25)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R^2 = 1

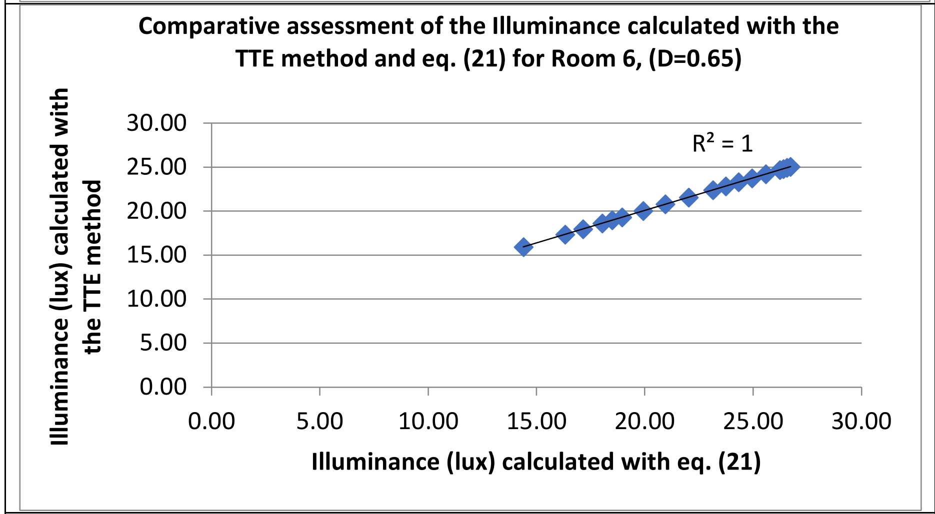

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 6, (D=0.35)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R^2 = 1

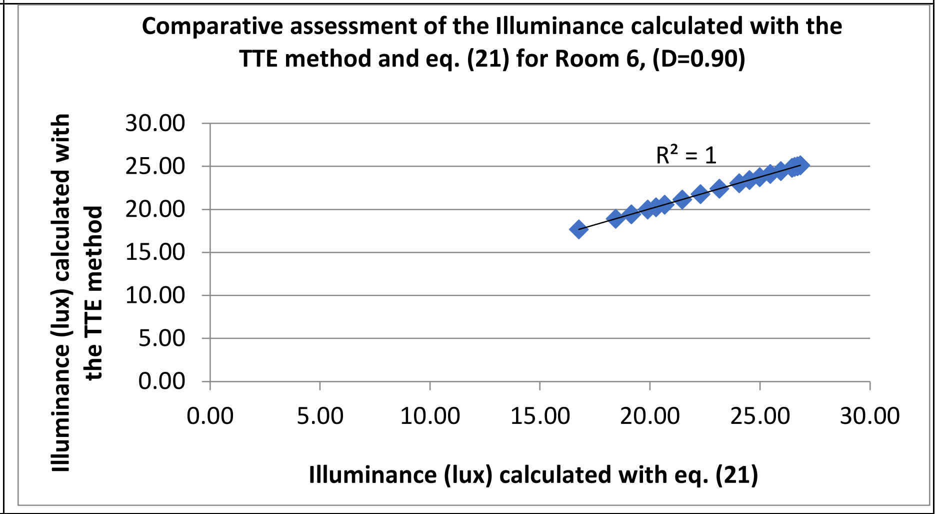
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
6.00	6.00	2.50	0.375	0.25	0.98	399.48	0.53	26.48	24.89
				0.50	0.97	395.21	0.52	26.20	24.68
				0.75	0.96	390.98	0.52	25.92	24.47
				1.00	0.95	386.80	0.51	25.64	24.26
				2.00	0.91	370.52	0.49	24.56	23.47
				3.00	0.87	354.93	0.47	23.53	22.70
				4.00	0.83	339.99	0.45	22.54	21.97
				5.00	0.80	325.68	0.43	21.59	21.27
				6.00	0.77	311.97	0.41	20.68	20.60
				8.00	0.70	286.26	0.38	18.98	19.34
				10.00	0.64	262.67	0.35	17.41	18.18
				12.00	0.59	241.03	0.32	15.98	17.12
				14.00	0.54	221.17	0.29	14.66	16.14
				15.00	0.52	211.86	0.28	14.04	15.69
				16.00	0.50	202.94	0.27	13.45	15.25
				18.00	0.46	186.22	0.25	12.34	14.43
				20.00	0.42	170.87	0.23	11.33	13.68
				25.00	0.34	137.82	0.18	9.14	12.06
6.00	6.00	2.50	0.53	0.25	0.99	803.27	0.53	26.66	25.02
				0.50	0.98	797.07	0.53	26.45	24.86
				0.75	0.97	790.92	0.52	26.25	24.71
				1.00	0.96	784.81	0.52	26.05	24.56
				2.00	0.94	760.85	0.51	25.25	23.98
				3.00	0.91	737.63	0.49	24.48	23.41
				4.00	0.88	715.11	0.47	23.73	22.85
				5.00	0.85	693.28	0.46	23.01	22.32
				6.00	0.83	672.12	0.45	22.31	21.80
				8.00	0.78	631.72	0.42	20.96	20.81
				10.00	0.73	593.74	0.39	19.70	19.87
				12.00	0.69	558.05	0.37	18.52	19.00
				14.00	0.64	524.50	0.35	17.41	18.17
				15.00	0.62	508.49	0.34	16.88	17.78
				16.00	0.61	492.97	0.33	16.36	17.40
				18.00	0.57	463.33	0.31	15.38	16.67
				20.00	0.54	435.48	0.29	14.45	15.99
				25.00	0.46	372.95	0.25	12.38	14.46

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
6.00	6.00	2.50	0.65	0.25	0.99	1211.10	0.53	26.72	25.06
				0.50	0.98	1203.56	0.53	26.56	24.94
				0.75	0.98	1196.06	0.53	26.39	24.82
				1.00	0.97	1188.60	0.52	26.23	24.70
				2.00	0.95	1159.26	0.51	25.58	24.22
				3.00	0.92	1130.64	0.50	24.95	23.75
				4.00	0.90	1102.72	0.49	24.33	23.30
				5.00	0.88	1075.49	0.47	23.73	22.85
				6.00	0.86	1048.94	0.46	23.14	22.42
				8.00	0.82	997.78	0.44	22.02	21.58
				10.00	0.78	949.12	0.42	20.94	20.79
				12.00	0.74	902.83	0.40	19.92	20.03
				14.00	0.70	858.80	0.38	18.95	19.32
				15.00	0.68	837.60	0.37	18.48	18.97
				16.00	0.67	816.92	0.36	18.02	18.63
				18.00	0.63	777.07	0.34	17.15	17.98
				20.00	0.60	739.18	0.33	16.31	17.36
				25.00	0.53	652.32	0.29	14.39	15.95
6.00	6.00	2.50	0.90	0.25	0.99	2331.67	0.54	26.83	25.15
				0.50	0.99	2320.62	0.53	26.71	25.05
				0.75	0.98	2309.62	0.53	26.58	24.96
				1.00	0.98	2298.67	0.53	26.46	24.87
				2.00	0.96	2255.41	0.52	25.96	24.50
				3.00	0.94	2212.96	0.51	25.47	24.14
				4.00	0.93	2171.31	0.50	24.99	23.78
				5.00	0.91	2130.45	0.49	24.52	23.43
				6.00	0.89	2090.35	0.48	24.06	23.09
				8.00	0.86	2012.41	0.46	23.16	22.43
				10.00	0.83	1937.37	0.45	22.30	21.79
				12.00	0.79	1865.13	0.43	21.47	21.18
				14.00	0.77	1795.59	0.41	20.67	20.58
				15.00	0.75	1761.79	0.41	20.28	20.30
				16.00	0.74	1728.64	0.40	19.89	20.01
				18.00	0.71	1664.18	0.38	19.15	19.47
				20.00	0.68	1602.13	0.37	18.44	18.94
				25.00	0.62	1456.93	0.34	16.77	17.70


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 6, (D=0.375)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00
30.00

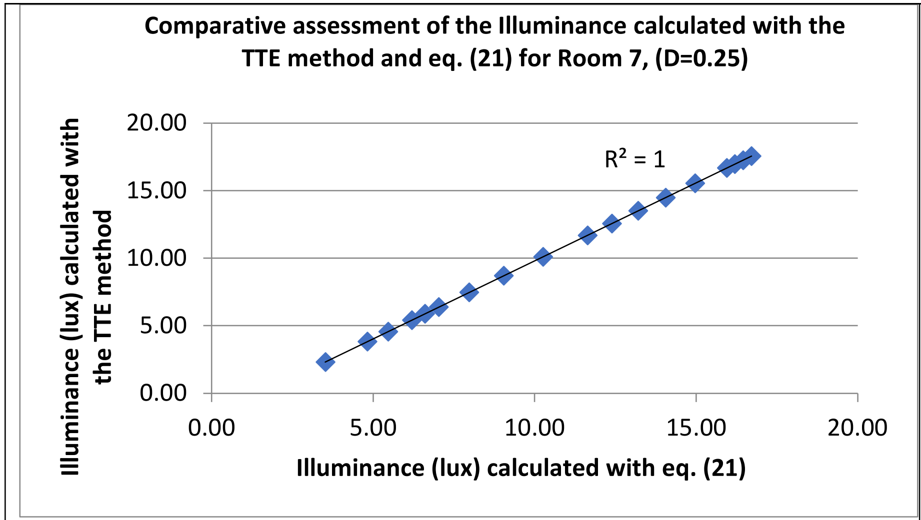

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 6, (D=0.53)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00
30.00

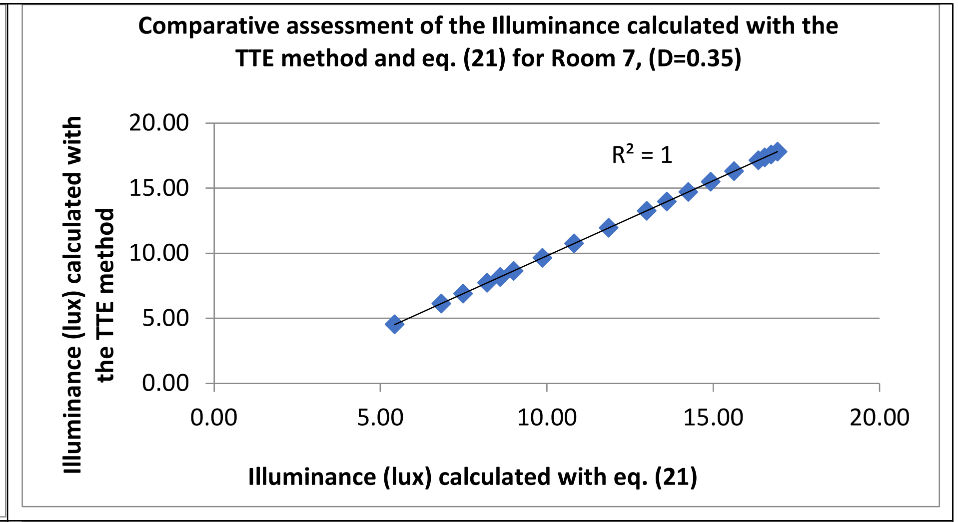

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 6, (D=0.65)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00
30.00

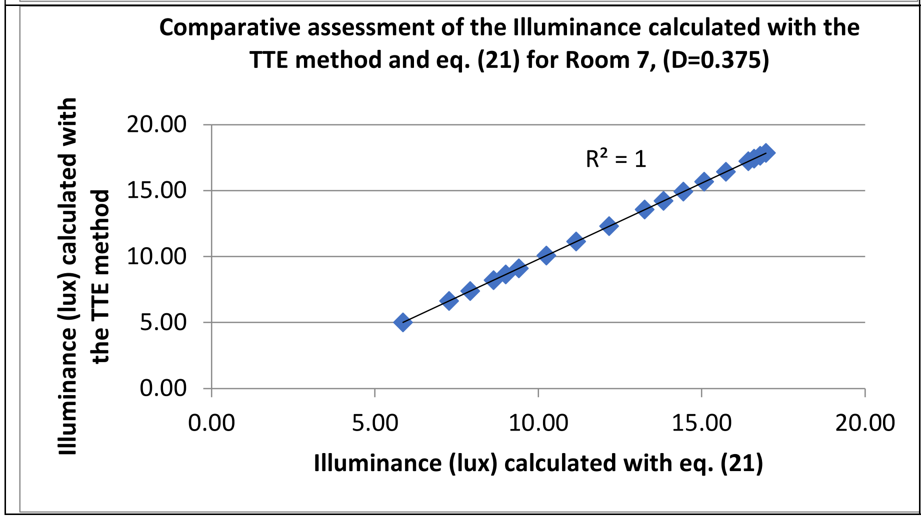

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 6, (D=0.90)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00
30.00

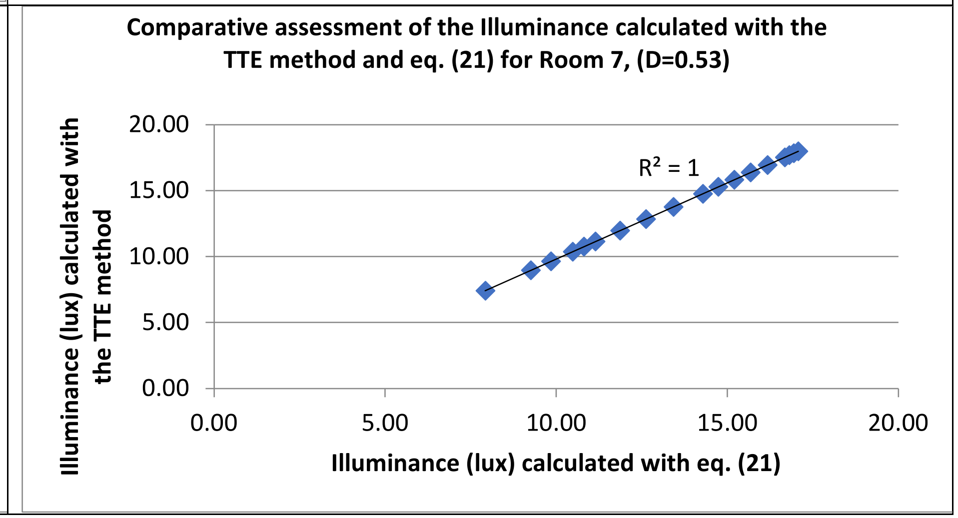
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
4.00	3.00	3.00	0.25	0.25	0.97	174.95	0.33	16.71	17.56
				0.50	0.95	172.22	0.33	16.45	17.26
				0.75	0.94	169.53	0.32	16.19	16.96
				1.00	0.92	166.88	0.32	15.94	16.67
				2.00	0.87	156.69	0.30	14.97	15.55
				3.00	0.81	147.12	0.28	14.05	14.49
				4.00	0.76	138.14	0.26	13.19	13.50
				5.00	0.72	129.70	0.25	12.39	12.57
				6.00	0.67	121.78	0.23	11.63	11.70
				8.00	0.59	107.37	0.21	10.26	10.11
				10.00	0.52	94.66	0.18	9.04	8.71
				12.00	0.46	83.45	0.16	7.97	7.47
				14.00	0.41	73.57	0.14	7.03	6.38
				15.00	0.38	69.08	0.13	6.60	5.88
				16.00	0.36	64.86	0.12	6.20	5.42
				18.00	0.32	57.18	0.11	5.46	4.57
				20.00	0.28	50.41	0.10	4.82	3.83
				25.00	0.20	36.79	0.07	3.51	2.32
4.00	3.00	3.00	0.35	0.25	0.98	347.31	0.34	16.93	17.81
				0.50	0.97	343.34	0.33	16.73	17.59
				0.75	0.96	339.41	0.33	16.54	17.37
				1.00	0.95	335.53	0.33	16.35	17.15
				2.00	0.90	320.45	0.31	15.62	16.30
				3.00	0.86	306.04	0.30	14.91	15.49
				4.00	0.82	292.28	0.28	14.24	14.71
				5.00	0.79	279.14	0.27	13.60	13.97
				6.00	0.75	266.59	0.26	12.99	13.27
				8.00	0.69	243.16	0.24	11.85	11.95
				10.00	0.63	221.79	0.22	10.81	10.75
				12.00	0.57	202.29	0.20	9.86	9.65
				14.00	0.52	184.51	0.18	8.99	8.65
				15.00	0.50	176.22	0.17	8.59	8.18
				16.00	0.47	168.29	0.16	8.20	7.74
				18.00	0.43	153.50	0.15	7.48	6.90
				20.00	0.39	140.01	0.14	6.82	6.14
				25.00	0.31	111.24	0.11	5.42	4.53

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
4.00	3.00	3.00	0.375	0.25	0.98	399.48	0.34	16.96	17.85
				0.50	0.97	395.21	0.34	16.78	17.64
				0.75	0.96	390.98	0.33	16.60	17.43
				1.00	0.95	386.80	0.33	16.42	17.23
				2.00	0.91	370.52	0.31	15.73	16.43
				3.00	0.87	354.93	0.30	15.07	15.66
				4.00	0.83	339.99	0.29	14.43	14.93
				5.00	0.80	325.68	0.28	13.83	14.23
				6.00	0.77	311.97	0.26	13.24	13.56
				8.00	0.70	286.26	0.24	12.15	12.30
				10.00	0.64	262.67	0.22	11.15	11.14
				12.00	0.59	241.03	0.20	10.23	10.08
				14.00	0.54	221.17	0.19	9.39	9.11
				15.00	0.52	211.86	0.18	8.99	8.65
				16.00	0.50	202.94	0.17	8.62	8.21
				18.00	0.46	186.22	0.16	7.91	7.39
				20.00	0.42	170.87	0.15	7.25	6.64
				25.00	0.34	137.82	0.12	5.85	5.02
4.00	3.00	3.00	0.53	0.25	0.99	803.27	0.34	17.07	17.98
				0.50	0.98	797.07	0.34	16.94	17.83
				0.75	0.97	790.92	0.34	16.81	17.67
				1.00	0.96	784.81	0.33	16.68	17.53
				2.00	0.94	760.85	0.32	16.17	16.94
				3.00	0.91	737.63	0.31	15.68	16.37
				4.00	0.88	715.11	0.30	15.20	15.81
				5.00	0.85	693.28	0.29	14.73	15.28
				6.00	0.83	672.12	0.29	14.28	14.76
				8.00	0.78	631.72	0.27	13.43	13.77
				10.00	0.73	593.74	0.25	12.62	12.84
				12.00	0.69	558.05	0.24	11.86	11.96
				14.00	0.64	524.50	0.22	11.15	11.14
				15.00	0.62	508.49	0.22	10.81	10.74
				16.00	0.61	492.97	0.21	10.48	10.36
				18.00	0.57	463.33	0.20	9.85	9.64
				20.00	0.54	435.48	0.19	9.26	8.95
				25.00	0.46	372.95	0.16	7.93	7.42


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 7, (D=0.25)
$R^2 = 1$
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00

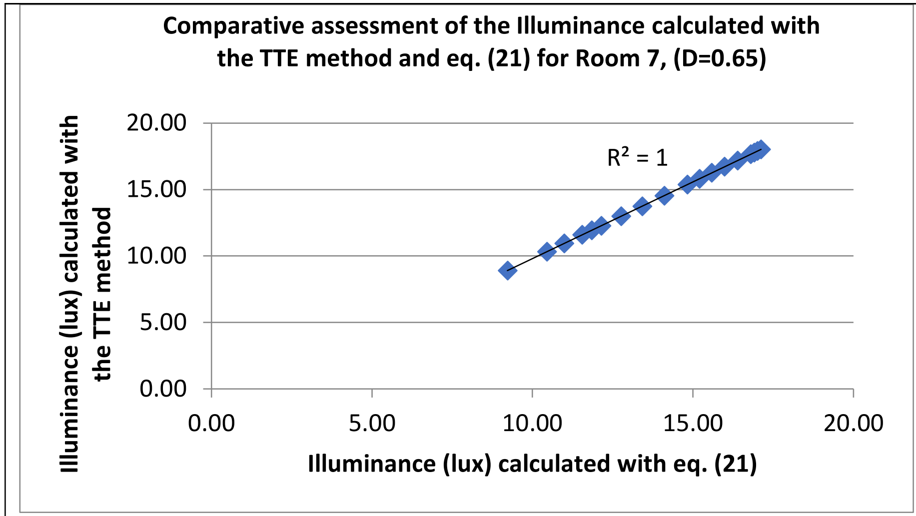

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 7, (D=0.35)
$R^2 = 1$
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00

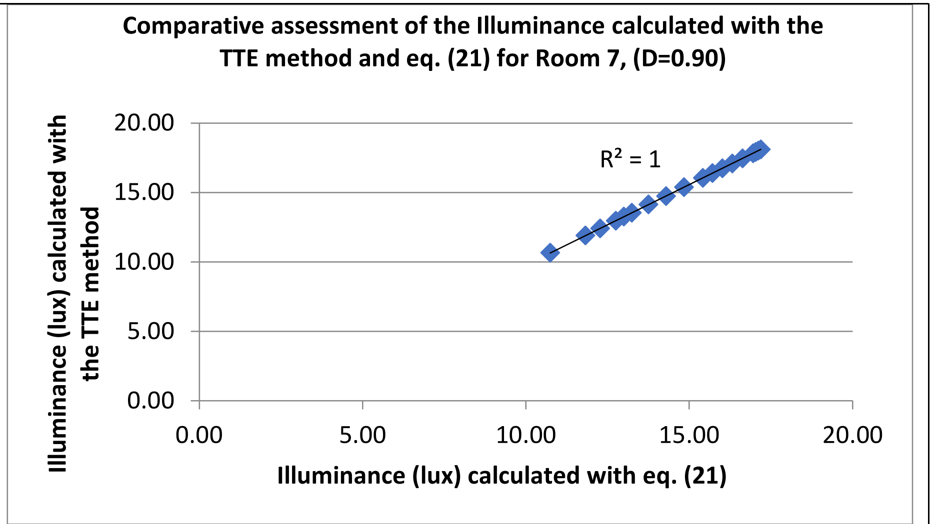

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 7, (D=0.375)
$R^2 = 1$
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00

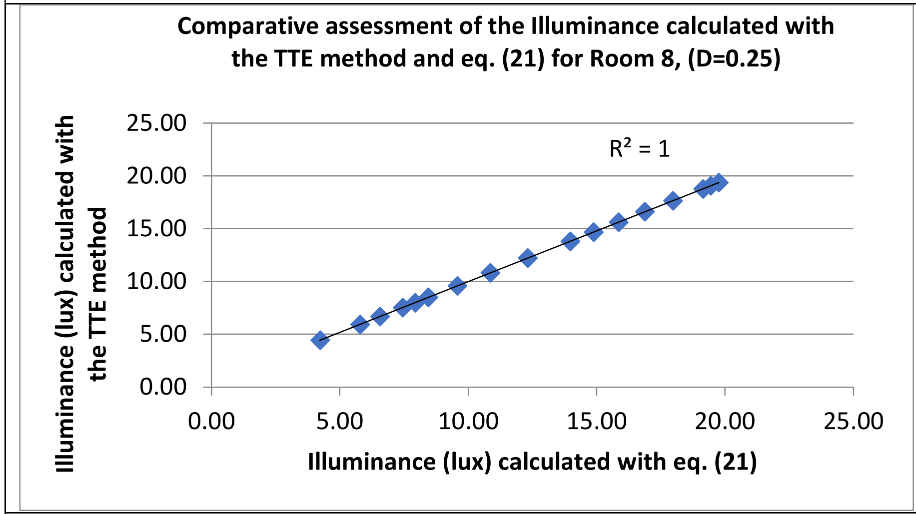

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 7, (D=0.53)
$R^2 = 1$
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00

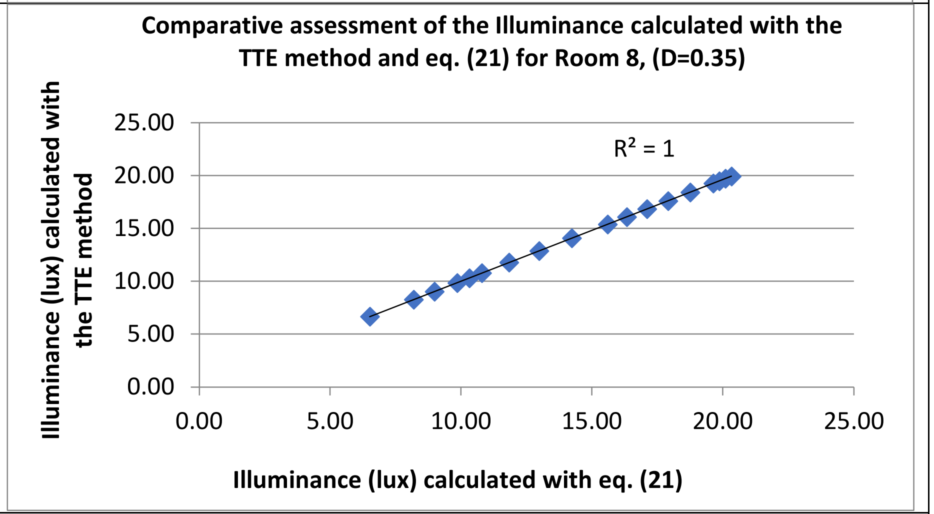
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
4.00	3.00	3.00	0.65	0.25	0.99	1211.10	0.34	17.11	18.03
				0.50	0.98	1203.56	0.34	17.01	17.90
				0.75	0.98	1196.06	0.34	16.90	17.78
				1.00	0.97	1188.60	0.34	16.80	17.66
				2.00	0.95	1159.26	0.33	16.38	17.18
				3.00	0.92	1130.64	0.32	15.98	16.71
				4.00	0.90	1102.72	0.31	15.58	16.26
				5.00	0.88	1075.49	0.30	15.20	15.81
				6.00	0.86	1048.94	0.30	14.82	15.38
				8.00	0.82	997.78	0.28	14.10	14.54
				10.00	0.78	949.12	0.27	13.41	13.75
				12.00	0.74	902.83	0.26	12.76	13.00
				14.00	0.70	858.80	0.24	12.13	12.28
				15.00	0.68	837.60	0.24	11.84	11.93
				16.00	0.67	816.92	0.23	11.54	11.59
				18.00	0.63	777.07	0.22	10.98	10.94
				20.00	0.60	739.18	0.21	10.44	10.33
				25.00	0.53	652.32	0.18	9.22	8.91
4.00	3.00	3.00	0.90	0.25	0.99	2331.67	0.34	17.19	18.11
				0.50	0.99	2320.62	0.34	17.10	18.01
				0.75	0.98	2309.62	0.34	17.02	17.92
				1.00	0.98	2298.67	0.34	16.94	17.83
				2.00	0.96	2255.41	0.33	16.62	17.46
				3.00	0.94	2212.96	0.33	16.31	17.10
				4.00	0.93	2171.31	0.32	16.00	16.74
				5.00	0.91	2130.45	0.31	15.70	16.40
				6.00	0.89	2090.35	0.31	15.41	16.06
				8.00	0.86	2012.41	0.30	14.83	15.39
				10.00	0.83	1937.37	0.29	14.28	14.75
				12.00	0.79	1865.13	0.27	13.75	14.14
				14.00	0.77	1795.59	0.26	13.23	13.55
				15.00	0.75	1761.79	0.26	12.98	13.26
				16.00	0.74	1728.64	0.25	12.74	12.98
				18.00	0.71	1664.18	0.25	12.27	12.43
				20.00	0.68	1602.13	0.24	11.81	11.90
				25.00	0.62	1456.93	0.21	10.74	10.66

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
5.00	4.00	3.00	0.25	0.25	0.97	174.95	0.40	20.06	19.69
				0.50	0.95	172.22	0.39	19.75	19.39
				0.75	0.94	169.53	0.39	19.44	19.10
				1.00	0.92	166.88	0.38	19.14	18.80
				2.00	0.87	156.69	0.36	17.97	17.68
				3.00	0.81	147.12	0.34	16.87	16.63
				4.00	0.76	138.14	0.32	15.84	15.63
				5.00	0.72	129.70	0.30	14.87	14.70
				6.00	0.67	121.78	0.28	13.97	13.83
				8.00	0.59	107.37	0.25	12.31	12.24
				10.00	0.52	94.66	0.22	10.85	10.84
				12.00	0.46	83.45	0.19	9.57	9.60
				14.00	0.41	73.57	0.17	8.44	8.51
				15.00	0.38	69.08	0.16	7.92	8.02
				16.00	0.36	64.86	0.15	7.44	7.55
				18.00	0.32	57.18	0.13	6.56	6.71
				20.00	0.28	50.41	0.12	5.78	5.96
				25.00	0.20	36.79	0.08	4.22	4.46
5.00	4.00	3.00	0.35	0.25	0.98	347.31	0.41	20.32	19.94
				0.50	0.97	343.34	0.40	20.09	19.72
				0.75	0.96	339.41	0.40	19.86	19.50
				1.00	0.95	335.53	0.39	19.63	19.28
				2.00	0.90	320.45	0.37	18.75	18.43
				3.00	0.86	306.04	0.36	17.91	17.62
				4.00	0.82	292.28	0.34	17.10	16.85
				5.00	0.79	279.14	0.33	16.33	16.11
				6.00	0.75	266.59	0.31	15.60	15.40
				8.00	0.69	243.16	0.28	14.23	14.08
				10.00	0.63	221.79	0.26	12.98	12.88
				12.00	0.57	202.29	0.24	11.84	11.78
				14.00	0.52	184.51	0.22	10.80	10.78
				15.00	0.50	176.22	0.21	10.31	10.31
				16.00	0.47	168.29	0.20	9.85	9.87
				18.00	0.43	153.50	0.18	8.98	9.04
				20.00	0.39	140.01	0.16	8.19	8.28
				25.00	0.31	111.24	0.13	6.51	6.66


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 7, (D=0.65)
$R^2 = 1$
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00

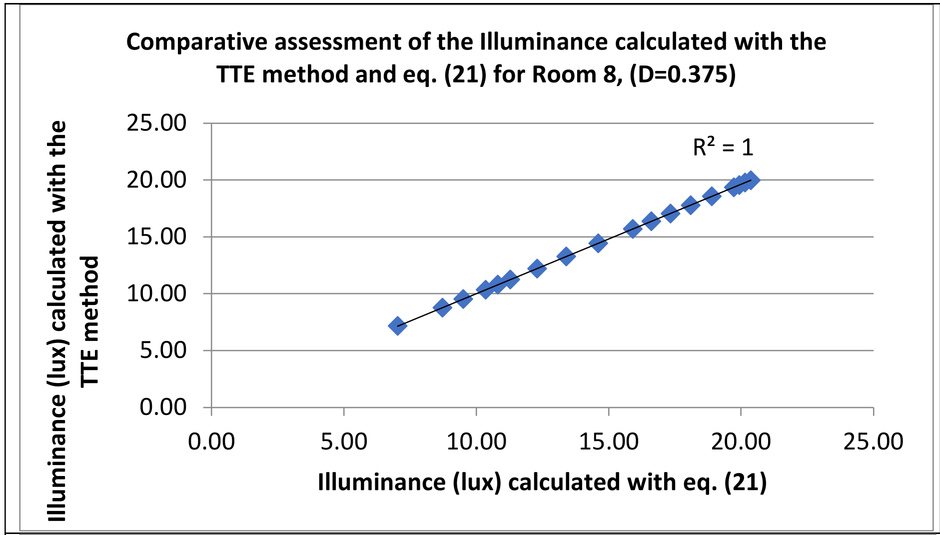

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 7, (D=0.90)
$R^2 = 1$
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00

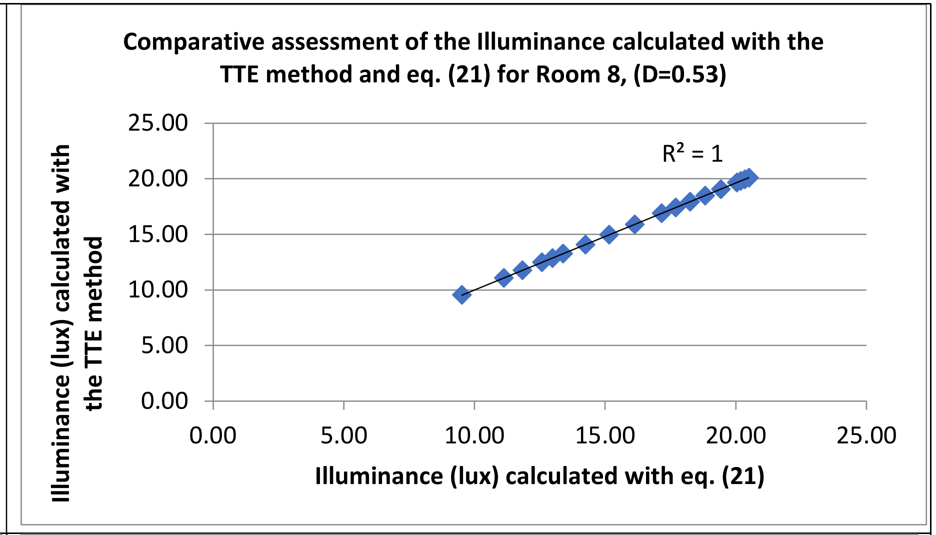

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 8, (D=0.25)
$R^2 = 1$
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00

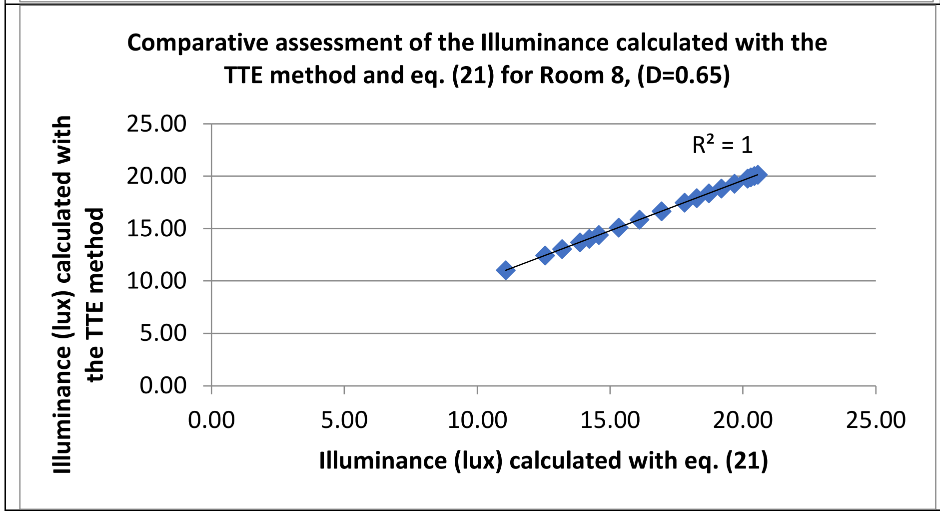

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 8, (D=0.35)
$R^2 = 1$
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00

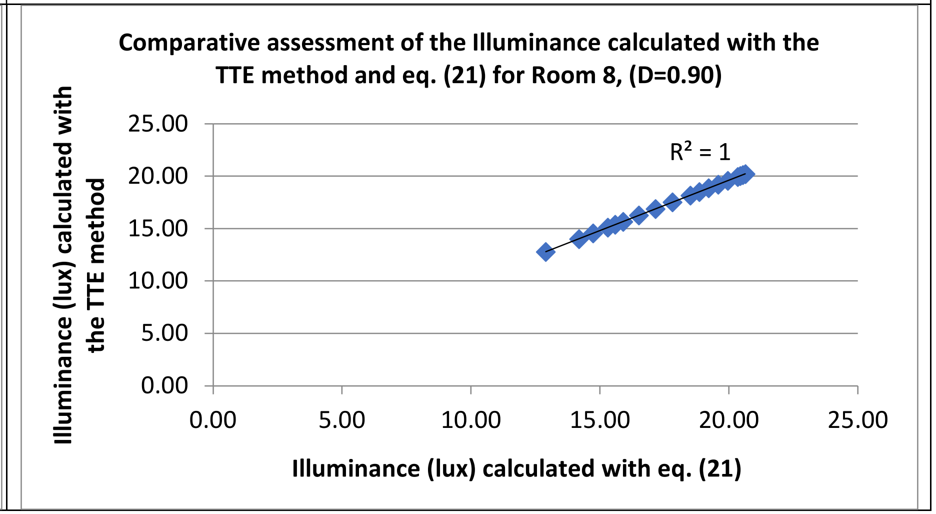
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
5.00	4.00	3.00	0.375	0.25	0.98	399.48	0.41	20.36	19.98
				0.50	0.97	395.21	0.40	20.14	19.77
				0.75	0.96	390.98	0.40	19.93	19.56
				1.00	0.95	386.80	0.39	19.71	19.36
				2.00	0.91	370.52	0.38	18.88	18.56
				3.00	0.87	354.93	0.36	18.09	17.80
				4.00	0.83	339.99	0.35	17.33	17.06
				5.00	0.80	325.68	0.33	16.60	16.36
				6.00	0.77	311.97	0.32	15.90	15.69
				8.00	0.70	286.26	0.29	14.59	14.43
				10.00	0.64	262.67	0.27	13.39	13.27
				12.00	0.59	241.03	0.25	12.28	12.21
				14.00	0.54	221.17	0.23	11.27	11.24
				15.00	0.52	211.86	0.22	10.80	10.78
				16.00	0.50	202.94	0.21	10.34	10.35
				18.00	0.46	186.22	0.19	9.49	9.53
				20.00	0.42	170.87	0.17	8.71	8.77
				25.00	0.34	137.82	0.14	7.02	7.15
5.00	4.00	3.00	0.53	0.25	0.99	803.27	0.41	20.50	20.11
				0.50	0.98	797.07	0.41	20.34	19.96
				0.75	0.97	790.92	0.40	20.18	19.81
				1.00	0.96	784.81	0.40	20.02	19.66
				2.00	0.94	760.85	0.39	19.41	19.07
				3.00	0.91	737.63	0.38	18.82	18.50
				4.00	0.88	715.11	0.36	18.25	17.95
				5.00	0.85	693.28	0.35	17.69	17.41
				6.00	0.83	672.12	0.34	17.15	16.89
				8.00	0.78	631.72	0.32	16.12	15.90
				10.00	0.73	593.74	0.30	15.15	14.97
				12.00	0.69	558.05	0.28	14.24	14.09
				14.00	0.64	524.50	0.27	13.38	13.27
				15.00	0.62	508.49	0.26	12.97	12.88
				16.00	0.61	492.97	0.25	12.58	12.50
				18.00	0.57	463.33	0.24	11.82	11.77
				20.00	0.54	435.48	0.22	11.11	11.09
				25.00	0.46	372.95	0.19	9.52	9.55

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
5.00	4.00	3.00	0.65	0.25	0.99	1211.10	0.41	20.54	20.16
				0.50	0.98	1203.56	0.41	20.42	20.04
				0.75	0.98	1196.06	0.41	20.29	19.91
				1.00	0.97	1188.60	0.40	20.16	19.79
				2.00	0.95	1159.26	0.39	19.67	19.31
				3.00	0.92	1130.64	0.38	19.18	18.85
				4.00	0.90	1102.72	0.37	18.71	18.39
				5.00	0.88	1075.49	0.36	18.24	17.95
				6.00	0.86	1048.94	0.36	17.79	17.51
				8.00	0.82	997.78	0.34	16.93	16.68
				10.00	0.78	949.12	0.32	16.10	15.88
				12.00	0.74	902.83	0.31	15.32	15.13
				14.00	0.70	858.80	0.29	14.57	14.41
				15.00	0.68	837.60	0.28	14.21	14.06
				16.00	0.67	816.92	0.28	13.86	13.73
				18.00	0.63	777.07	0.26	13.18	13.08
				20.00	0.60	739.18	0.25	12.54	12.46
				25.00	0.53	652.32	0.22	11.07	11.04
5.00	4.00	3.00	0.90	0.25	0.99	2331.67	0.41	20.63	20.24
				0.50	0.99	2320.62	0.41	20.53	20.15
				0.75	0.98	2309.62	0.41	20.44	20.05
				1.00	0.98	2298.67	0.41	20.34	19.96
				2.00	0.96	2255.41	0.40	19.96	19.59
				3.00	0.94	2212.96	0.39	19.58	19.23
				4.00	0.93	2171.31	0.38	19.21	18.88
				5.00	0.91	2130.45	0.38	18.85	18.53
				6.00	0.89	2090.35	0.37	18.50	18.19
				8.00	0.86	2012.41	0.36	17.81	17.52
				10.00	0.83	1937.37	0.34	17.14	16.89
				12.00	0.79	1865.13	0.33	16.50	16.27
				14.00	0.77	1795.59	0.32	15.89	15.68
				15.00	0.75	1761.79	0.31	15.59	15.39
				16.00	0.74	1728.64	0.31	15.30	15.11
				18.00	0.71	1664.18	0.29	14.73	14.56
				20.00	0.68	1602.13	0.28	14.18	14.03
				25.00	0.62	1456.93	0.26	12.89	12.80


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 8, (D=0.375)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 8, (D=0.53)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 8, (D=0.65)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 8, (D=0.90)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00

Room surface reflectances (%): Walls/Ceiling/Floor-Reference Plane=50/70/30

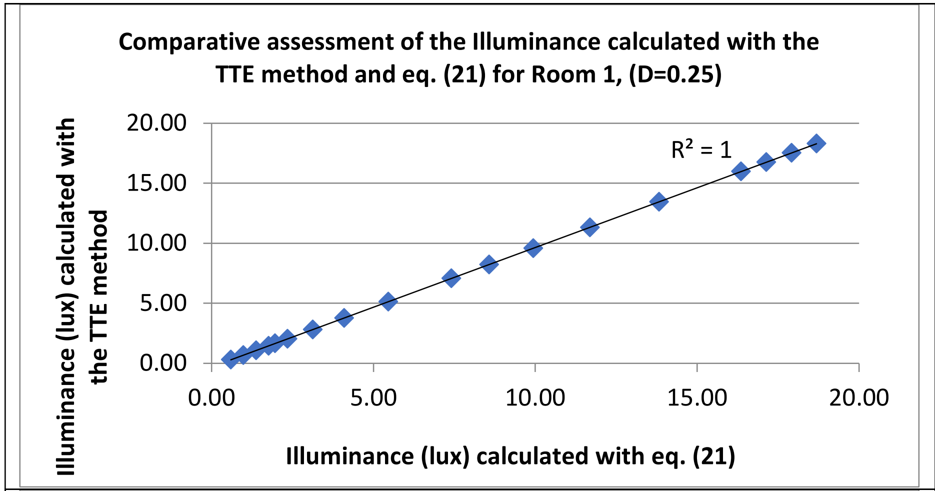
Reference plane: 0.85m above the floor and 0.50m offset from the walls

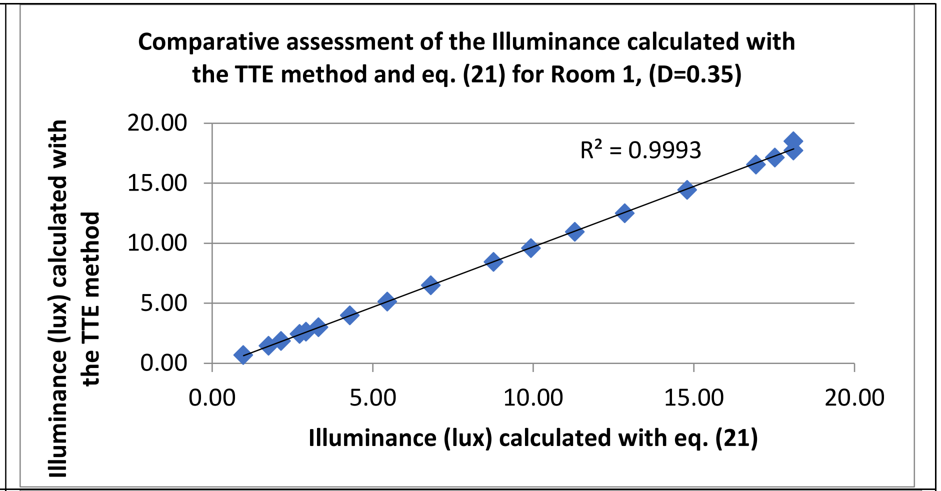
τ_{dome} x τ_{dif}=0.82. R_{pipe}=0.95. MF=0.9

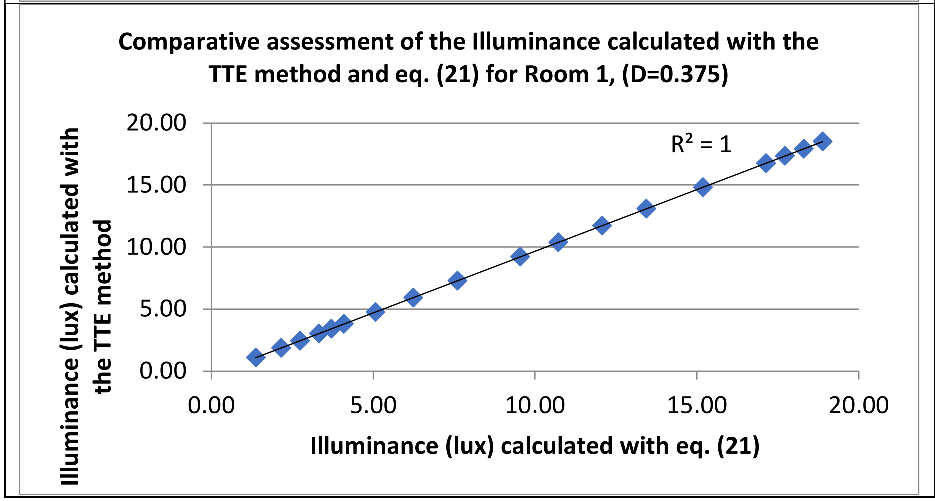
E_{ex}=5,000lux

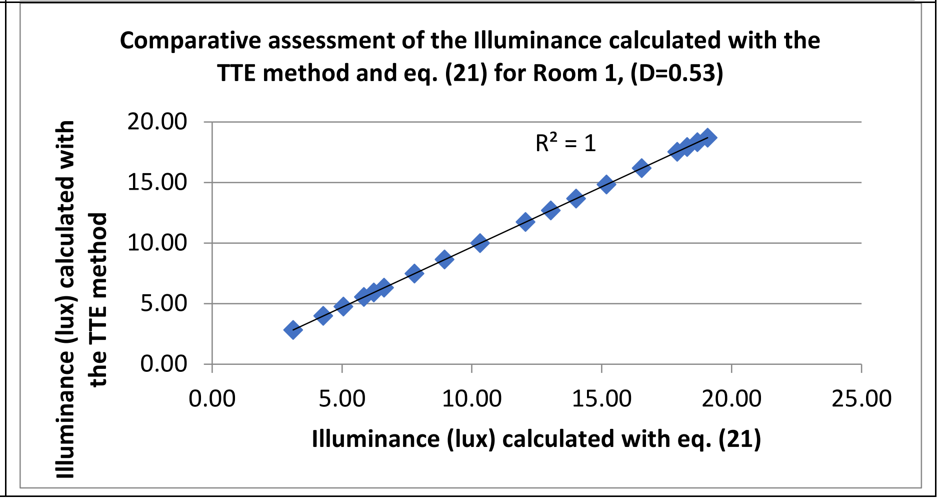
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
4.00	4.00	3.00	0.25	0.25	0.96	173.80	0.37	18.68	18.31
				0.50	0.92	166.56	0.36	17.91	17.54
				0.75	0.88	159.32	0.34	17.13	16.76
				1.00	0.84	152.07	0.33	16.35	15.99
				2.00	0.71	128.54	0.28	13.82	13.47
				3.00	0.6	108.62	0.23	11.68	11.34
				4.00	0.51	92.33	0.20	9.93	9.60
				5.00	0.44	79.66	0.17	8.56	8.24
				6.00	0.38	68.80	0.15	7.40	7.08
				8.00	0.28	50.69	0.11	5.45	5.15
				10.00	0.21	38.02	0.08	4.09	3.79
				12.00	0.16	28.97	0.06	3.11	2.82
				14.00	0.12	21.72	0.05	2.34	2.05
				15.00	0.1	18.10	0.04	1.95	1.66
				16.00	0.09	16.29	0.04	1.75	1.47
				18.00	0.07	12.67	0.03	1.36	1.08
				20.00	0.05	9.05	0.02	0.97	0.69
				25.00	0.03	5.43	0.01	0.58	0.31
4.00	4.00	3.00	0.35	0.25	0.97	330.00	0.36	18.10	18.50
				0.50	0.93	330.00	0.36	18.10	17.73
				0.75	0.9	319.36	0.35	17.52	17.15
				1.00	0.87	308.71	0.34	16.93	16.57
				2.00	0.76	269.68	0.30	14.79	14.44
				3.00	0.66	234.19	0.26	12.85	12.50
				4.00	0.58	205.81	0.23	11.29	10.95
				5.00	0.51	180.97	0.20	9.93	9.60
				6.00	0.45	159.68	0.18	8.76	8.44
				8.00	0.35	124.19	0.14	6.81	6.50
				10.00	0.28	99.36	0.11	5.45	5.15
				12.00	0.22	78.06	0.09	4.28	3.98
				14.00	0.17	60.32	0.07	3.31	3.02
				15.00	0.15	53.23	0.06	2.92	2.63
				16.00	0.14	49.68	0.05	2.72	2.44
				18.00	0.11	39.03	0.04	2.14	1.86
				20.00	0.09	31.94	0.04	1.75	1.47
				25.00	0.05	17.74	0.02	0.97	0.69

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
4.00	4.00	3.00	0.375	0.25	0.97	395.12	0.38	18.88	17.92
				0.50	0.94	382.90	0.37	18.29	17.34
				0.75	0.91	370.68	0.35	17.71	16.76
				1.00	0.88	358.46	0.34	17.13	14.83
				2.00	0.78	317.73	0.30	15.18	13.08
				3.00	0.69	281.07	0.27	13.43	11.73
				4.00	0.62	252.55	0.24	12.07	10.37
				5.00	0.55	224.04	0.21	10.70	9.21
				6.00	0.49	199.60	0.19	9.54	7.28
				8.00	0.39	158.86	0.15	7.59	5.92
				10.00	0.32	130.35	0.12	6.23	4.76
				12.00	0.26	105.91	0.10	5.06	3.79
				14.00	0.21	85.54	0.08	4.09	3.40
				15.00	0.19	77.39	0.07	3.70	3.02
				16.00	0.17	69.25	0.07	3.31	2.44
				18.00	0.14	57.03	0.05	2.72	1.86
				20.00	0.11	44.81	0.04	2.14	1.08
				25.00	0.07	28.51	0.03	1.36	0.35
4.00	4.00	3.00	0.53	0.25	0.98	797.40	0.38	19.07	18.70
				0.50	0.96	781.12	0.37	18.68	18.31
				0.75	0.94	764.85	0.37	18.29	17.92
				1.00	0.92	748.58	0.36	17.91	17.54
				2.00	0.85	691.62	0.33	16.54	16.18
				3.00	0.78	634.66	0.30	15.18	14.83
				4.00	0.72	585.84	0.28	14.01	13.66
				5.00	0.67	545.16	0.26	13.04	12.70
				6.00	0.62	504.47	0.24	12.07	11.73
				8.00	0.53	431.24	0.21	10.32	9.99
				10.00	0.46	374.29	0.18	8.95	8.63
				12.00	0.4	325.47	0.16	7.79	7.47
				14.00	0.34	276.65	0.13	6.62	6.31
				15.00	0.32	260.37	0.12	6.23	5.92
				16.00	0.3	244.10	0.12	5.84	5.53
				18.00	0.26	211.55	0.10	5.06	4.76
				20.00	0.22	179.01	0.09	4.28	3.98
				25.00	0.16	130.19	0.06	3.11	2.82


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 1, (D=0.25)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00

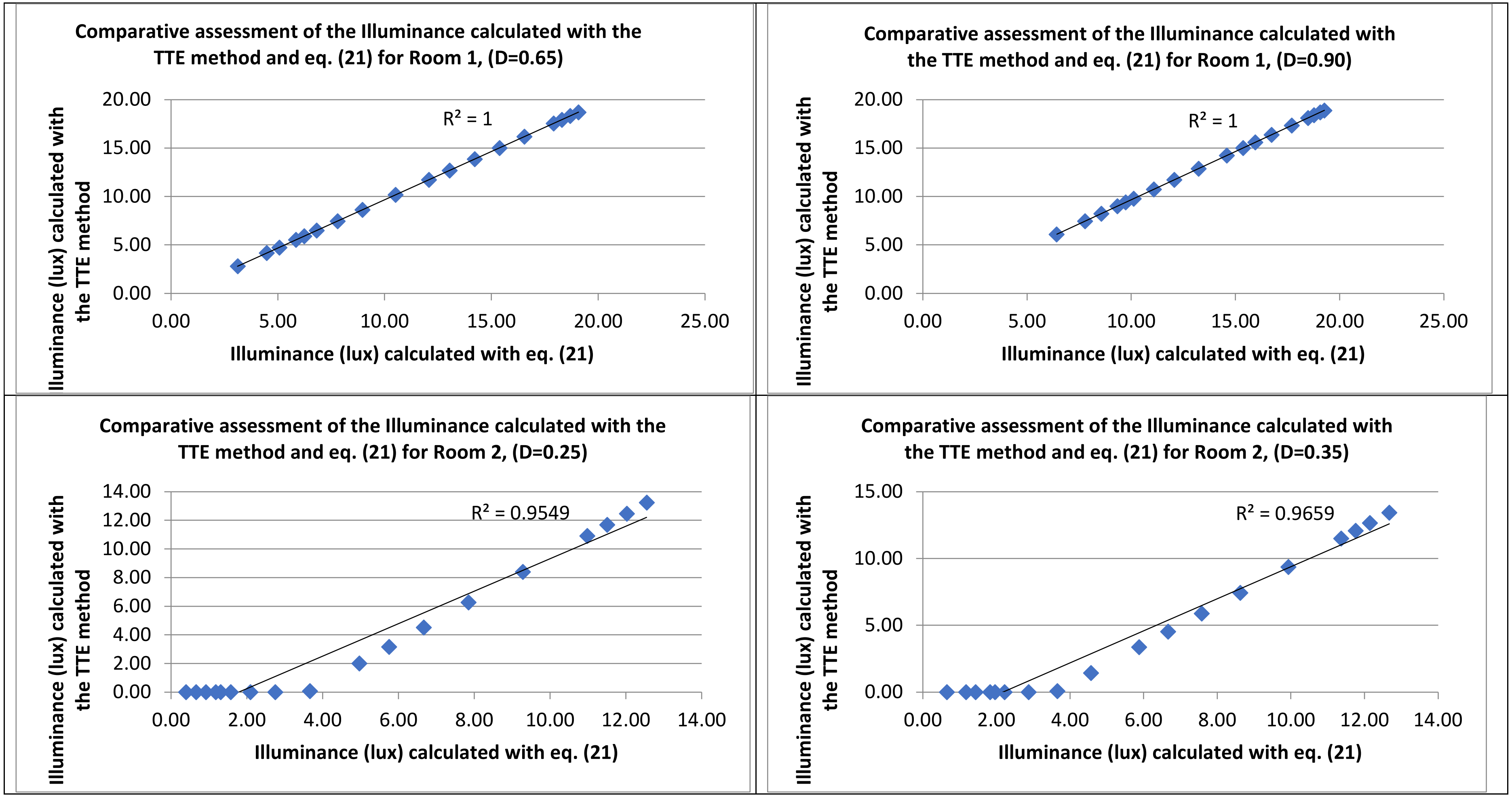

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 1, (D=0.35)
R² = 0.9993
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 1, (D=0.375)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 1, (D=0.53)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00

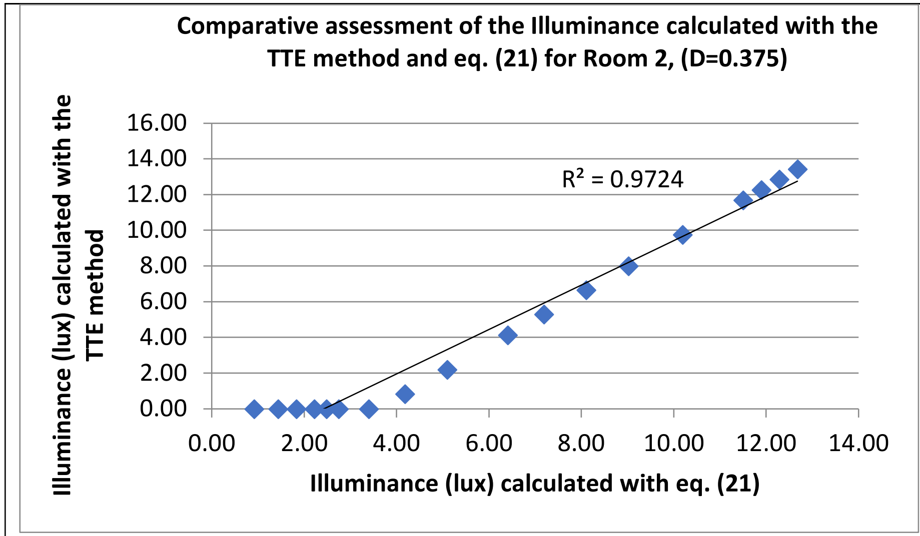
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
				0.25	0.98	1199.36	0.38	19.07	18.70
				0.50	0.96	1174.88	0.37	18.68	18.31
				0.75	0.94	1150.40	0.37	18.29	17.92
				1.00	0.92	1125.93	0.36	17.91	17.54
				2.00	0.85	1040.26	0.33	16.54	16.18
				3.00	0.79	966.83	0.31	15.38	15.02
				4.00	0.73	893.40	0.28	14.21	13.86
				5.00	0.67	819.97	0.26	13.04	12.70
4.00	4.00	3.00	0.65	6.00	0.62	758.78	0.24	12.07	11.73
				8.00	0.54	660.87	0.21	10.51	10.18
				10.00	0.46	562.96	0.18	8.95	8.63
				12.00	0.4	489.53	0.16	7.79	7.47
				14.00	0.35	428.34	0.14	6.81	6.50
				15.00	0.32	391.63	0.12	6.23	5.92
				16.00	0.3	367.15	0.12	5.84	5.53
				18.00	0.26	318.20	0.10	5.06	4.76
				20.00	0.23	281.48	0.09	4.48	4.18
				25.00	0.16	195.81	0.06	3.11	2.82
				0.25	0.99	2322.82	0.39	19.27	18.70
				0.50	0.98	2299.36	0.38	19.07	18.41
				0.75	0.965	2264.17	0.38	18.78	18.12
				1.00	0.95	2228.97	0.37	18.49	17.34
				2.00	0.91	2135.12	0.35	17.71	16.37
				3.00	0.86	2017.81	0.33	16.74	15.60
				4.00	0.82	1923.95	0.32	15.96	15.02
				5.00	0.79	1853.57	0.31	15.38	14.24
4.00	4.00	3.00	0.90	6.00	0.75	1759.71	0.29	14.60	12.89
				8.00	0.68	1595.47	0.26	13.23	11.73
				10.00	0.62	1454.70	0.24	12.07	10.76
				12.00	0.57	1337.38	0.22	11.09	9.79
				14.00	0.52	1220.07	0.20	10.12	9.41
				15.00	0.5	1173.14	0.19	9.73	9.02
				16.00	0.48	1126.22	0.19	9.34	8.24
				18.00	0.44	1032.37	0.17	8.56	7.47
				20.00	0.4	938.51	0.16	7.79	6.11
				25.00	0.33	774.27	0.13	6.42	18.70

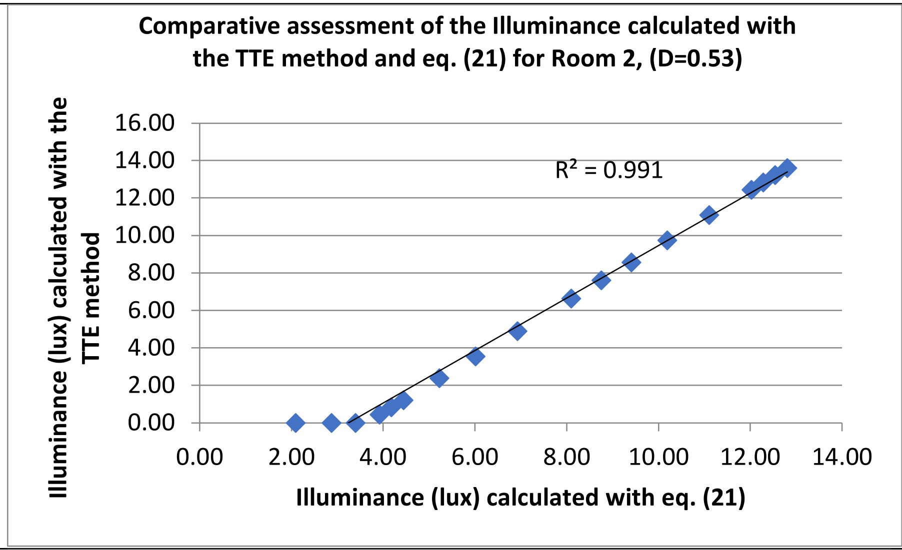
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
4.00	4.00	5.00	0.25	0.25	0.96	173.80	0.25	12.55	10.91
				0.50	0.92	166.56	0.24	12.02	8.39
				0.75	0.88	159.32	0.23	11.50	6.26
				1.00	0.84	152.07	0.22	10.98	4.52
				2.00	0.71	128.54	0.19	9.28	3.16
				3.00	0.6	108.62	0.16	7.84	2.00
				4.00	0.51	92.33	0.13	6.66	0.07
				5.00	0.44	79.66	0.11	5.75	0.00
				6.00	0.38	68.80	0.10	4.97	0.00
				8.00	0.28	50.69	0.07	3.66	0.00
				10.00	0.21	38.02	0.05	2.74	0.00
				12.00	0.16	28.97	0.04	2.09	0.00
				14.00	0.12	21.72	0.03	1.57	0.00
				15.00	0.1	18.10	0.03	1.31	0.00
				16.00	0.09	16.29	0.02	1.18	0.00
				18.00	0.07	12.67	0.02	0.91	10.91
				20.00	0.05	9.05	0.01	0.65	8.39
				25.00	0.03	5.43	0.01	0.39	6.26
4.00	4.00	5.00	0.35	0.25	0.97	344.19	0.25	12.68	13.42
				0.50	0.93	330.00	0.24	12.15	12.65
				0.75	0.9	319.36	0.24	11.76	12.07
				1.00	0.87	308.71	0.23	11.37	11.49
				2.00	0.76	269.68	0.20	9.93	9.36
				3.00	0.66	234.19	0.17	8.62	7.42
				4.00	0.58	205.81	0.15	7.58	5.87
				5.00	0.51	180.97	0.13	6.66	4.52
				6.00	0.45	159.68	0.12	5.88	3.36
				8.00	0.35	124.19	0.09	4.57	1.42
				10.00	0.28	99.36	0.07	3.66	0.07
				12.00	0.22	78.06	0.06	2.87	0.00
				14.00	0.17	60.32	0.04	2.22	0.00
				15.00	0.15	53.23	0.04	1.96	0.00
				16.00	0.14	49.68	0.04	1.83	0.00
				18.00	0.11	39.03	0.03	1.44	0.00
				20.00	0.09	31.94	0.02	1.18	0.00
				25.00	0.05	17.74	0.01	0.65	0.00

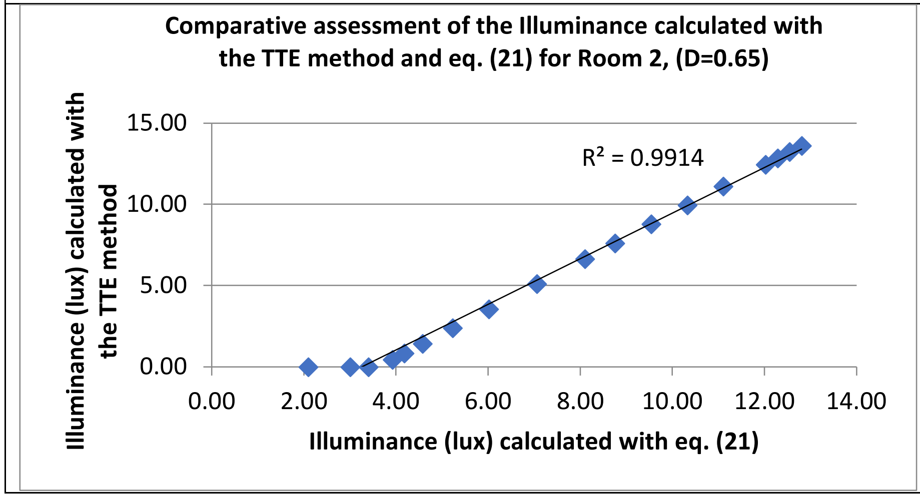

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 1, (D=0.65)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 1, (D=0.90)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 2, (D=0.25)
R² = 0.9549
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 2, (D=0.35)
R² = 0.9659
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)

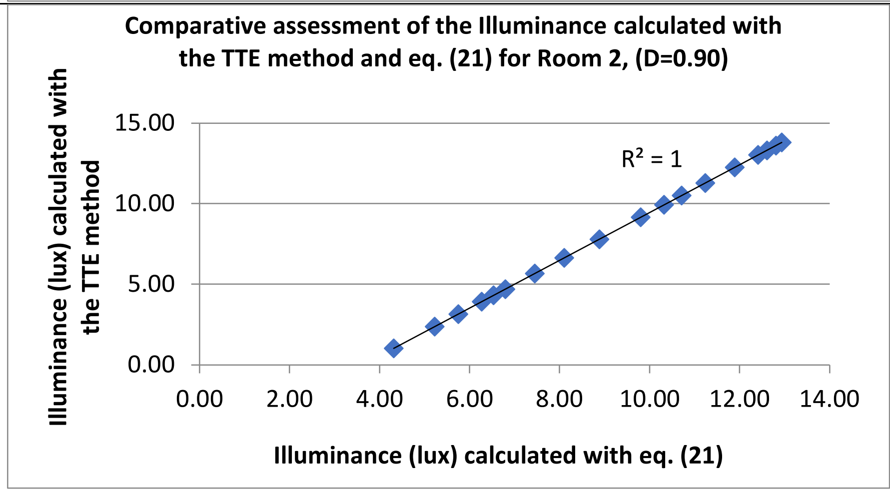
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
4.00	4.00	5.00	0.375	0.25	0.97	395.12	0.25	12.68	13.42
				0.50	0.94	382.90	0.25	12.28	12.84
				0.75	0.91	370.68	0.24	11.89	12.26
				1.00	0.88	358.46	0.23	11.50	11.68
				2.00	0.78	317.73	0.20	10.19	9.75
				3.00	0.69	281.07	0.18	9.02	8.00
				4.00	0.62	252.55	0.16	8.10	6.65
				5.00	0.55	224.04	0.14	7.19	5.29
				6.00	0.49	199.60	0.13	6.40	4.13
				8.00	0.39	158.86	0.10	5.10	2.20
				10.00	0.32	130.35	0.08	4.18	0.84
				12.00	0.26	105.91	0.07	3.40	0.00
				14.00	0.21	85.54	0.05	2.74	0.00
				15.00	0.19	77.39	0.05	2.48	0.00
				16.00	0.17	69.25	0.04	2.22	0.00
				18.00	0.14	57.03	0.04	1.83	0.00
				20.00	0.11	44.81	0.03	1.44	0.00
				25.00	0.07	28.51	0.02	0.91	0.00
4.00	4.00	5.00	0.53	0.25	0.98	797.40	0.26	12.81	13.23
				0.50	0.96	781.12	0.25	12.55	12.84
				0.75	0.94	764.85	0.25	12.28	12.46
				1.00	0.92	748.58	0.24	12.02	11.10
				2.00	0.85	691.62	0.22	11.11	9.75
				3.00	0.78	634.66	0.20	10.19	8.58
				4.00	0.72	585.84	0.19	9.41	7.62
				5.00	0.67	545.16	0.18	8.76	6.65
				6.00	0.62	504.47	0.16	8.10	4.91
				8.00	0.53	431.24	0.14	6.93	3.55
				10.00	0.46	374.29	0.12	6.01	2.39
				12.00	0.4	325.47	0.10	5.23	1.23
				14.00	0.34	276.65	0.09	4.44	0.84
				15.00	0.32	260.37	0.08	4.18	0.45
				16.00	0.3	244.10	0.08	3.92	0.00
				18.00	0.26	211.55	0.07	3.40	0.00
				20.00	0.22	179.01	0.06	2.87	0.00
				25.00	0.16	130.19	0.04	2.09	13.23

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
4.00	4.00	5.00	0.65	0.25	0.98	1199.36	0.26	12.81	13.62
				0.50	0.96	1174.88	0.25	12.55	13.23
				0.75	0.94	1150.40	0.25	12.28	12.84
				1.00	0.92	1125.93	0.24	12.02	12.46
				2.00	0.85	1040.26	0.22	11.11	11.10
				3.00	0.79	966.83	0.21	10.32	9.94
				4.00	0.73	893.40	0.19	9.54	8.78
				5.00	0.67	819.97	0.18	8.76	7.62
				6.00	0.62	758.78	0.16	8.10	6.65
				8.00	0.54	660.87	0.14	7.06	5.10
				10.00	0.46	562.96	0.12	6.01	3.55
				12.00	0.4	489.53	0.10	5.23	2.39
				14.00	0.35	428.34	0.09	4.57	1.42
				15.00	0.32	391.63	0.08	4.18	0.84
				16.00	0.3	367.15	0.08	3.92	0.45
				18.00	0.26	318.20	0.07	3.40	0.00
				20.00	0.23	281.48	0.06	3.01	0.00
				25.00	0.16	195.81	0.04	2.09	0.00
4.00	4.00	5.00	0.90	0.25	0.99	2322.82	0.26	12.94	13.81
				0.50	0.98	2299.36	0.26	12.81	13.62
				0.75	0.965	2264.17	0.25	12.61	13.33
				1.00	0.95	2228.97	0.25	12.41	13.04
				2.00	0.91	2135.12	0.24	11.89	12.26
				3.00	0.86	2017.81	0.22	11.24	11.29
				4.00	0.82	1923.95	0.21	10.72	10.52
				5.00	0.79	1853.57	0.21	10.32	9.94
				6.00	0.75	1759.71	0.20	9.80	9.17
				8.00	0.68	1595.47	0.18	8.89	7.81
				10.00	0.62	1454.70	0.16	8.10	6.65
				12.00	0.57	1337.38	0.15	7.45	5.68
				14.00	0.52	1220.07	0.14	6.80	4.71
				15.00	0.5	1173.14	0.13	6.53	4.33
				16.00	0.48	1126.22	0.13	6.27	3.94
				18.00	0.44	1032.37	0.11	5.75	3.16
				20.00	0.4	938.51	0.10	5.23	2.39
				25.00	0.33	774.27	0.09	4.31	1.03


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 2, (D=0.375)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 0.9724
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00

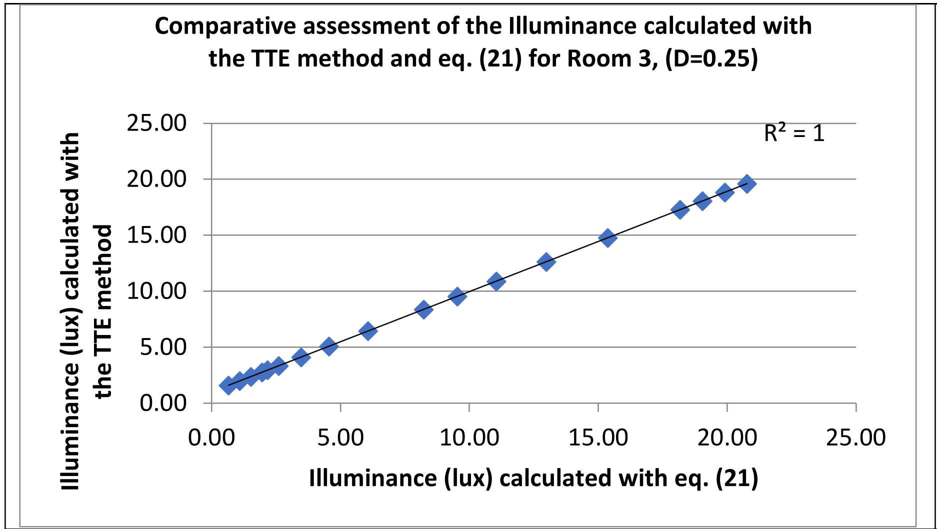

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 2, (D=0.53)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 0.991
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00

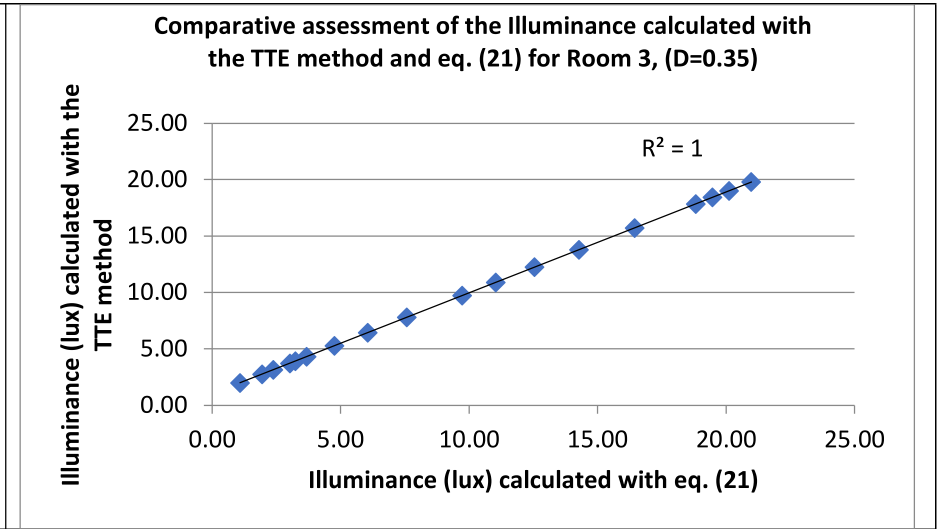

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 2, (D=0.65)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 0.9914
0.00
5.00
10.00
15.00
2.00
4.00
6.00
8.00
12.00
14.00

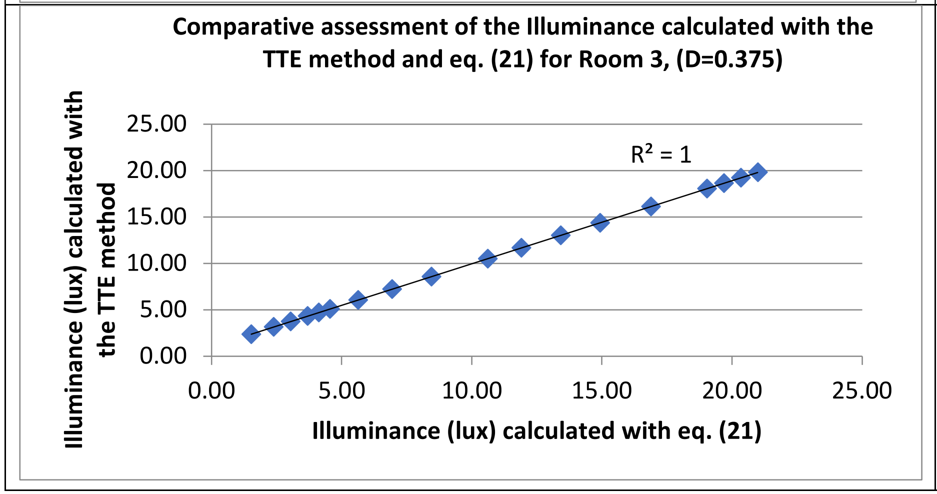

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 2, (D=0.90)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
2.00
4.00
6.00
8.00
12.00
14.00

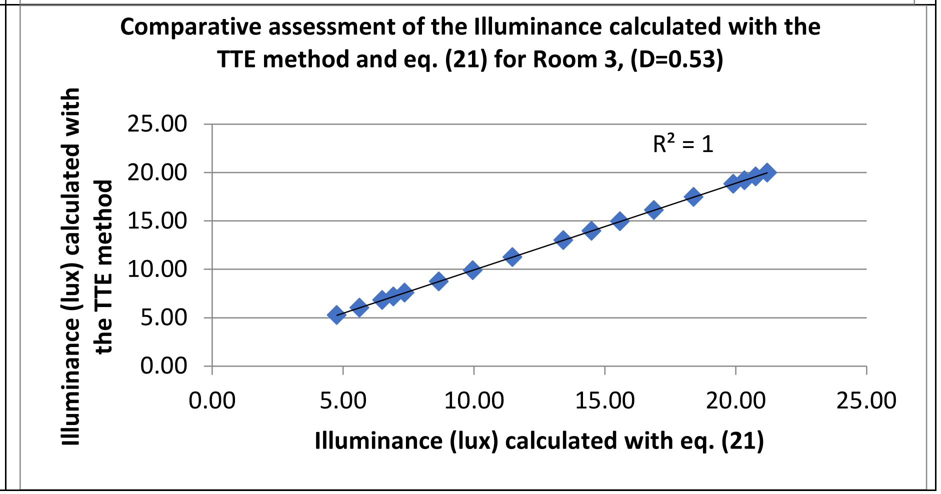
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
6.00	4.00	3.00	0.25	0.25	0.96	173.80	0.42	20.77	19.61
				0.50	0.92	166.56	0.40	19.90	18.83
				0.75	0.88	159.32	0.38	19.04	18.06
				1.00	0.84	152.07	0.36	18.17	17.29
				2.00	0.71	128.54	0.31	15.36	14.77
				3.00	0.6	108.62	0.26	12.98	12.64
				4.00	0.51	92.33	0.22	11.03	10.90
				5.00	0.44	79.66	0.19	9.52	9.54
				6.00	0.38	68.80	0.16	8.22	8.38
				8.00	0.28	50.69	0.12	6.06	6.45
				10.00	0.21	38.02	0.09	4.54	5.09
				12.00	0.16	28.97	0.07	3.46	4.12
				14.00	0.12	21.72	0.05	2.60	3.35
				15.00	0.1	18.10	0.04	2.16	2.96
				16.00	0.09	16.29	0.04	1.95	2.77
				18.00	0.07	12.67	0.03	1.51	2.38
				20.00	0.05	9.05	0.02	1.08	1.99
				25.00	0.03	5.43	0.01	0.65	1.61
6.00	4.00	3.00	0.35	0.25	0.97	344.19	0.42	20.98	19.80
				0.50	0.93	330.00	0.40	20.12	19.03
				0.75	0.9	319.36	0.39	19.47	18.45
				1.00	0.87	308.71	0.38	18.82	17.87
				2.00	0.76	269.68	0.33	16.44	15.74
				3.00	0.66	234.19	0.29	14.28	13.80
				4.00	0.58	205.81	0.25	12.55	12.25
				5.00	0.51	180.97	0.22	11.03	10.90
				6.00	0.45	159.68	0.19	9.73	9.74
				8.00	0.35	124.19	0.15	7.57	7.80
				10.00	0.28	99.36	0.12	6.06	6.45
				12.00	0.22	78.06	0.10	4.76	5.28
				14.00	0.17	60.32	0.07	3.68	4.32
				15.00	0.15	53.23	0.06	3.24	3.93
				16.00	0.14	49.68	0.06	3.03	3.73
				18.00	0.11	39.03	0.05	2.38	3.15
				20.00	0.09	31.94	0.04	1.95	2.77
				25.00	0.05	17.74	0.02	1.08	1.99

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
6.00	4.00	3.00	0.375	0.25	0.97	395.12	0.42	20.98	19.80
				0.50	0.94	382.90	0.41	20.33	19.22
				0.75	0.91	370.68	0.39	19.69	18.64
				1.00	0.88	358.46	0.38	19.04	18.06
				2.00	0.78	317.73	0.34	16.87	16.12
				3.00	0.69	281.07	0.30	14.93	14.38
				4.00	0.62	252.55	0.27	13.41	13.03
				5.00	0.55	224.04	0.24	11.90	11.67
				6.00	0.49	199.60	0.21	10.60	10.51
				8.00	0.39	158.86	0.17	8.44	8.57
				10.00	0.32	130.35	0.14	6.92	7.22
				12.00	0.26	105.91	0.11	5.62	6.06
				14.00	0.21	85.54	0.09	4.54	5.09
				15.00	0.19	77.39	0.08	4.11	4.70
				16.00	0.17	69.25	0.07	3.68	4.32
				18.00	0.14	57.03	0.06	3.03	3.73
				20.00	0.11	44.81	0.05	2.38	3.15
				25.00	0.07	28.51	0.03	1.51	2.38
6.00	4.00	3.00	0.53	0.25	0.98	797.40	0.42	21.20	20.00
				0.50	0.96	781.12	0.42	20.77	19.61
				0.75	0.94	764.85	0.41	20.33	19.22
				1.00	0.92	748.58	0.40	19.90	18.83
				2.00	0.85	691.62	0.37	18.39	17.48
				3.00	0.78	634.66	0.34	16.87	16.12
				4.00	0.72	585.84	0.31	15.58	14.96
				5.00	0.67	545.16	0.29	14.49	13.99
				6.00	0.62	504.47	0.27	13.41	13.03
				8.00	0.53	431.24	0.23	11.47	11.28
				10.00	0.46	374.29	0.20	9.95	9.93
				12.00	0.4	325.47	0.17	8.65	8.77
				14.00	0.34	276.65	0.15	7.35	7.61
				15.00	0.32	260.37	0.14	6.92	7.22
				16.00	0.3	244.10	0.13	6.49	6.83
				18.00	0.26	211.55	0.11	5.62	6.06
				20.00	0.22	179.01	0.10	4.76	5.28
				25.00	0.16	130.19	0.07	3.46	4.12


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 3, (D=0.25)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00

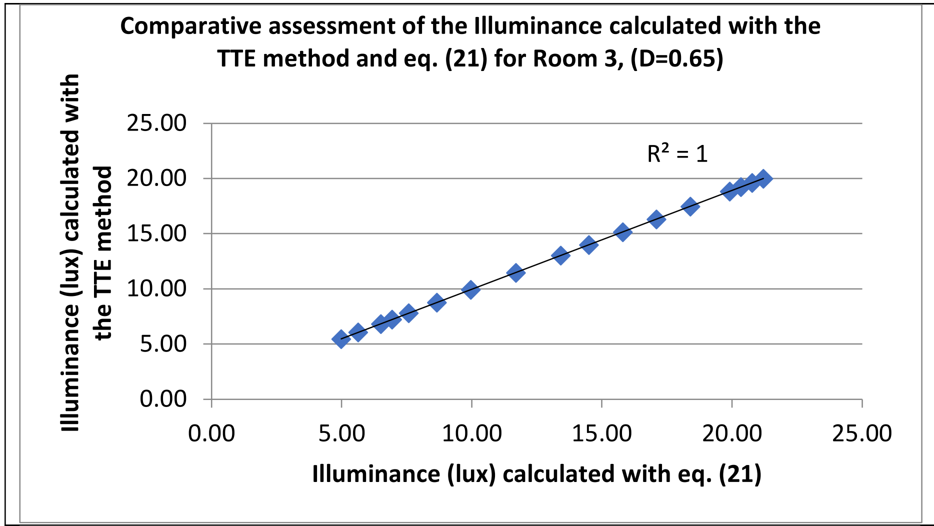

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 3, (D=0.35)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00

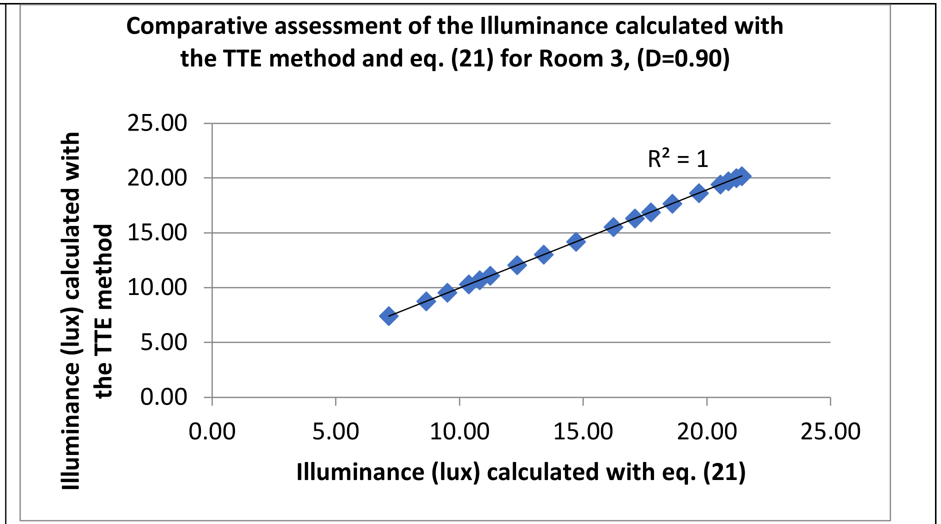

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 3, (D=0.375)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00

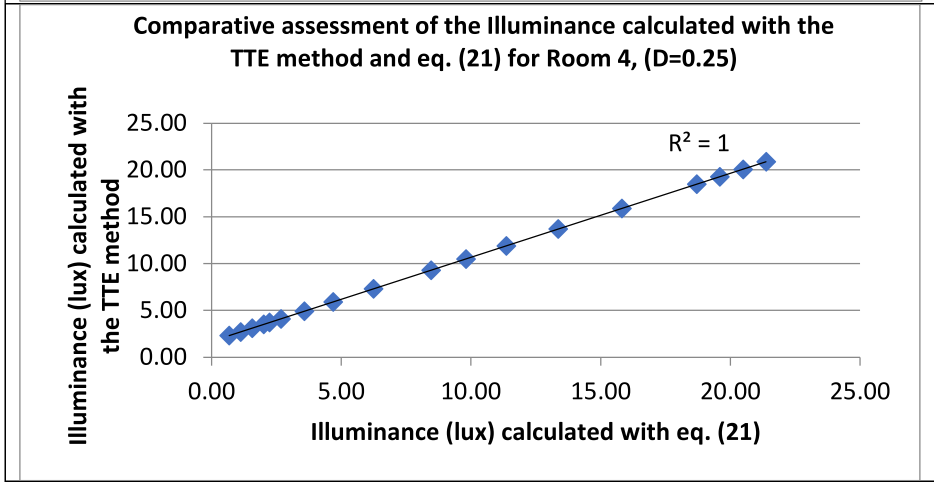

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 3, (D=0.53)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00

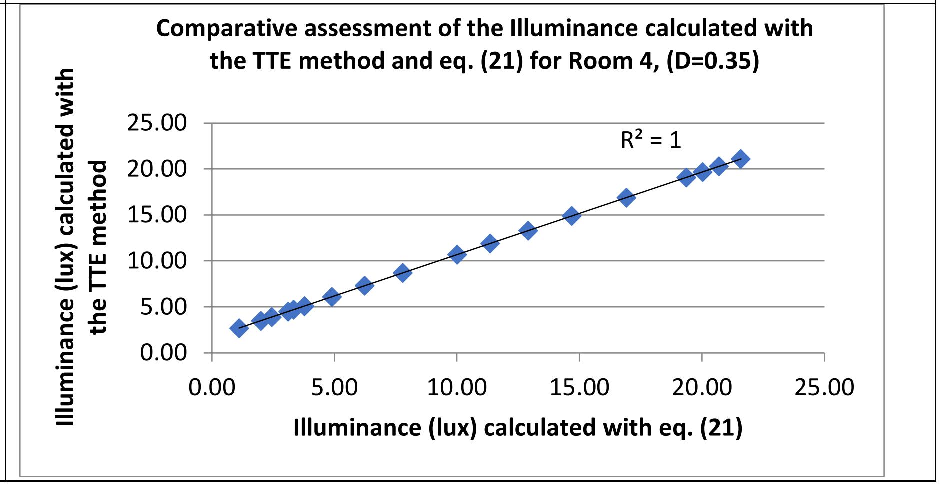
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
6.00	4.00	3.00	0.65	0.25	0.98	1199.36	0.42	21.20	20.00
				0.50	0.96	1174.88	0.42	20.77	19.61
				0.75	0.94	1150.40	0.41	20.33	19.22
				1.00	0.92	1125.93	0.40	19.90	18.83
				2.00	0.85	1040.26	0.37	18.39	17.48
				3.00	0.79	966.83	0.34	17.09	16.32
				4.00	0.73	893.40	0.32	15.79	15.16
				5.00	0.67	819.97	0.29	14.49	13.99
				6.00	0.62	758.78	0.27	13.41	13.03
				8.00	0.54	660.87	0.23	11.68	11.48
				10.00	0.46	562.96	0.20	9.95	9.93
				12.00	0.4	489.53	0.17	8.65	8.77
				14.00	0.35	428.34	0.15	7.57	7.80
				15.00	0.32	391.63	0.14	6.92	7.22
				16.00	0.3	367.15	0.13	6.49	6.83
				18.00	0.26	318.20	0.11	5.62	6.06
				20.00	0.23	281.48	0.10	4.98	5.48
				25.00	0.16	195.81	0.07	3.46	4.12
6.00	4.00	3.00	0.90	0.25	0.99	2322.82	0.43	21.42	20.19
				0.50	0.98	2299.36	0.42	21.20	20.00
				0.75	0.965	2264.17	0.42	20.88	19.71
				1.00	0.95	2228.97	0.41	20.55	19.42
				2.00	0.91	2135.12	0.39	19.69	18.64
				3.00	0.86	2017.81	0.37	18.60	17.67
				4.00	0.82	1923.95	0.35	17.74	16.90
				5.00	0.79	1853.57	0.34	17.09	16.32
				6.00	0.75	1759.71	0.32	16.22	15.54
				8.00	0.68	1595.47	0.29	14.71	14.19
				10.00	0.62	1454.70	0.27	13.41	13.03
				12.00	0.57	1337.38	0.25	12.33	12.06
				14.00	0.52	1220.07	0.22	11.25	11.09
				15.00	0.5	1173.14	0.22	10.82	10.70
				16.00	0.48	1126.22	0.21	10.38	10.32
				18.00	0.44	1032.37	0.19	9.52	9.54
				20.00	0.4	938.51	0.17	8.65	8.77
				25.00	0.33	774.27	0.14	7.14	7.41

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
7.00	4.00	3.00	0.25	0.25	0.96	173.80	0.43	21.37	20.90
				0.50	0.92	166.56	0.41	20.48	20.10
				0.75	0.88	159.32	0.39	19.59	19.30
				1.00	0.84	152.07	0.37	18.70	18.50
				2.00	0.71	128.54	0.32	15.80	15.91
				3.00	0.6	108.62	0.27	13.36	13.71
				4.00	0.51	92.33	0.23	11.35	11.91
				5.00	0.44	79.66	0.20	9.79	10.51
				6.00	0.38	68.80	0.17	8.46	9.32
				8.00	0.28	50.69	0.12	6.23	7.32
				10.00	0.21	38.02	0.09	4.67	5.92
				12.00	0.16	28.97	0.07	3.56	4.92
				14.00	0.12	21.72	0.05	2.67	4.12
				15.00	0.1	18.10	0.04	2.23	3.72
				16.00	0.09	16.29	0.04	2.00	3.52
				18.00	0.07	12.67	0.03	1.56	3.12
				20.00	0.05	9.05	0.02	1.11	2.73
				25.00	0.03	5.43	0.01	0.67	2.33
6.00	4.00	3.00	0.35	0.25	0.97	344.19	0.43	21.59	21.10
				0.50	0.93	330.00	0.41	20.70	20.30
				0.75	0.9	319.36	0.40	20.03	19.70
				1.00	0.87	308.71	0.39	19.37	19.10
				2.00	0.76	269.68	0.34	16.92	16.90
				3.00	0.66	234.19	0.29	14.69	14.91
				4.00	0.58	205.81	0.26	12.91	13.31
				5.00	0.51	180.97	0.23	11.35	11.91
				6.00	0.45	159.68	0.20	10.02	10.71
				8.00	0.35	124.19	0.16	7.79	8.72
				10.00	0.28	99.36	0.12	6.23	7.32
				12.00	0.22	78.06	0.10	4.90	6.12
				14.00	0.17	60.32	0.08	3.78	5.12
				15.00	0.15	53.23	0.07	3.34	4.72
				16.00	0.14	49.68	0.06	3.12	4.52
				18.00	0.11	39.03	0.05	2.45	3.92
				20.00	0.09	31.94	0.04	2.00	3.52
				25.00	0.05	17.74	0.02	1.11	2.73


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 3, (D=0.65)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00

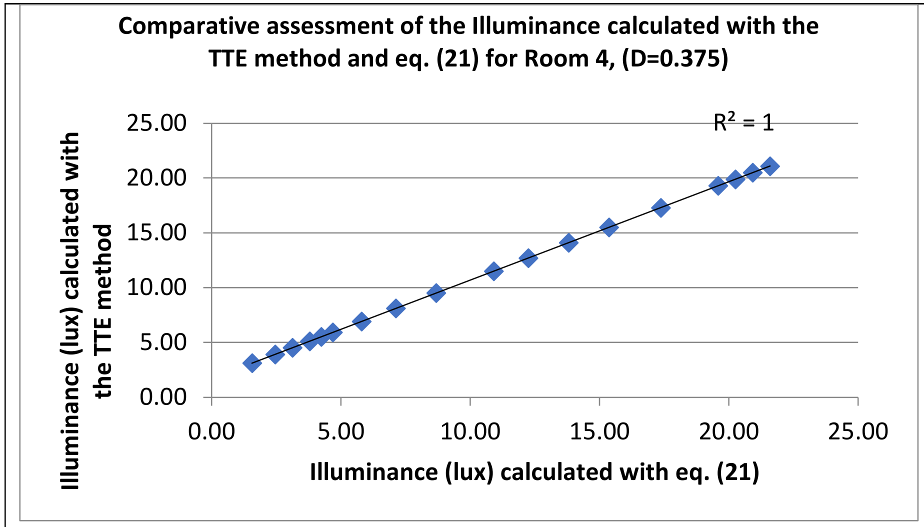

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 3, (D=0.90)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00

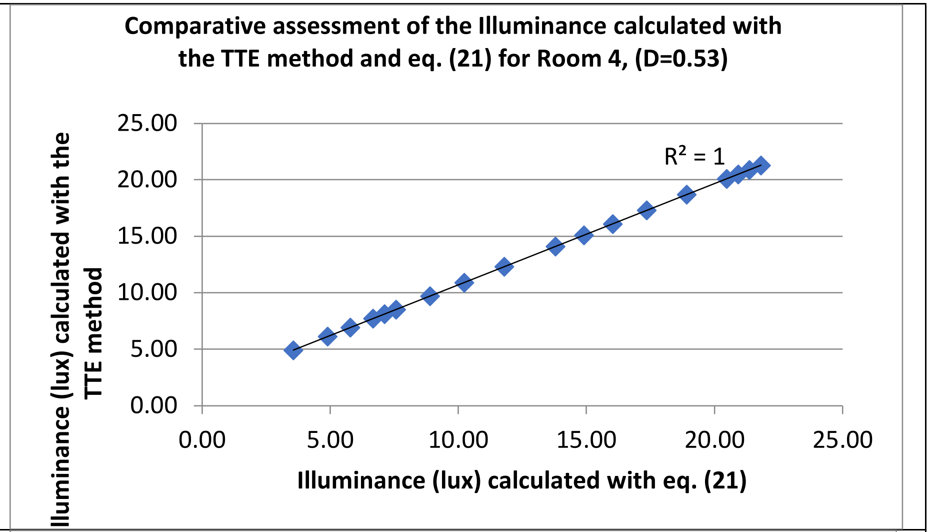

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 4, (D=0.25)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00

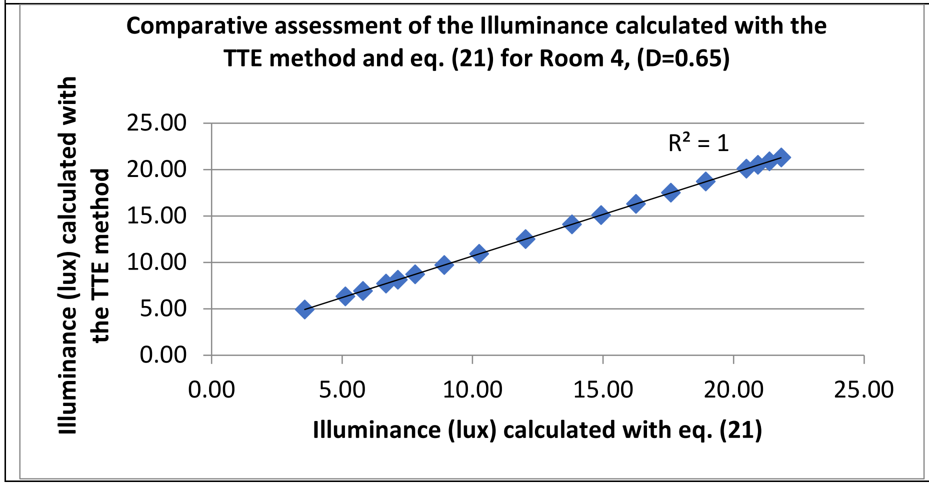

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 4, (D=0.35)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00

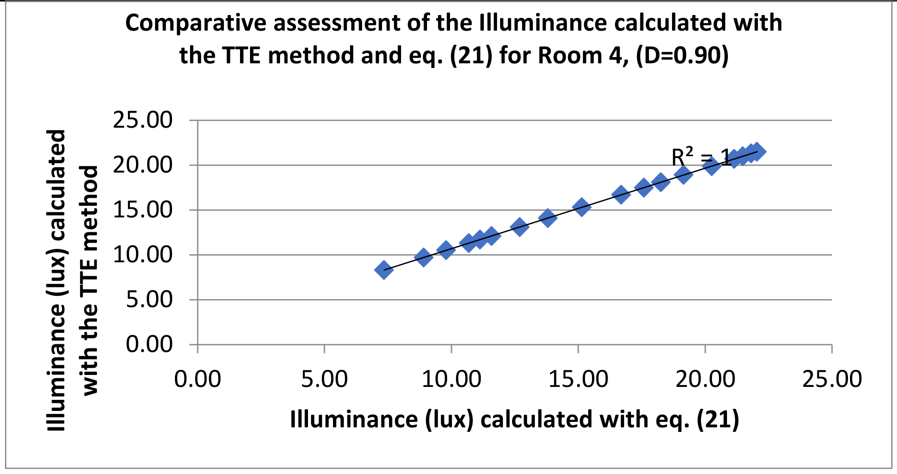
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
7.00	4.00	3.00	0.375	0.25	0.97	395.12	0.43	21.59	21.10
				0.50	0.94	382.90	0.42	20.92	20.50
				0.75	0.91	370.68	0.41	20.26	19.90
				1.00	0.88	358.46	0.39	19.59	19.30
				2.00	0.78	317.73	0.35	17.36	17.30
				3.00	0.69	281.07	0.31	15.36	15.51
				4.00	0.62	252.55	0.28	13.80	14.11
				5.00	0.55	224.04	0.24	12.24	12.71
				6.00	0.49	199.60	0.22	10.91	11.51
				8.00	0.39	158.86	0.17	8.68	9.52
				10.00	0.32	130.35	0.14	7.12	8.12
				12.00	0.26	105.91	0.12	5.79	6.92
				14.00	0.21	85.54	0.09	4.67	5.92
				15.00	0.19	77.39	0.08	4.23	5.52
				16.00	0.17	69.25	0.08	3.78	5.12
				18.00	0.14	57.03	0.06	3.12	4.52
				20.00	0.11	44.81	0.05	2.45	3.92
				25.00	0.07	28.51	0.03	1.56	3.12
6.00	4.00	3.00	0.53	0.25	0.98	797.40	0.44	21.81	21.30
				0.50	0.96	781.12	0.43	21.37	20.90
				0.75	0.94	764.85	0.42	20.92	20.50
				1.00	0.92	748.58	0.41	20.48	20.10
				2.00	0.85	691.62	0.38	18.92	18.70
				3.00	0.78	634.66	0.35	17.36	17.30
				4.00	0.72	585.84	0.32	16.03	16.11
				5.00	0.67	545.16	0.30	14.91	15.11
				6.00	0.62	504.47	0.28	13.80	14.11
				8.00	0.53	431.24	0.24	11.80	12.31
				10.00	0.46	374.29	0.20	10.24	10.91
				12.00	0.4	325.47	0.18	8.90	9.72
				14.00	0.34	276.65	0.15	7.57	8.52
				15.00	0.32	260.37	0.14	7.12	8.12
				16.00	0.3	244.10	0.13	6.68	7.72
				18.00	0.26	211.55	0.12	5.79	6.92
				20.00	0.22	179.01	0.10	4.90	6.12
				25.00	0.16	130.19	0.07	3.56	4.92

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
				0.25	0.98	1199.36	0.44	21.81	21.30
				0.50	0.96	1174.88	0.43	21.37	20.90
				0.75	0.94	1150.40	0.42	20.92	20.50
				1.00	0.92	1125.93	0.41	20.48	20.10
				2.00	0.85	1040.26	0.38	18.92	18.70
				3.00	0.79	966.83	0.35	17.59	17.50
				4.00	0.73	893.40	0.32	16.25	16.31
				5.00	0.67	819.97	0.30	14.91	15.11
7.00	4.00	3.00	0.65	6.00	0.62	758.78	0.28	13.80	14.11
				8.00	0.54	660.87	0.24	12.02	12.51
				10.00	0.46	562.96	0.20	10.24	10.91
				12.00	0.4	489.53	0.18	8.90	9.72
				14.00	0.35	428.34	0.16	7.79	8.72
				15.00	0.32	391.63	0.14	7.12	8.12
				16.00	0.3	367.15	0.13	6.68	7.72
				18.00	0.26	318.20	0.12	5.79	6.92
				20.00	0.23	281.48	0.10	5.12	6.32
				25.00	0.16	195.81	0.07	3.56	4.92
				0.25	0.99	2322.82	0.44	22.04	21.50
				0.50	0.98	2299.36	0.44	21.81	21.30
				0.75	0.965	2264.17	0.43	21.48	21.00
				1.00	0.95	2228.97	0.42	21.15	20.70
				2.00	0.91	2135.12	0.41	20.26	19.90
				3.00	0.86	2017.81	0.38	19.14	18.90
				4.00	0.82	1923.95	0.37	18.25	18.10
				5.00	0.79	1853.57	0.35	17.59	17.50
6.00	4.00	3.00	0.90	6.00	0.75	1759.71	0.33	16.69	16.70
				8.00	0.68	1595.47	0.30	15.14	15.31
				10.00	0.62	1454.70	0.28	13.80	14.11
				12.00	0.57	1337.38	0.25	12.69	13.11
				14.00	0.52	1220.07	0.23	11.58	12.11
				15.00	0.5	1173.14	0.22	11.13	11.71
				16.00	0.48	1126.22	0.21	10.68	11.31
				18.00	0.44	1032.37	0.20	9.79	10.51
				20.00	0.4	938.51	0.18	8.90	9.72
				25.00	0.33	774.27	0.15	7.35	8.32


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 4, (D=0.375)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00

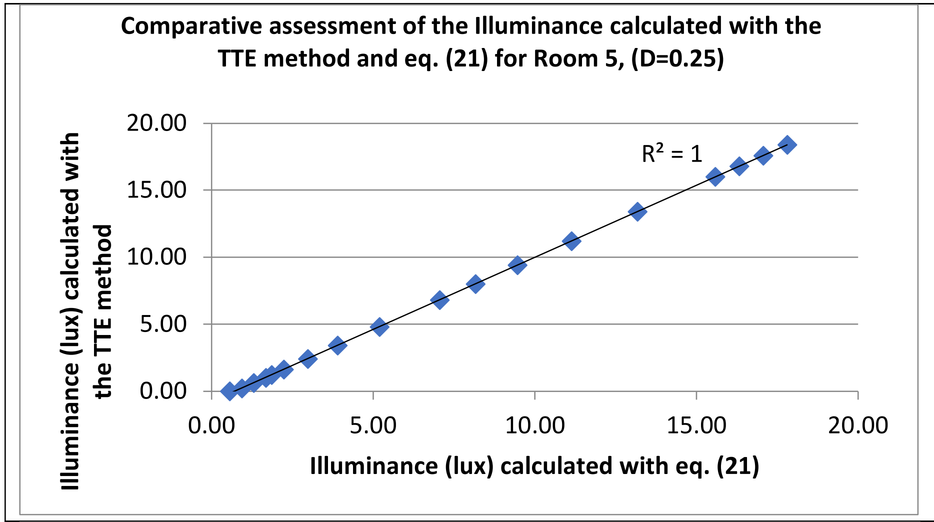

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 4, (D=0.53)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00

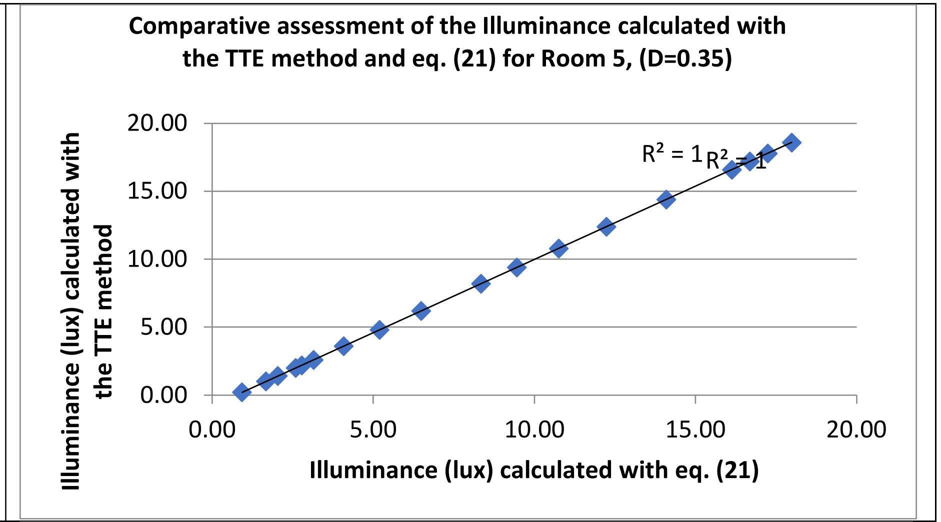

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 4, (D=0.65)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00

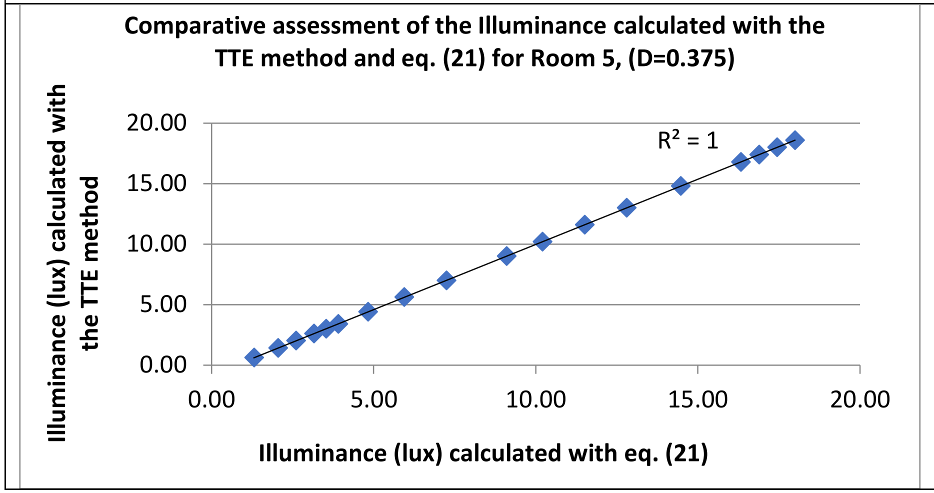

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 4, (D=0.90)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00

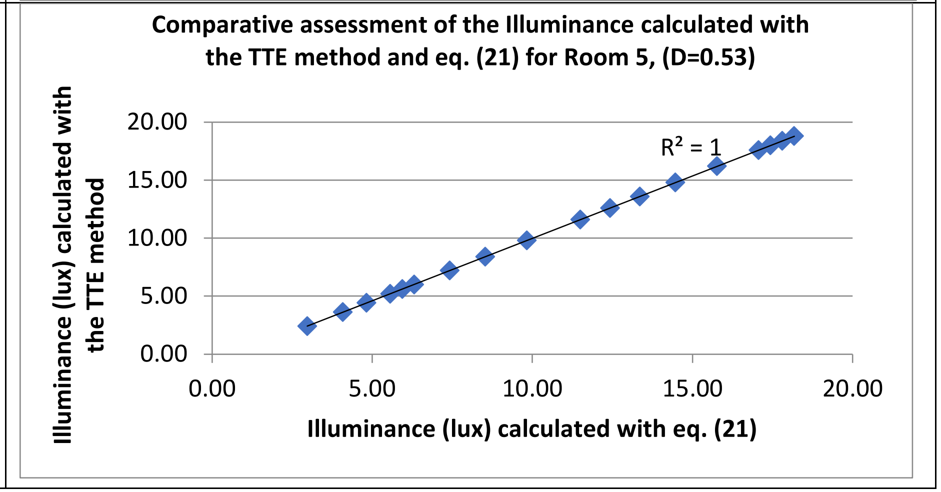
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
5.00	5.00	4.00	0.25	0.25	0.96	173.80	0.36	17.80	18.40
				0.50	0.92	166.56	0.34	17.06	17.60
				0.75	0.88	159.32	0.33	16.32	16.80
				1.00	0.84	152.07	0.31	15.58	16.00
				2.00	0.71	128.54	0.26	13.17	13.41
				3.00	0.6	108.62	0.22	11.13	11.21
				4.00	0.51	92.33	0.19	9.46	9.41
				5.00	0.44	79.66	0.16	8.16	8.01
				6.00	0.38	68.80	0.14	7.05	6.82
				8.00	0.28	50.69	0.10	5.19	4.82
				10.00	0.21	38.02	0.08	3.89	3.42
				12.00	0.16	28.97	0.06	2.97	2.42
				14.00	0.12	21.72	0.04	2.23	1.62
				15.00	0.1	18.10	0.04	1.85	1.22
				16.00	0.09	16.29	0.03	1.67	1.02
				18.00	0.07	12.67	0.03	1.30	0.62
				20.00	0.05	9.05	0.02	0.93	0.23
				25.00	0.03	5.43	0.01	0.56	0.00
5.00	5.00	4.00	0.35	0.25	0.97	344.19	0.36	17.99	18.60
				0.50	0.93	330.00	0.34	17.25	17.80
				0.75	0.9	319.36	0.33	16.69	17.20
				1.00	0.87	308.71	0.32	16.14	16.60
				2.00	0.76	269.68	0.28	14.10	14.40
				3.00	0.66	234.19	0.24	12.24	12.41
				4.00	0.58	205.81	0.22	10.76	10.81
				5.00	0.51	180.97	0.19	9.46	9.41
				6.00	0.45	159.68	0.17	8.35	8.21
				8.00	0.35	124.19	0.13	6.49	6.22
				10.00	0.28	99.36	0.10	5.19	4.82
				12.00	0.22	78.06	0.08	4.08	3.62
				14.00	0.17	60.32	0.06	3.15	2.62
				15.00	0.15	53.23	0.06	2.78	2.22
				16.00	0.14	49.68	0.05	2.60	2.02
				18.00	0.11	39.03	0.04	2.04	1.42
				20.00	0.09	31.94	0.03	1.67	1.02
				25.00	0.05	17.74	0.02	0.93	0.23

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
5.00	5.00	4.00	0.375	0.25	0.97	395.12	0.36	17.99	18.60
				0.50	0.94	382.90	0.35	17.43	18.00
				0.75	0.91	370.68	0.34	16.88	17.40
				1.00	0.88	358.46	0.33	16.32	16.80
				2.00	0.78	317.73	0.29	14.47	14.80
				3.00	0.69	281.07	0.26	12.80	13.01
				4.00	0.62	252.55	0.23	11.50	11.61
				5.00	0.55	224.04	0.20	10.20	10.21
				6.00	0.49	199.60	0.18	9.09	9.01
				8.00	0.39	158.86	0.14	7.23	7.02
				10.00	0.32	130.35	0.12	5.93	5.62
				12.00	0.26	105.91	0.10	4.82	4.42
				14.00	0.21	85.54	0.08	3.89	3.42
				15.00	0.19	77.39	0.07	3.52	3.02
				16.00	0.17	69.25	0.06	3.15	2.62
				18.00	0.14	57.03	0.05	2.60	2.02
				20.00	0.11	44.81	0.04	2.04	1.42
				25.00	0.07	28.51	0.03	1.30	0.62
5.00	5.00	4.00	0.53	0.25	0.98	797.40	0.36	18.18	18.80
				0.50	0.96	781.12	0.36	17.80	18.40
				0.75	0.94	764.85	0.35	17.43	18.00
				1.00	0.92	748.58	0.34	17.06	17.60
				2.00	0.85	691.62	0.32	15.76	16.20
				3.00	0.78	634.66	0.29	14.47	14.80
				4.00	0.72	585.84	0.27	13.35	13.61
				5.00	0.67	545.16	0.25	12.43	12.61
				6.00	0.62	504.47	0.23	11.50	11.61
				8.00	0.53	431.24	0.20	9.83	9.81
				10.00	0.46	374.29	0.17	8.53	8.41
				12.00	0.4	325.47	0.15	7.42	7.22
				14.00	0.34	276.65	0.13	6.31	6.02
				15.00	0.32	260.37	0.12	5.93	5.62
				16.00	0.3	244.10	0.11	5.56	5.22
				18.00	0.26	211.55	0.10	4.82	4.42
				20.00	0.22	179.01	0.08	4.08	3.62
				25.00	0.16	130.19	0.06	2.97	2.42


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 5, (D=0.25)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 5, (D=0.35)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
R² = 1
0.00
5.00
10.00
15.00
20.00

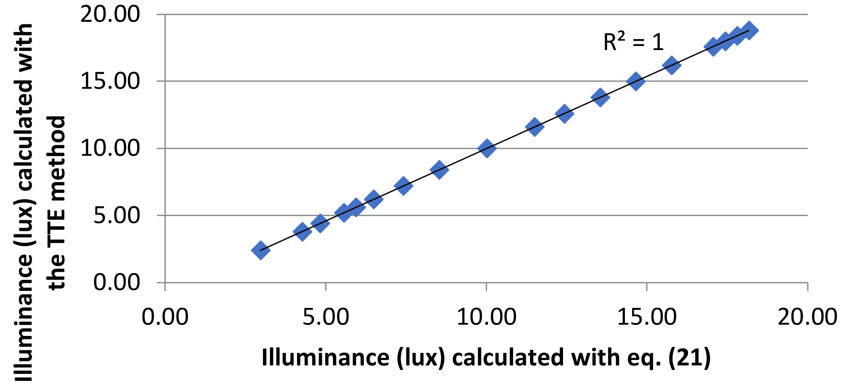

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 5, (D=0.375)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 5, (D=0.53)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00

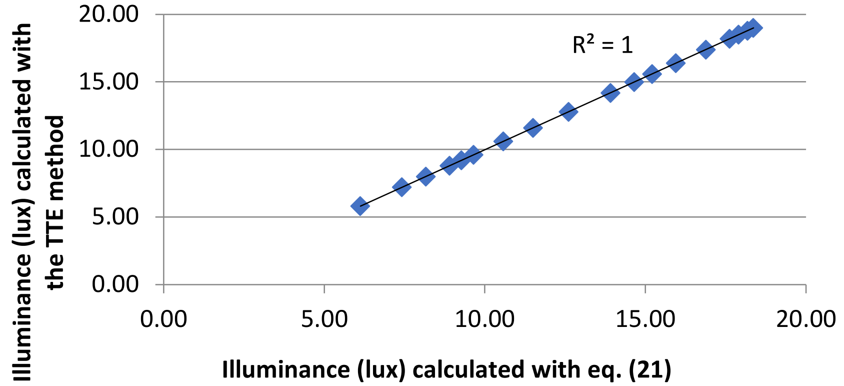
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
5.00	5.00	4.00	0.65	0.25	0.98	1199.36	0.36	18.18	18.80
				0.50	0.96	1174.88	0.36	17.80	18.40
				0.75	0.94	1150.40	0.35	17.43	18.00
				1.00	0.92	1125.93	0.34	17.06	17.60
				2.00	0.85	1040.26	0.32	15.76	16.20
				3.00	0.79	966.83	0.29	14.65	15.00
				4.00	0.73	893.40	0.27	13.54	13.81
				5.00	0.67	819.97	0.25	12.43	12.61
				6.00	0.62	758.78	0.23	11.50	11.61
				8.00	0.54	660.87	0.20	10.01	10.01
				10.00	0.46	562.96	0.17	8.53	8.41
				12.00	0.4	489.53	0.15	7.42	7.22
				14.00	0.35	428.34	0.13	6.49	6.22
				15.00	0.32	391.63	0.12	5.93	5.62
				16.00	0.3	367.15	0.11	5.56	5.22
				18.00	0.26	318.20	0.10	4.82	4.42
				20.00	0.23	281.48	0.09	4.27	3.82
				25.00	0.16	195.81	0.06	2.97	2.42
5.00	5.00	4.00	0.90	0.25	0.99	2322.82	0.37	18.36	19.00
				0.50	0.98	2299.36	0.36	18.18	18.80
				0.75	0.965	2264.17	0.36	17.90	18.50
				1.00	0.95	2228.97	0.35	17.62	18.20
				2.00	0.91	2135.12	0.34	16.88	17.40
				3.00	0.86	2017.81	0.32	15.95	16.40
				4.00	0.82	1923.95	0.30	15.21	15.60
				5.00	0.79	1853.57	0.29	14.65	15.00
				6.00	0.75	1759.71	0.28	13.91	14.20
				8.00	0.68	1595.47	0.25	12.61	12.81
				10.00	0.62	1454.70	0.23	11.50	11.61
				12.00	0.57	1337.38	0.21	10.57	10.61
				14.00	0.52	1220.07	0.19	9.64	9.61
				15.00	0.5	1173.14	0.19	9.27	9.21
				16.00	0.48	1126.22	0.18	8.90	8.81
				18.00	0.44	1032.37	0.16	8.16	8.01
				20.00	0.4	938.51	0.15	7.42	7.22
				25.00	0.33	774.27	0.12	6.12	5.82

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
6.00	6.00	2.50	0.25	0.25	0.96	173.80	0.52	25.92	24.46
6.00	6.00	2.50	0.25	0.50	0.92	166.56	0.50	24.84	23.66
6.00	6.00	2.50	0.25	0.75	0.88	159.32	0.48	23.76	22.86
6.00	6.00	2.50	0.25	1.00	0.84	152.07	0.45	22.68	22.06
6.00	6.00	2.50	0.25	2.00	0.71	128.54	0.38	19.17	19.47
6.00	6.00	2.50	0.25	3.00	0.6	108.62	0.32	16.20	17.27
6.00	6.00	2.50	0.25	4.00	0.51	92.33	0.28	13.77	15.47
6.00	6.00	2.50	0.25	5.00	0.44	79.66	0.24	11.88	14.07
6.00	6.00	2.50	0.25	6.00	0.38	68.80	0.21	10.26	12.88
6.00	6.00	2.50	0.25	8.00	0.28	50.69	0.15	7.56	10.88
6.00	6.00	2.50	0.25	10.00	0.21	38.02	0.11	5.67	9.48
6.00	6.00	2.50	0.25	12.00	0.16	28.97	0.09	4.32	8.48
6.00	6.00	2.50	0.25	14.00	0.12	21.72	0.06	3.24	7.68
6.00	6.00	2.50	0.25	15.00	0.1	18.10	0.05	2.70	7.28
6.00	6.00	2.50	0.25	16.00	0.09	16.29	0.05	2.43	7.08
6.00	6.00	2.50	0.25	18.00	0.07	12.67	0.04	1.89	6.68
6.00	6.00	2.50	0.25	20.00	0.05	9.05	0.03	1.35	6.29
6.00	6.00	2.50	0.25	25.00	0.03	5.43	0.02	0.81	5.89
6.00	6.00	2.50	0.35	0.25	0.97	344.19	0.52	26.19	24.66
6.00	6.00	2.50	0.35	0.50	0.93	330.00	0.50	25.11	23.86
6.00	6.00	2.50	0.35	0.75	0.9	319.36	0.49	24.30	23.26
6.00	6.00	2.50	0.35	1.00	0.87	308.71	0.47	23.49	22.66
6.00	6.00	2.50	0.35	2.00	0.76	269.68	0.41	20.52	20.46
6.00	6.00	2.50	0.35	3.00	0.66	234.19	0.36	17.82	18.47
6.00	6.00	2.50	0.35	4.00	0.58	205.81	0.31	15.66	16.87
6.00	6.00	2.50	0.35	5.00	0.51	180.97	0.28	13.77	15.47
6.00	6.00	2.50	0.35	6.00	0.45	159.68	0.24	12.15	14.27
6.00	6.00	2.50	0.35	8.00	0.35	124.19	0.19	9.45	12.28
6.00	6.00	2.50	0.35	10.00	0.28	99.36	0.15	7.56	10.88
6.00	6.00	2.50	0.35	12.00	0.22	78.06	0.12	5.94	9.68
6.00	6.00	2.50	0.35	14.00	0.17	60.32	0.09	4.59	8.68
6.00	6.00	2.50	0.35	15.00	0.15	53.23	0.08	4.05	8.28
6.00	6.00	2.50	0.35	16.00	0.14	49.68	0.08	3.78	8.08
6.00	6.00	2.50	0.35	18.00	0.11	39.03	0.06	2.97	7.48
6.00	6.00	2.50	0.35	20.00	0.09	31.94	0.05	2.43	7.08
6.00	6.00	2.50	0.35	25.00	0.05	17.74	0.03	1.35	6.29

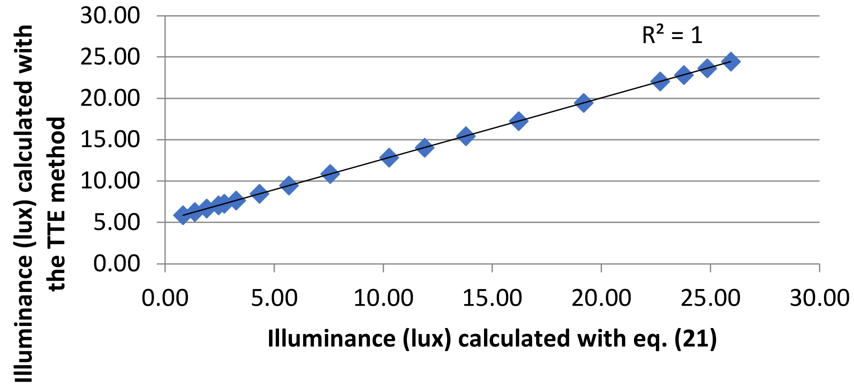
Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 5, (D=0.65)



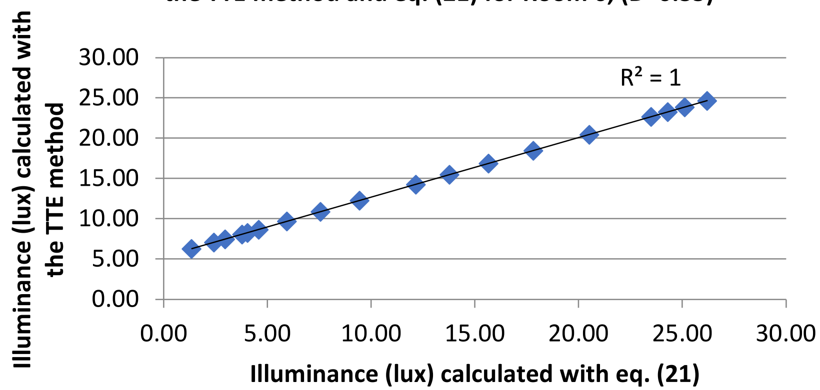
Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 5, (D=0.90)



Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 6, (D=0.25)

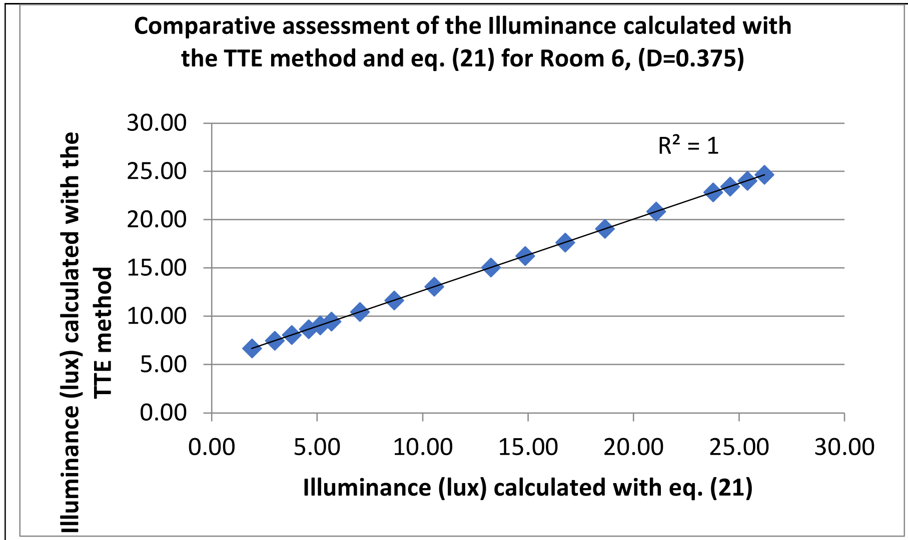


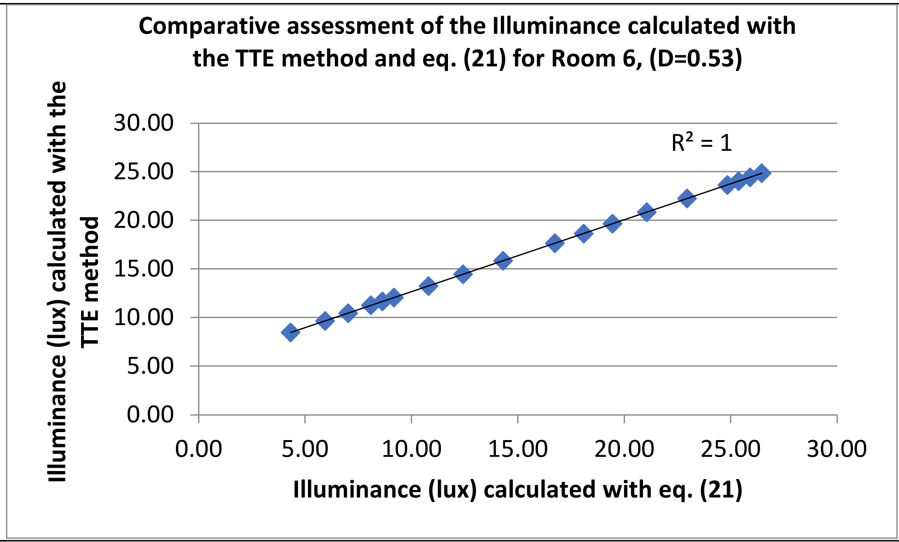
Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 6, (D=0.35)

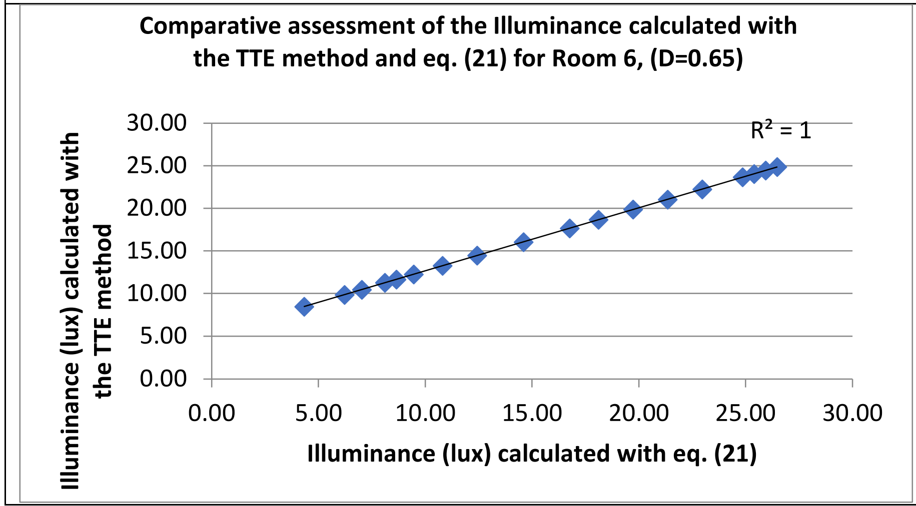


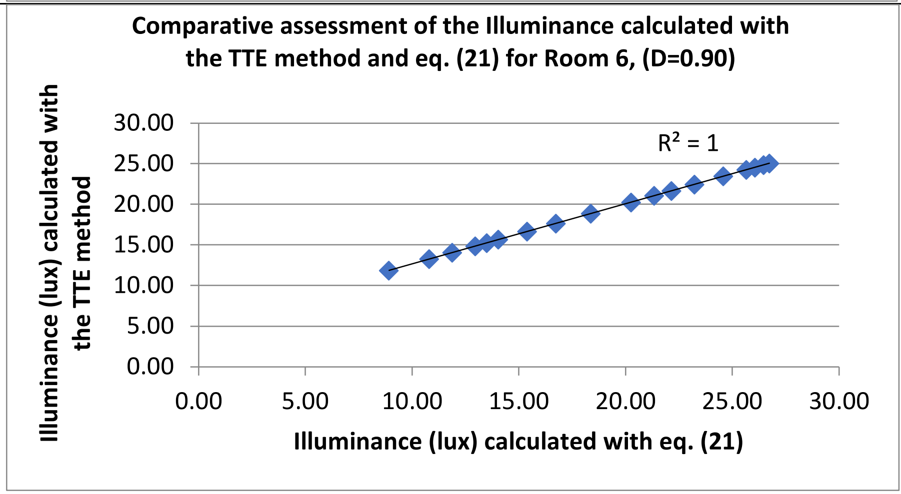
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
6.00	6.00	2.50	0.375	0.25	0.97	395.12	0.52	26.19	24.66
				0.50	0.94	382.90	0.51	25.38	24.06
				0.75	0.91	370.68	0.49	24.57	23.46
				1.00	0.88	358.46	0.48	23.76	22.86
				2.00	0.78	317.73	0.42	21.06	20.86
				3.00	0.69	281.07	0.37	18.63	19.07
				4.00	0.62	252.55	0.33	16.74	17.67
				5.00	0.55	224.04	0.30	14.85	16.27
				6.00	0.49	199.60	0.26	13.23	15.07
				8.00	0.39	158.86	0.21	10.53	13.08
				10.00	0.32	130.35	0.17	8.64	11.68
				12.00	0.26	105.91	0.14	7.02	10.48
				14.00	0.21	85.54	0.11	5.67	9.48
				15.00	0.19	77.39	0.10	5.13	9.08
				16.00	0.17	69.25	0.09	4.59	8.68
				18.00	0.14	57.03	0.08	3.78	8.08
				20.00	0.11	44.81	0.06	2.97	7.48
				25.00	0.07	28.51	0.04	1.89	6.68
6.00	6.00	2.50	0.53	0.25	0.98	797.40	0.53	26.46	24.86
				0.50	0.96	781.12	0.52	25.92	24.46
				0.75	0.94	764.85	0.51	25.38	24.06
				1.00	0.92	748.58	0.50	24.84	23.66
				2.00	0.85	691.62	0.46	22.95	22.26
				3.00	0.78	634.66	0.42	21.06	20.86
				4.00	0.72	585.84	0.39	19.44	19.67
				5.00	0.67	545.16	0.36	18.09	18.67
				6.00	0.62	504.47	0.33	16.74	17.67
				8.00	0.53	431.24	0.29	14.31	15.87
				10.00	0.46	374.29	0.25	12.42	14.47
				12.00	0.4	325.47	0.22	10.80	13.28
				14.00	0.34	276.65	0.18	9.18	12.08
				15.00	0.32	260.37	0.17	8.64	11.68
				16.00	0.3	244.10	0.16	8.10	11.28
				18.00	0.26	211.55	0.14	7.02	10.48
				20.00	0.22	179.01	0.12	5.94	9.68
				25.00	0.16	130.19	0.09	4.32	8.48

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
6.00	6.00	2.50	0.65	0.25	0.98	1199.36	0.53	26.46	24.86
				0.50	0.96	1174.88	0.52	25.92	24.46
				0.75	0.94	1150.40	0.51	25.38	24.06
				1.00	0.92	1125.93	0.50	24.84	23.66
				2.00	0.85	1040.26	0.46	22.95	22.26
				3.00	0.79	966.83	0.43	21.33	21.06
				4.00	0.73	893.40	0.39	19.71	19.87
				5.00	0.67	819.97	0.36	18.09	18.67
				6.00	0.62	758.78	0.33	16.74	17.67
				8.00	0.54	660.87	0.29	14.58	16.07
				10.00	0.46	562.96	0.25	12.42	14.47
				12.00	0.4	489.53	0.22	10.80	13.28
				14.00	0.35	428.34	0.19	9.45	12.28
				15.00	0.32	391.63	0.17	8.64	11.68
				16.00	0.3	367.15	0.16	8.10	11.28
				18.00	0.26	318.20	0.14	7.02	10.48
				20.00	0.23	281.48	0.12	6.21	9.88
				25.00	0.16	195.81	0.09	4.32	8.48
6.00	6.00	2.50	0.90	0.25	0.99	2322.82	0.53	26.73	25.06
				0.50	0.98	2299.36	0.53	26.46	24.86
				0.75	0.965	2264.17	0.52	26.06	24.56
				1.00	0.95	2228.97	0.51	25.65	24.26
				2.00	0.91	2135.12	0.49	24.57	23.46
				3.00	0.86	2017.81	0.46	23.22	22.46
				4.00	0.82	1923.95	0.44	22.14	21.66
				5.00	0.79	1853.57	0.43	21.33	21.06
				6.00	0.75	1759.71	0.41	20.25	20.26
				8.00	0.68	1595.47	0.37	18.36	18.87
				10.00	0.62	1454.70	0.33	16.74	17.67
				12.00	0.57	1337.38	0.31	15.39	16.67
				14.00	0.52	1220.07	0.28	14.04	15.67
				15.00	0.5	1173.14	0.27	13.50	15.27
				16.00	0.48	1126.22	0.26	12.96	14.87
				18.00	0.44	1032.37	0.24	11.88	14.07
				20.00	0.4	938.51	0.22	10.80	13.28
				25.00	0.33	774.27	0.18	8.91	11.88


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 6, (D=0.375)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00
30.00

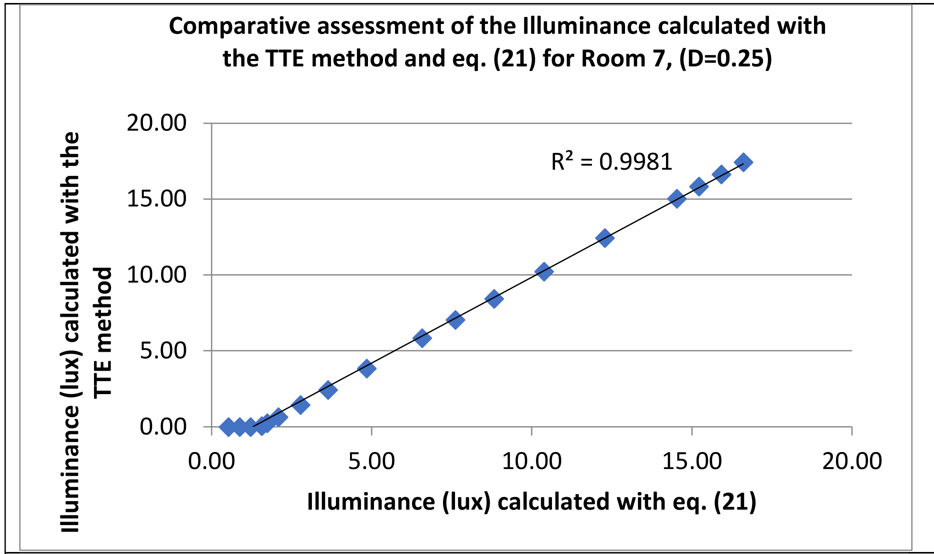

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 6, (D=0.53)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00
30.00

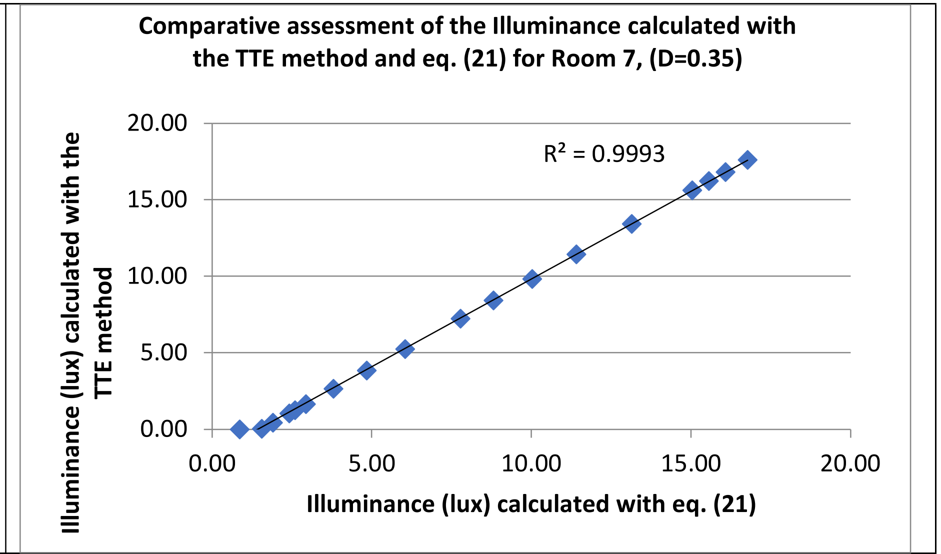

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 6, (D=0.65)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00
30.00

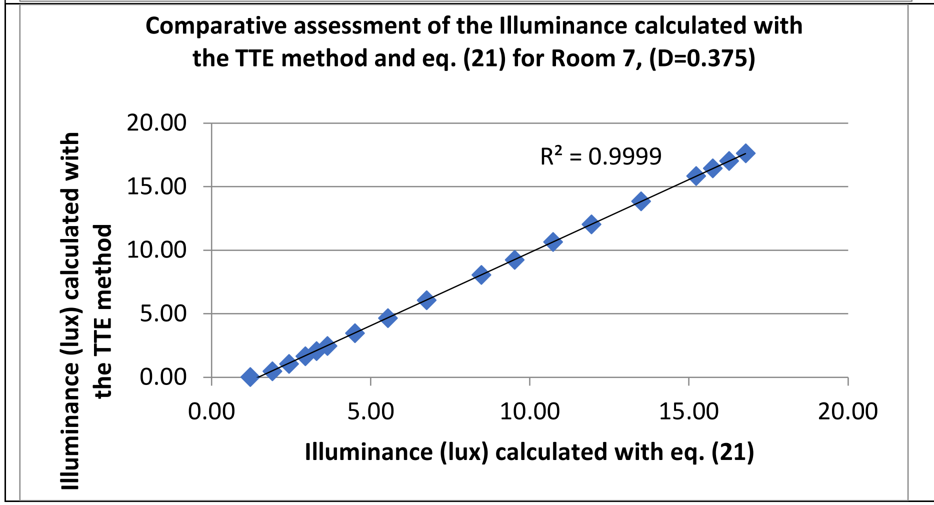

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 6, (D=0.90)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00
30.00

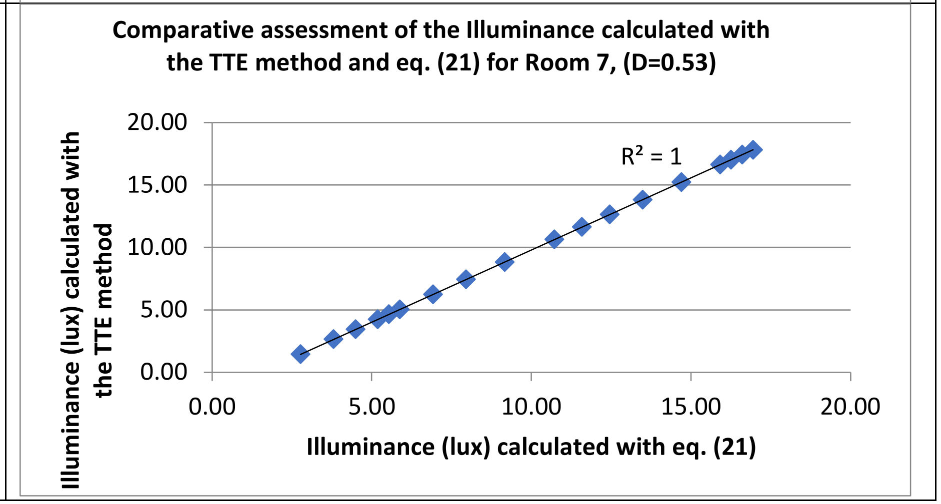
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
4.00	3.00	3.00	0.25	0.25	0.96	173.80	0.33	16.60	17.43
				0.50	0.92	166.56	0.32	15.91	16.63
				0.75	0.88	159.32	0.30	15.22	15.83
				1.00	0.84	152.07	0.29	14.53	15.03
				2.00	0.71	128.54	0.25	12.28	12.44
				3.00	0.6	108.62	0.21	10.38	10.24
				4.00	0.51	92.33	0.18	8.82	8.44
				5.00	0.44	79.66	0.15	7.61	7.04
				6.00	0.38	68.80	0.13	6.57	5.85
				8.00	0.28	50.69	0.10	4.84	3.85
				10.00	0.21	38.02	0.07	3.63	2.45
				12.00	0.16	28.97	0.06	2.77	1.45
				14.00	0.12	21.72	0.04	2.08	0.65
				15.00	0.1	18.10	0.03	1.73	0.25
				16.00	0.09	16.29	0.03	1.56	0.05
				18.00	0.07	12.67	0.02	1.21	0.00
				20.00	0.05	9.05	0.02	0.86	0.00
				25.00	0.03	5.43	0.01	0.52	0.00
4.00	3.00	3.00	0.35	0.25	0.97	344.19	0.34	16.77	17.63
				0.50	0.93	330.00	0.32	16.08	16.83
				0.75	0.9	319.36	0.31	15.56	16.23
				1.00	0.87	308.71	0.30	15.04	15.63
				2.00	0.76	269.68	0.26	13.14	13.43
				3.00	0.66	234.19	0.23	11.41	11.44
				4.00	0.58	205.81	0.20	10.03	9.84
				5.00	0.51	180.97	0.18	8.82	8.44
				6.00	0.45	159.68	0.16	7.78	7.24
				8.00	0.35	124.19	0.12	6.05	5.25
				10.00	0.28	99.36	0.10	4.84	3.85
				12.00	0.22	78.06	0.08	3.80	2.65
				14.00	0.17	60.32	0.06	2.94	1.65
				15.00	0.15	53.23	0.05	2.59	1.25
				16.00	0.14	49.68	0.05	2.42	1.05
				18.00	0.11	39.03	0.04	1.90	0.45
				20.00	0.09	31.94	0.03	1.56	0.05
				25.00	0.05	17.74	0.02	0.86	0.00

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
4.00	3.00	3.00	0.375	0.25	0.97	395.12	0.34	16.77	17.63
4.00	3.00	3.00	0.375	0.50	0.94	382.90	0.33	16.26	17.03
4.00	3.00	3.00	0.375	0.75	0.91	370.68	0.31	15.74	16.43
4.00	3.00	3.00	0.375	1.00	0.88	358.46	0.30	15.22	15.83
4.00	3.00	3.00	0.375	2.00	0.78	317.73	0.27	13.49	13.83
4.00	3.00	3.00	0.375	3.00	0.69	281.07	0.24	11.93	12.04
4.00	3.00	3.00	0.375	4.00	0.62	252.55	0.21	10.72	10.64
4.00	3.00	3.00	0.375	5.00	0.55	224.04	0.19	9.51	9.24
4.00	3.00	3.00	0.375	6.00	0.49	199.60	0.17	8.47	8.04
4.00	3.00	3.00	0.375	8.00	0.39	158.86	0.13	6.74	6.05
4.00	3.00	3.00	0.375	10.00	0.32	130.35	0.11	5.53	4.65
4.00	3.00	3.00	0.375	12.00	0.26	105.91	0.09	4.50	3.45
4.00	3.00	3.00	0.375	14.00	0.21	85.54	0.07	3.63	2.45
4.00	3.00	3.00	0.375	15.00	0.19	77.39	0.07	3.29	2.05
4.00	3.00	3.00	0.375	16.00	0.17	69.25	0.06	2.94	1.65
4.00	3.00	3.00	0.375	18.00	0.14	57.03	0.05	2.42	1.05
4.00	3.00	3.00	0.375	20.00	0.11	44.81	0.04	1.90	0.45
4.00	3.00	3.00	0.375	25.00	0.07	28.51	0.02	1.21	0.00
4.00	3.00	3.00	0.53	0.25	0.98	797.40	0.34	16.95	17.83
4.00	3.00	3.00	0.53	0.50	0.96	781.12	0.33	16.60	17.43
4.00	3.00	3.00	0.53	0.75	0.94	764.85	0.33	16.26	17.03
4.00	3.00	3.00	0.53	1.00	0.92	748.58	0.32	15.91	16.63
4.00	3.00	3.00	0.53	2.00	0.85	691.62	0.29	14.70	15.23
4.00	3.00	3.00	0.53	3.00	0.78	634.66	0.27	13.49	13.83
4.00	3.00	3.00	0.53	4.00	0.72	585.84	0.25	12.45	12.64
4.00	3.00	3.00	0.53	5.00	0.67	545.16	0.23	11.59	11.64
4.00	3.00	3.00	0.53	6.00	0.62	504.47	0.21	10.72	10.64
4.00	3.00	3.00	0.53	8.00	0.53	431.24	0.18	9.17	8.84
4.00	3.00	3.00	0.53	10.00	0.46	374.29	0.16	7.95	7.44
4.00	3.00	3.00	0.53	12.00	0.4	325.47	0.14	6.92	6.25
4.00	3.00	3.00	0.53	14.00	0.34	276.65	0.12	5.88	5.05
4.00	3.00	3.00	0.53	15.00	0.32	260.37	0.11	5.53	4.65
4.00	3.00	3.00	0.53	16.00	0.3	244.10	0.10	5.19	4.25
4.00	3.00	3.00	0.53	18.00	0.26	211.55	0.09	4.50	3.45
4.00	3.00	3.00	0.53	20.00	0.22	179.01	0.08	3.80	2.65
4.00	3.00	3.00	0.53	25.00	0.16	130.19	0.06	2.77	1.45


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 7, (D=0.25)
R² = 0.9981
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00

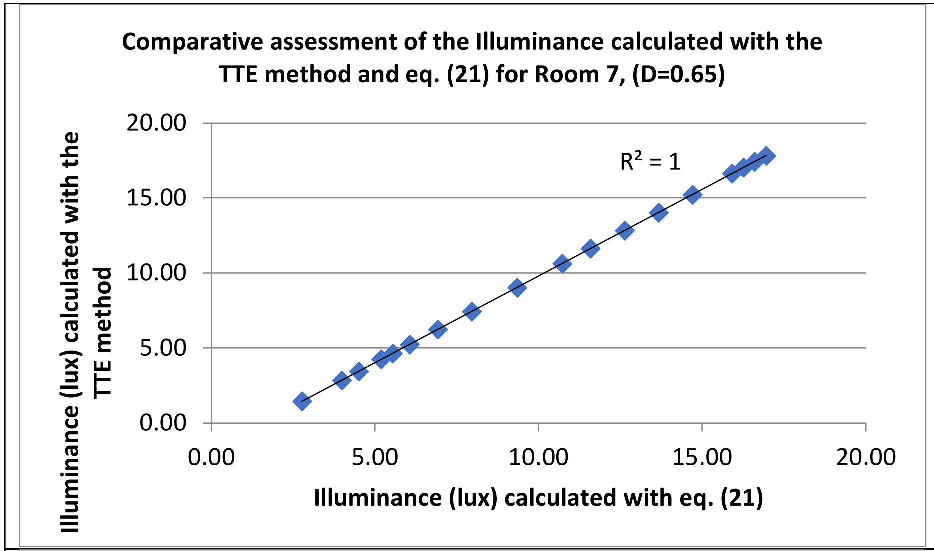

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 7, (D=0.35)
R² = 0.9993
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00

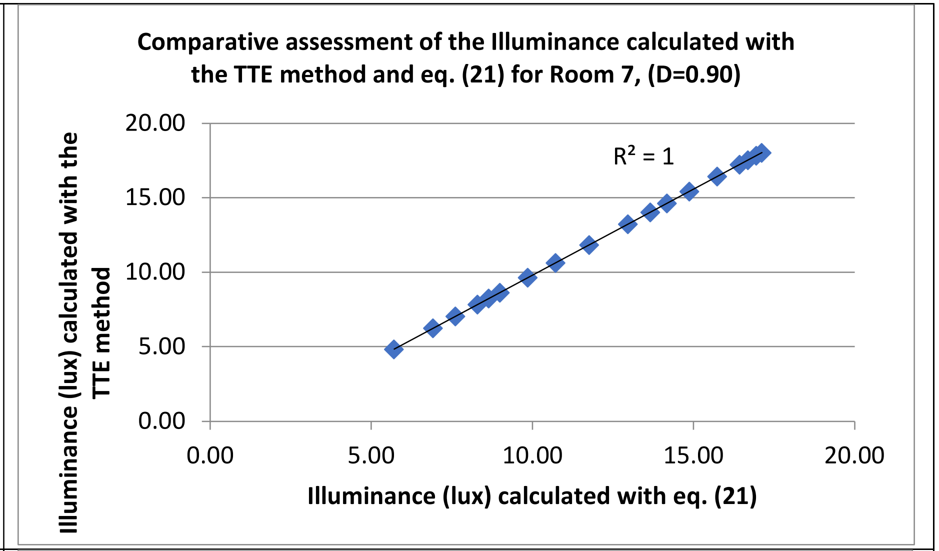

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 7, (D=0.375)
R² = 0.9999
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00

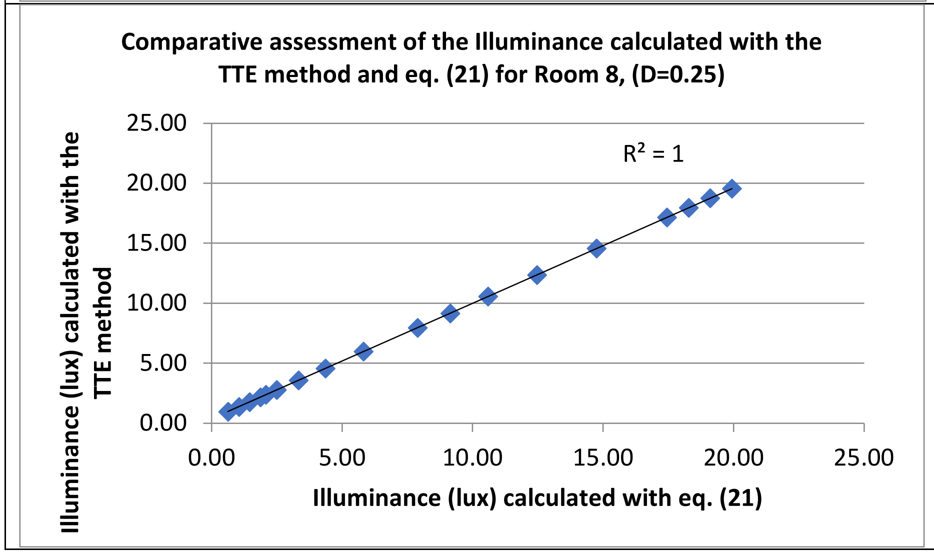

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 7, (D=0.53)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00

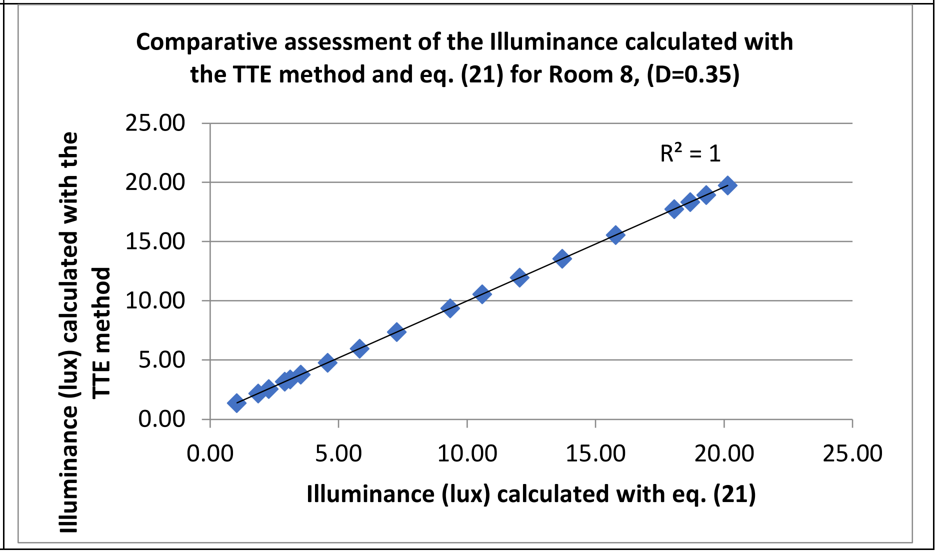
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
				0.25	0.98	1174.88	0.34	16.95	17.83
				0.50	0.96	1150.40	0.33	16.60	17.43
				0.75	0.94	1125.93	0.33	16.26	17.03
				1.00	0.92	1040.26	0.32	15.91	16.63
				2.00	0.85	966.83	0.29	14.70	15.23
				3.00	0.79	893.40	0.27	13.66	14.03
				4.00	0.73	819.97	0.25	12.62	12.84
				5.00	0.67	758.78	0.23	11.59	11.64
4.00	3.00	3.00	0.65	6.00	0.62	660.87	0.21	10.72	10.64
				8.00	0.54	562.96	0.19	9.34	9.04
				10.00	0.46	489.53	0.16	7.95	7.44
				12.00	0.4	428.34	0.14	6.92	6.25
				14.00	0.35	391.63	0.12	6.05	5.25
				15.00	0.32	367.15	0.11	5.53	4.65
				16.00	0.3	318.20	0.10	5.19	4.25
				18.00	0.26	281.48	0.09	4.50	3.45
				20.00	0.23	195.81	0.08	3.98	2.85
				25.00	0.16		0.06	2.77	1.45
				0.25	0.99	2322.82	0.34	17.12	18.03
				0.50	0.98	2299.36	0.34	16.95	17.83
				0.75	0.965	2264.17	0.33	16.69	17.53
				1.00	0.95	2228.97	0.33	16.43	17.23
				2.00	0.91	2135.12	0.31	15.74	16.43
				3.00	0.86	2017.81	0.30	14.87	15.43
				4.00	0.82	1923.95	0.28	14.18	14.63
				5.00	0.79	1853.57	0.27	13.66	14.03
4.00	3.00	3.00	0.90	6.00	0.75	1759.71	0.26	12.97	13.23
				8.00	0.68	1595.47	0.24	11.76	11.84
				10.00	0.62	1454.70	0.21	10.72	10.64
				12.00	0.57	1337.38	0.20	9.86	9.64
				14.00	0.52	1220.07	0.18	8.99	8.64
				15.00	0.5	1173.14	0.17	8.65	8.24
				16.00	0.48	1126.22	0.17	8.30	7.84
				18.00	0.44	1032.37	0.15	7.61	7.04
				20.00	0.4	938.51	0.14	6.92	6.25
				25.00	0.33	774.27	0.11	5.71	4.85

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
5.00	4.00	3.00	0.25	0.25	0.96	173.80	0.40	19.93	19.56
				0.50	0.92	166.56	0.38	19.10	18.76
				0.75	0.88	159.32	0.37	18.27	17.96
				1.00	0.84	152.07	0.35	17.44	17.16
				2.00	0.71	128.54	0.29	14.74	14.57
				3.00	0.6	108.62	0.25	12.46	12.37
				4.00	0.51	92.33	0.21	10.59	10.57
				5.00	0.44	79.66	0.18	9.13	9.17
				6.00	0.38	68.80	0.16	7.89	7.98
				8.00	0.28	50.69	0.12	5.81	5.98
				10.00	0.21	38.02	0.09	4.36	4.58
				12.00	0.16	28.97	0.07	3.32	3.58
				14.00	0.12	21.72	0.05	2.49	2.78
				15.00	0.1	18.10	0.04	2.08	2.38
				16.00	0.09	16.29	0.04	1.87	2.18
				18.00	0.07	12.67	0.03	1.45	1.78
				20.00	0.05	9.05	0.02	1.04	1.39
				25.00	0.03	5.43	0.01	0.62	0.99
5.00	4.00	3.00	0.25	0.25	0.97	344.19	0.40	20.14	19.76
				0.50	0.93	330.00	0.39	19.31	18.96
				0.75	0.9	319.36	0.37	18.68	18.36
				1.00	0.87	308.71	0.36	18.06	17.76
				2.00	0.76	269.68	0.32	15.78	15.56
				3.00	0.66	234.19	0.27	13.70	13.57
				4.00	0.58	205.81	0.24	12.04	11.97
				5.00	0.51	180.97	0.21	10.59	10.57
				6.00	0.45	159.68	0.19	9.34	9.37
				8.00	0.35	124.19	0.15	7.27	7.38
				10.00	0.28	99.36	0.12	5.81	5.98
				12.00	0.22	78.06	0.09	4.57	4.78
				14.00	0.17	60.32	0.07	3.53	3.78
				15.00	0.15	53.23	0.06	3.11	3.38
				16.00	0.14	49.68	0.06	2.91	3.18
				18.00	0.11	39.03	0.05	2.28	2.58
				20.00	0.09	31.94	0.04	1.87	2.18
				25.00	0.05	17.74	0.02	1.04	1.39


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 7, (D=0.65)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00

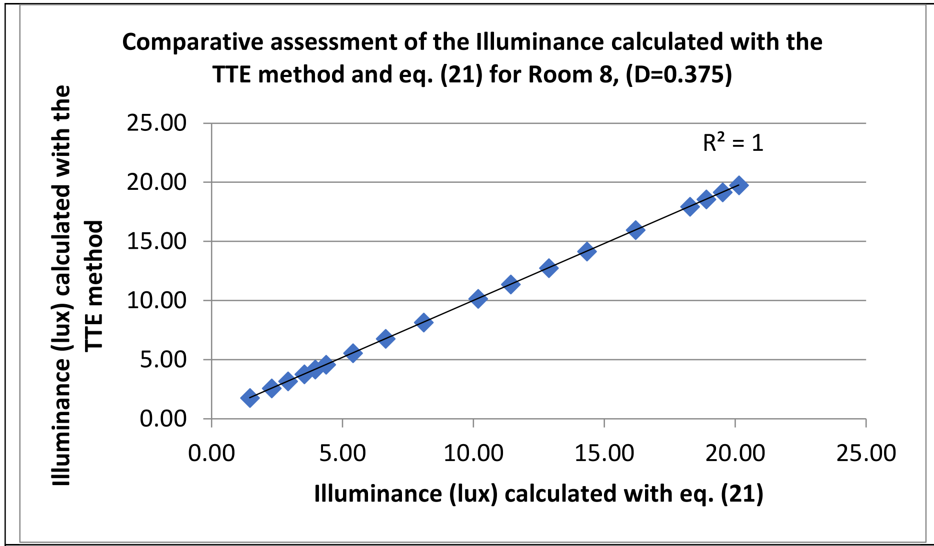

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 7, (D=0.90)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00

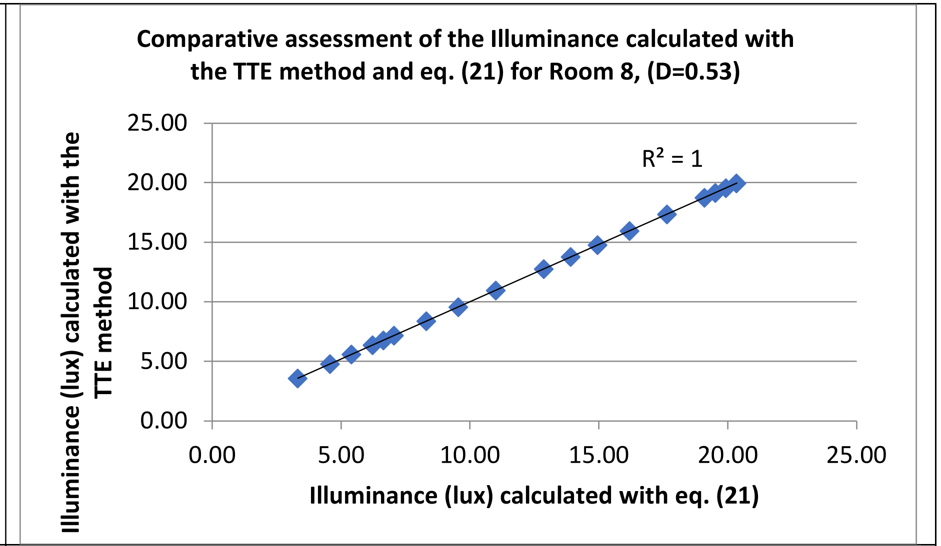

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 8, (D=0.25)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00

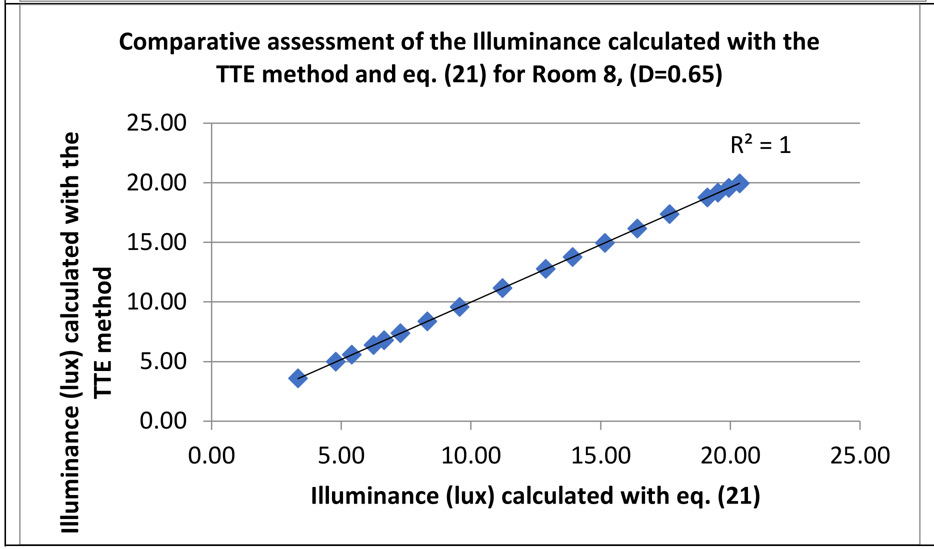

Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 8, (D=0.35)
R² = 1
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
0.00
5.00
10.00
15.00
20.00
25.00

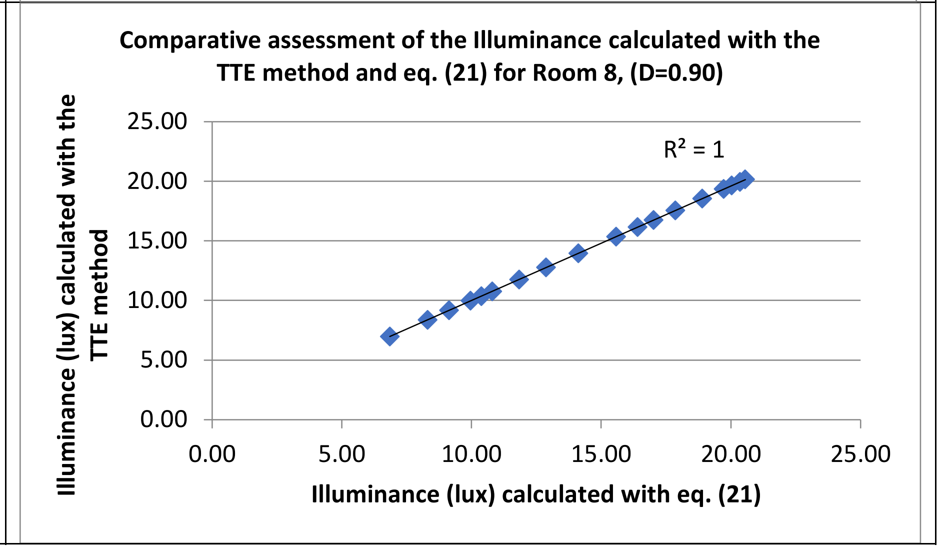
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
5.00	4.00	3.00	0.375	0.25	0.97	395.12	0.40	20.14	19.76
				0.50	0.94	382.90	0.39	19.52	19.16
				0.75	0.91	370.68	0.38	18.89	18.56
				1.00	0.88	358.46	0.37	18.27	17.96
				2.00	0.78	317.73	0.32	16.19	15.96
				3.00	0.69	281.07	0.29	14.32	14.17
				4.00	0.62	252.55	0.26	12.87	12.77
				5.00	0.55	224.04	0.23	11.42	11.37
				6.00	0.49	199.60	0.20	10.17	10.17
				8.00	0.39	158.86	0.16	8.10	8.18
				10.00	0.32	130.35	0.13	6.64	6.78
				12.00	0.26	105.91	0.11	5.40	5.58
				14.00	0.21	85.54	0.09	4.36	4.58
				15.00	0.19	77.39	0.08	3.94	4.18
				16.00	0.17	69.25	0.07	3.53	3.78
				18.00	0.14	57.03	0.06	2.91	3.18
				20.00	0.11	44.81	0.05	2.28	2.58
				25.00	0.07	28.51	0.03	1.45	1.78
5.00	4.00	3.00	0.53	0.25	0.98	797.40	0.41	20.35	19.96
				0.50	0.96	781.12	0.40	19.93	19.56
				0.75	0.94	764.85	0.39	19.52	19.16
				1.00	0.92	748.58	0.38	19.10	18.76
				2.00	0.85	691.62	0.35	17.65	17.36
				3.00	0.78	634.66	0.32	16.19	15.96
				4.00	0.72	585.84	0.30	14.95	14.77
				5.00	0.67	545.16	0.28	13.91	13.77
				6.00	0.62	504.47	0.26	12.87	12.77
				8.00	0.53	431.24	0.22	11.00	10.97
				10.00	0.46	374.29	0.19	9.55	9.57
				12.00	0.4	325.47	0.17	8.30	8.38
				14.00	0.34	276.65	0.14	7.06	7.18
				15.00	0.32	260.37	0.13	6.64	6.78
				16.00	0.3	244.10	0.12	6.23	6.38
				18.00	0.26	211.55	0.11	5.40	5.58
				20.00	0.22	179.01	0.09	4.57	4.78
				25.00	0.16	130.19	0.07	3.32	3.58

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	TTE	Flux (lm)	DPF (%)	ILLUMINANCE (lux) calculated with TTE method	ILLUMINANCE (lux) calculated with eq. (21)
5.00	4.00	3.00	0.65	0.25	0.98	1199.36	0.41	20.35	19.96
				0.50	0.96	1174.88	0.40	19.93	19.56
				0.75	0.94	1150.40	0.39	19.52	19.16
				1.00	0.92	1125.93	0.38	19.10	18.76
				2.00	0.85	1040.26	0.35	17.65	17.36
				3.00	0.79	966.83	0.33	16.40	16.16
				4.00	0.73	893.40	0.30	15.16	14.97
				5.00	0.67	819.97	0.28	13.91	13.77
				6.00	0.62	758.78	0.26	12.87	12.77
				8.00	0.54	660.87	0.22	11.21	11.17
				10.00	0.46	562.96	0.19	9.55	9.57
				12.00	0.4	489.53	0.17	8.30	8.38
				14.00	0.35	428.34	0.15	7.27	7.38
				15.00	0.32	391.63	0.13	6.64	6.78
				16.00	0.3	367.15	0.12	6.23	6.38
				18.00	0.26	318.20	0.11	5.40	5.58
				20.00	0.23	281.48	0.10	4.77	4.98
				25.00	0.16	195.81	0.07	3.32	3.58
5.00	4.00	3.00	0.90	0.25	0.99	2322.82	0.41	20.55	20.16
				0.50	0.98	2299.36	0.41	20.35	19.96
				0.75	0.965	2264.17	0.40	20.03	19.66
				1.00	0.95	2228.97	0.39	19.72	19.36
				2.00	0.91	2135.12	0.38	18.89	18.56
				3.00	0.86	2017.81	0.36	17.85	17.56
				4.00	0.82	1923.95	0.34	17.02	16.76
				5.00	0.79	1853.57	0.33	16.40	16.16
				6.00	0.75	1759.71	0.31	15.57	15.36
				8.00	0.68	1595.47	0.28	14.12	13.97
				10.00	0.62	1454.70	0.26	12.87	12.77
				12.00	0.57	1337.38	0.24	11.83	11.77
				14.00	0.52	1220.07	0.22	10.80	10.77
				15.00	0.5	1173.14	0.21	10.38	10.37
				16.00	0.48	1126.22	0.20	9.97	9.97
				18.00	0.44	1032.37	0.18	9.13	9.17
				20.00	0.4	938.51	0.17	8.30	8.38
				25.00	0.33	774.27	0.14	6.85	6.98


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 8, (D=0.375)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 8, (D=0.53)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 8, (D=0.65)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00


Comparative assessment of the Illuminance calculated with the TTE method and eq. (21) for Room 8, (D=0.90)
Illuminance (lux) calculated with the TTE method
Illuminance (lux) calculated with eq. (21)
R² = 1
0.00
5.00
10.00
15.00
20.00
25.00

Appendix II

Application of the TTE method for light pipes with bends

For the calculation of the performance of light pipes that include elbows, eighteen different combinations of light pipe lengths and elbow angles, were tested for four light pipe diameters (0.25, 0.375, 0.53, 0.65m), in the rooms described in Table 4. The characteristics of the light pipes tested are given in Table 5. The rest of the parameters (MF, UF, E_{ex}, etc) remain as described in Chapter 3:. In total, 576 scenarios were calculated.

Light pipe lengths and elbow angles used for the application of the TTE method in light pipes with elbows

Pipe Length 1 (m)	Pipe Length 2 (m)	Pipe Length 3 (m)	Bend Angle 1 (°)	Bend Angle 2 (°)
1	1	0	30	0
1	1	0	60	0
1	1	0	90	0
1	1	1	30	30
1	1	1	30	60
1	1	1	30	90
2	1	0	30	0
2	1	0	60	0
2	1	0	90	0
2	1	1	30	30
2	1	1	30	60
2	1	1	30	90
3	2	0	30	0
3	2	0	60	0
3	2	0	90	0
3	2	1	30	30
3	2	1	30	60
3	2	1	30	90

The results of the application of the TTE method to light pipes with bends led to relations relating the Flux output of the pipe with the Aspect Ratio of the system (i.e., the sum of the aspect ratios of the straight and bended parts of the tube), depending on the diameter of the system. These relations, which resulted from regression analysis, are given in the following Table.

Relations for the calculation of the Flux (lm) emitted by light pipes with bends, depending on the Aspect Ratio

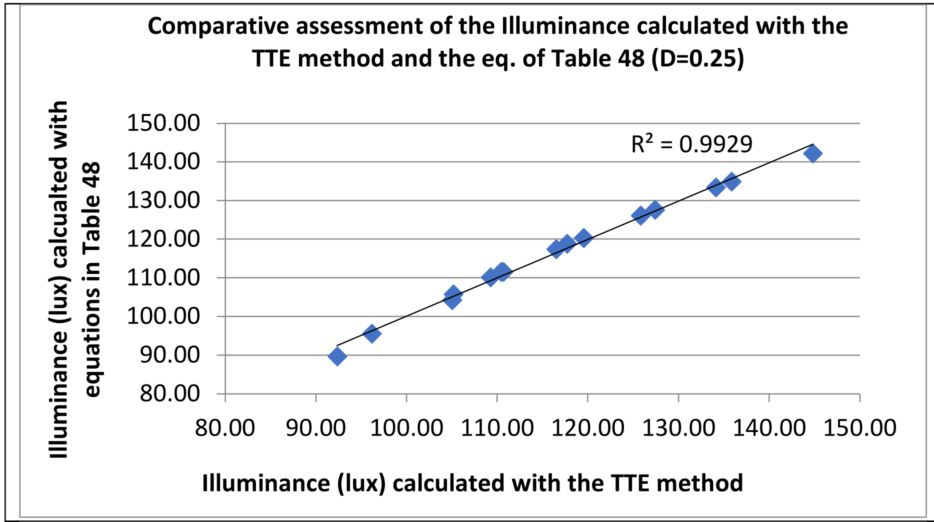
Radius	Relations for Flux (lm) emitted by a light pipe with bends, of Aspect Ratio Ap
0.25	-1.8212 Ap+ 165.53
0.375	-4.9682 Ap+ 392.24
0.53	-10.664 Ap+ 796.04
0.65	-17.667 Ap+ 1,205.80

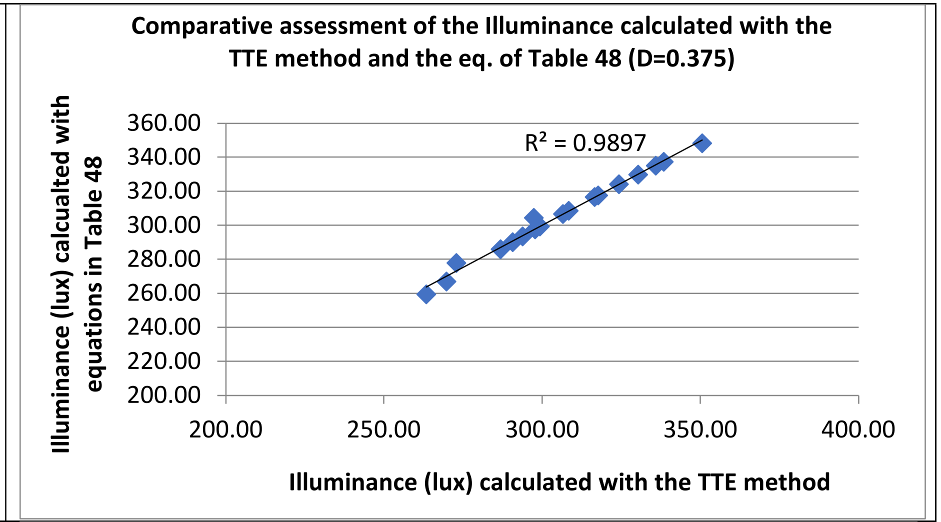
After calculating the Flux emitted by the light pipe diffuser, the average illuminance in a space can be calculated by using one of the methodologies already analysed or the algorithms developed and provided in Chapter 3:.

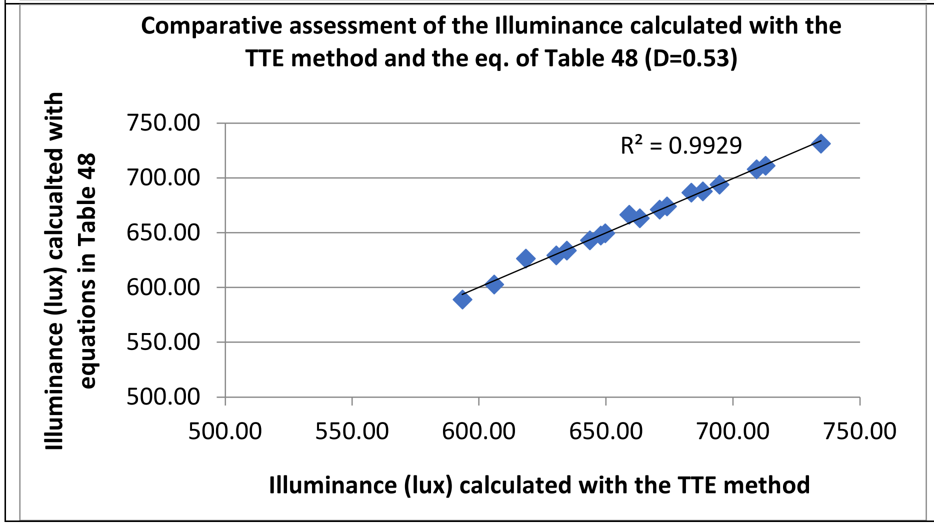
The comparison of Flux values (lm), emitted by light pipes with bends, calculated with eq. (13) and with the algorithms provided in the above table is included in the following tables and the respective graphs.

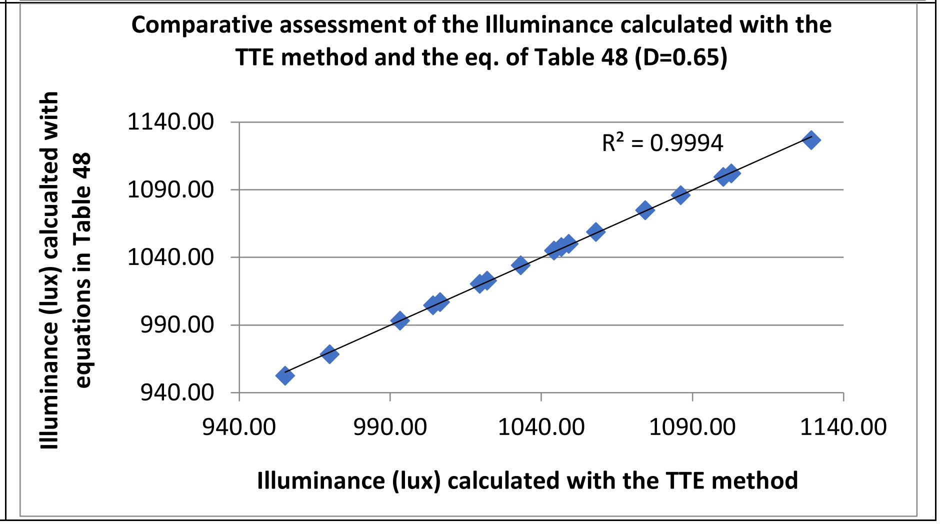
Light Pipe Diameter (m)	Pipe Length 1 (m)	Pipe Length 2 (m)	Pipe Length 3 (m)	Bend Angle 1 (°)	Bend Angle 2 (°)	Aspect Ratio P1	Aspect Ratio P2	Aspect Ratio P3	Aspect Ratio B1	Aspect Ratio B2	Sum of Aspect Ratios	TTE	FLUX (lm) calculated with eq. (13)	FLUX (lm) calculated with relations depending on Aspect Ratio
0.25	1	1	0	30	0	4.00	4.00	0.00	4.80	0.00	12.80	0.80	144.81	142.21
	1	1	0	60	0	4.00	4.00	0.00	9.60	0.00	17.60	0.74	134.11	133.46
	1	1	0	90	0	4.00	4.00	0.00	12.80	0.00	20.80	0.70	127.42	127.63
	1	1	1	30	30	4.00	4.00	4.00	4.80	4.80	21.60	0.69	125.79	126.17
	1	1	1	30	60	4.00	4.00	4.00	4.80	9.60	26.40	0.64	116.50	117.43
	1	1	1	30	90	4.00	4.00	4.00	4.80	12.80	29.60	0.61	110.43	111.60
	2	1	0	30	0	8.00	4.00	0.00	4.80	0.00	16.80	0.75	135.84	134.92
	2	1	0	60	0	8.00	4.00	0.00	9.60	0.00	21.60	0.69	125.79	126.17
	2	1	0	90	0	8.00	4.00	0.00	12.80	0.00	24.80	0.66	119.52	120.34
	2	1	1	30	30	8.00	4.00	4.00	4.80	4.80	25.60	0.65	117.68	118.88
	2	1	1	30	60	8.00	4.00	4.00	4.80	9.60	30.40	0.60	109.27	110.14
	2	1	1	30	90	8.00	4.00	4.00	4.80	12.80	33.60	0.58	105.00	104.31
	3	2	0	30	0	12.00	8.00	0.00	4.80	0.00	24.80	0.66	119.52	120.34
	3	2	0	60	0	12.00	8.00	0.00	9.60	0.00	29.60	0.61	110.68	111.60
	3	2	0	90	0	12.00	8.00	0.00	12.80	0.00	32.80	0.58	105.16	105.76
	3	2	1	30	30	12.00	8.00	4.00	4.80	4.80	33.60	0.58	105.00	104.31
	3	2	1	30	60	12.00	8.00	4.00	4.80	9.60	38.40	0.53	96.14	95.56
	3	2	1	30	90	12.00	8.00	4.00	4.80	12.80	41.60	0.51	92.33	89.73
0.375	1	1	0	30	0	4.00	4.00	0.00	3.50	0.00	8.83	0.86	350.54	348.35
	1	1	0	60	0	4.00	4.00	0.00	5.70	0.00	11.03	0.83	338.42	337.42
	1	1	0	90	0	4.00	4.00	0.00	7.20	0.00	12.53	0.81	330.39	329.97
	1	1	1	30	30	4.00	4.00	4.00	3.50	3.50	15.00	0.78	317.73	317.72
	1	1	1	30	60	4.00	4.00	4.00	3.50	5.70	17.20	0.75	306.62	306.79
	1	1	1	30	90	4.00	4.00	4.00	3.50	7.20	18.70	0.73	299.35	299.33
	2	1	0	30	0	8.00	4.00	0.00	3.50	0.00	11.50	0.82	335.90	335.11
	2	1	0	60	0	8.00	4.00	0.00	5.70	0.00	13.70	0.80	324.28	324.18
	2	1	0	90	0	8.00	4.00	0.00	7.20	0.00	15.20	0.78	316.59	316.72
	2	1	1	30	30	8.00	4.00	4.00	3.50	3.50	17.67	0.73	297.36	304.47
	2	1	1	30	60	8.00	4.00	4.00	3.50	5.70	19.87	0.72	293.81	293.54
	2	1	1	30	90	8.00	4.00	4.00	3.50	7.20	21.37	0.70	286.85	286.09
	3	2	0	30	0	12.00	8.00	0.00	3.50	0.00	16.83	0.76	308.43	308.61
	3	2	0	60	0	12.00	8.00	0.00	5.70	0.00	19.03	0.73	297.76	297.68
	3	2	0	90	0	12.00	8.00	0.00	7.20	0.00	20.53	0.71	290.70	290.23
	3	2	1	30	30	12.00	8.00	4.00	3.50	3.50	23.00	0.67	272.92	277.97
	3	2	1	30	60	12.00	8.00	4.00	3.50	5.70	25.20	0.66	269.78	267.04
	3	2	1	30	90	12.00	8.00	4.00	3.50	7.20	26.70	0.65	263.38	259.59

Light Pipe Diameter (m)	Pipe Length 1 (m)	Pipe Length 2 (m)	Pipe Length 3 (m)	Bend Angle 1 (°)	Bend Angle 2 (°)	Aspect Ratio P1	Aspect Ratio P2	Aspect Ratio P3	Aspect Ratio B1	Aspect Ratio B2	Sum of Aspect Ratios	TTE	FLUX (lm) calculated with eq. (13)	FLUX (lm) calculated with relations depending on Aspect Ratio
	1	1	0	30	0	4.00	4.00	0.00	2.30	0.00	6.07	0.90	734.63	731.27
	1	1	0	60	0	4.00	4.00	0.00	4.50	0.00	8.27	0.87	709.22	707.81
	1	1	0	90	0	4.00	4.00	0.00	5.80	0.00	9.57	0.85	694.62	693.95
	1	1	1	30	30	4.00	4.00	4.00	2.30	2.30	10.26	0.84	683.48	686.62
	1	1	1	30	60	4.00	4.00	4.00	2.30	4.50	12.46	0.82	663.27	663.16
	1	1	1	30	90	4.00	4.00	4.00	2.30	5.80	13.76	0.80	649.61	649.30
	2	1	0	30	0	8.00	4.00	0.00	2.30	0.00	7.96	0.88	712.78	711.15
	2	1	0	60	0	8.00	4.00	0.00	4.50	0.00	10.16	0.85	688.13	687.69
	2	1	0	90	0	8.00	4.00	0.00	5.80	0.00	11.46	0.83	673.96	673.83
	2	1	1	30	30	8.00	4.00	4.00	2.30	2.30	12.15	0.81	659.07	666.50
	2	1	1	30	60	8.00	4.00	4.00	2.30	4.50	14.35	0.79	643.54	643.04
	2	1	1	30	90	8.00	4.00	4.00	2.30	5.80	15.65	0.77	630.29	629.18
	3	2	0	30	0	12.00	8.00	0.00	2.30	0.00	11.73	0.82	671.02	670.91
	3	2	0	60	0	12.00	8.00	0.00	4.50	0.00	13.93	0.80	647.81	647.45
	3	2	0	90	0	12.00	8.00	0.00	5.80	0.00	15.23	0.78	634.47	633.59
	3	2	1	30	30	12.00	8.00	4.00	2.30	2.30	15.92	0.76	618.39	626.26
	3	2	1	30	60	12.00	8.00	4.00	2.30	4.50	18.12	0.74	605.84	602.80
0.53	3	2	1	30	90	12.00	8.00	4.00	2.30	5.80	19.42	0.73	593.36	588.94
	1	1	0	30	0	4.00	4.00	0.00	1.40	0.00	4.48	0.92	1129.38	1126.71
	1	1	0	60	0	4.00	4.00	0.00	2.80	0.00	5.88	0.90	1102.82	1101.97
	1	1	0	90	0	4.00	4.00	0.00	3.70	0.00	6.78	0.89	1086.08	1086.07
	1	1	1	30	30	4.00	4.00	4.00	1.40	1.40	7.42	0.88	1074.35	1074.79
	1	1	1	30	60	4.00	4.00	4.00	1.40	2.80	8.82	0.86	1049.09	1050.06
	1	1	1	30	90	4.00	4.00	4.00	1.40	3.70	9.72	0.84	1033.16	1034.16
	2	1	0	30	0	8.00	4.00	0.00	1.40	0.00	6.02	0.90	1100.23	1099.53
	2	1	0	60	0	8.00	4.00	0.00	2.80	0.00	7.42	0.88	1074.35	1074.79
0.65	2	1	0	90	0	8.00	4.00	0.00	3.70	0.00	8.32	0.86	1058.04	1058.89
	2	1	1	30	30	8.00	4.00	4.00	1.40	1.40	8.95	0.86	1046.62	1047.61
	2	1	1	30	60	8.00	4.00	4.00	1.40	2.80	10.35	0.84	1022.00	1022.88
	2	1	1	30	90	8.00	4.00	4.00	1.40	3.70	11.25	0.82	1006.49	1006.98
	3	2	0	30	0	12.00	8.00	0.00	1.40	0.00	9.09	0.85	1044.16	1045.17
	3	2	0	60	0	12.00	8.00	0.00	2.80	0.00	10.49	0.83	1019.60	1020.43
	3	2	0	90	0	12.00	8.00	0.00	3.70	0.00	11.39	0.82	1004.12	1004.53
	3	2	1	30	30	12.00	8.00	4.00	1.40	1.40	12.03	0.81	993.28	993.25
	3	2	1	30	60	12.00	8.00	4.00	1.40	2.80	13.43	0.79	969.92	968.52
	3	2	1	30	90	12.00	8.00	4.00	1.40	3.70	14.33	0.78	955.19	952.62


Comparative assessment of the Illuminance calculated with the TTE method and the eq. of Table 48 (D=0.25)
R² = 0.9929
Illuminance (lux) calcualted with equations in Table 48
Illuminance (lux) calculated with the TTE method
80.00
90.00
100.00
110.00
120.00
130.00
140.00
150.00


Comparative assessment of the Illuminance calculated with the TTE method and the eq. of Table 48 (D=0.375)
R² = 0.9897
Illuminance (lux) calcualted with equations in Table 48
Illuminance (lux) calculated with the TTE method
200.00
220.00
240.00
260.00
280.00
300.00
320.00
340.00
360.00
250.00
350.00
400.00


Comparative assessment of the Illuminance calculated with the TTE method and the eq. of Table 48 (D=0.53)
R² = 0.9929
Illuminance (lux) calcualted with equations in Table 48
Illuminance (lux) calculated with the TTE method
500.00
550.00
600.00
650.00
700.00
750.00


Comparative assessment of the Illuminance calculated with the TTE method and the eq. of Table 48 (D=0.65)
R² = 0.9994
Illuminance (lux) calcualted with equations in Table 48
Illuminance (lux) calculated with the TTE method
940.00
990.00
1040.00
1090.00
1140.00

Appendix III

Flux (lm) emitted from the diffuser of the light pipe, calculated with the TTE and the Luxplot methods.

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.25	0.13	0.25	1.00	0.73	180.20	174.95
		0.50	2.00	0.66	161.43	172.22
		0.75	3.00	0.59	144.62	169.53
		1.00	4.00	0.53	129.55	166.88
		2.00	8.00	0.34	83.44	156.69
		3.00	12.00	0.22	53.74	147.12
		4.00	16.00	0.14	34.61	138.14
		5.00	20.00	0.09	22.29	129.70
		6.00	24.00	0.06	14.35	121.78
		8.00	32.00	0.02	5.95	107.37
		10.00	40.00	0.01	2.47	94.66
		12.00	48.00	0.00	1.02	83.45
		14.00	56.00	0.00	0.42	73.57
		15.00	60.00	0.00	0.27	69.08
		16.00	64.00	0.00	0.18	64.86
		18.00	72.00	0.00	0.07	57.18
		20.00	80.00	0.00	0.03	50.41
		25.00	100.00	0.00	0.00	36.79
Pipe Diameter (m)	**Pipe Radius (m)**	**Pipe Length (m)**	**Pipe Aspect Ratio**	**τ**	**FLUX (lm) calculated with the Luxplot method**	**FLUX (lm) calculated with the TTE method**
0.35	0.18	0.25	0.71	0.76	364.47	347.31
		0.50	1.43	0.70	336.93	343.34
		0.75	2.14	0.65	311.47	339.41
		1.00	2.86	0.60	287.94	335.53
		2.00	5.71	0.44	210.28	320.45
		3.00	8.57	0.32	153.57	306.04
		4.00	11.43	0.23	112.16	292.28
		5.00	14.29	0.17	81.91	279.14
		6.00	17.14	0.12	59.82	266.59
		8.00	22.86	0.07	31.90	243.16
		10.00	28.57	0.04	17.02	221.79
		12.00	34.29	0.02	9.08	202.29
		14.00	40.00	0.01	4.84	184.51
		15.00	42.86	0.01	3.54	176.22
		16.00	45.71	0.01	2.58	168.29
		18.00	51.43	0.00	1.38	153.50
		20.00	57.14	0.00	0.73	140.01
		25.00	71.43	0.00	0.15	111.24

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.38	0.19	0.25	0.67	0.76	420.60	399.48
		0.50	1.33	0.71	390.86	395.21
		0.75	2.00	0.66	363.22	390.98
		1.00	2.67	0.61	337.54	386.80
		2.00	5.33	0.46	251.73	370.52
		3.00	8.00	0.34	187.73	354.93
		4.00	10.67	0.25	140.01	339.99
		5.00	13.33	0.19	104.41	325.68
		6.00	16.00	0.14	77.87	311.97
		8.00	21.33	0.08	43.31	286.26
		10.00	26.67	0.04	24.09	262.67
		12.00	32.00	0.02	13.40	241.03
		14.00	37.33	0.01	7.45	221.17
		15.00	40.00	0.01	5.56	211.86
		16.00	42.67	0.01	4.14	202.94
		18.00	48.00	0.00	2.30	186.22
		20.00	53.33	0.00	1.28	170.87
		25.00	66.67	0.00	0.30	137.82
Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.53	0.27	0.25	0.47	0.78	858.36	803.27
		0.50	0.94	0.74	814.96	797.07
		0.75	1.42	0.70	773.75	790.92
		1.00	1.89	0.67	734.63	784.81
		2.00	3.77	0.54	596.94	760.85
		3.00	5.66	0.44	485.06	737.63
		4.00	7.55	0.36	394.15	715.11
		5.00	9.43	0.29	320.27	693.28
		6.00	11.32	0.24	260.25	672.12
		8.00	15.09	0.16	171.84	631.72
		10.00	18.87	0.10	113.46	593.74
		12.00	22.64	0.07	74.91	558.05
		14.00	26.42	0.04	49.46	524.50
		15.00	28.30	0.04	40.19	508.49
		16.00	30.19	0.03	32.66	492.97
		18.00	33.96	0.02	21.56	463.33
		20.00	37.74	0.01	14.24	435.48
		25.00	47.17	0.00	5.04	372.95

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.65	0.33	0.25	0.38	0.79	1303.49	1211.10
		0.50	0.77	0.75	1249.49	1203.56
		0.75	1.15	0.72	1197.73	1196.06
		1.00	1.54	0.69	1148.11	1188.60
		2.00	3.08	0.58	969.37	1159.26
		3.00	4.62	0.49	818.45	1130.64
		4.00	6.15	0.42	691.03	1102.72
		5.00	7.69	0.35	583.45	1075.49
		6.00	9.23	0.30	492.61	1048.94
		8.00	12.31	0.21	351.17	997.78
		10.00	15.38	0.15	250.33	949.12
		12.00	18.46	0.11	178.45	902.83
		14.00	21.54	0.08	127.21	858.80
		15.00	23.08	0.06	107.41	837.60
		16.00	24.62	0.05	90.69	816.92
		18.00	27.69	0.04	64.65	777.07
		20.00	30.77	0.03	46.09	739.18
		25.00	38.46	0.01	19.77	652.32
Pipe Diameter (m)	**Pipe Radius (m)**	**Pipe Length (m)**	**Pipe Aspect Ratio**	**τ**	**FLUX (lm) calculated with the Luxplot method**	**FLUX (lm) calculated with the TTE method**
0.90	0.45	0.25	0.28	0.80	2528.53	2331.67
		0.50	0.56	0.77	2452.44	2320.62
		0.75	0.83	0.75	2378.64	2309.62
		1.00	1.11	0.73	2307.06	2298.67
		2.00	2.22	0.64	2041.63	2255.41
		3.00	3.33	0.57	1806.75	2212.96
		4.00	4.44	0.50	1598.88	2171.31
		5.00	5.56	0.45	1414.93	2130.45
		6.00	6.67	0.39	1252.15	2090.35
		8.00	8.89	0.31	980.61	2012.41
		10.00	11.11	0.24	767.95	1937.37
		12.00	13.33	0.19	601.41	1865.13
		14.00	15.56	0.15	470.99	1795.59
		15.00	16.67	0.13	416.80	1761.79
		16.00	17.78	0.12	368.85	1728.64
		18.00	20.00	0.09	288.86	1664.18
		20.00	22.22	0.07	226.22	1602.13
		25.00	27.78	0.04	122.78	1456.93

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.25	0.13	0.25	1.00	0.73	180.20	174.95
		0.50	2.00	0.66	161.43	172.22
		0.75	3.00	0.59	144.62	169.53
		1.00	4.00	0.53	129.55	166.88
		2.00	8.00	0.34	83.44	156.69
		3.00	12.00	0.22	53.74	147.12
		4.00	16.00	0.14	34.61	138.14
		5.00	20.00	0.09	22.29	129.70
		6.00	24.00	0.06	14.35	121.78
		8.00	32.00	0.02	5.95	107.37
		10.00	40.00	0.01	2.47	94.66
		12.00	48.00	0.00	1.02	83.45
		14.00	56.00	0.00	0.42	73.57
		15.00	60.00	0.00	0.27	69.08
		16.00	64.00	0.00	0.18	64.86
		18.00	72.00	0.00	0.07	57.18
		20.00	80.00	0.00	0.03	50.41
		25.00	100.00	0.00	0.00	36.79
Pipe Diameter (m)	**Pipe Radius (m)**	**Pipe Length (m)**	**Pipe Aspect Ratio**	**τ**	**FLUX (lm) calculated with the Luxplot method**	**FLUX (lm) calculated with the TTE method**
0.35	0.18	0.25	0.71	0.76	364.47	347.31
		0.50	1.43	0.70	336.93	343.34
		0.75	2.14	0.65	311.47	339.41
		1.00	2.86	0.60	287.94	335.53
		2.00	5.71	0.44	210.28	320.45
		3.00	8.57	0.32	153.57	306.04
		4.00	11.43	0.23	112.16	292.28
		5.00	14.29	0.17	81.91	279.14
		6.00	17.14	0.12	59.82	266.59
		8.00	22.86	0.07	31.90	243.16
		10.00	28.57	0.04	17.02	221.79
		12.00	34.29	0.02	9.08	202.29
		14.00	40.00	0.01	4.84	184.51
		15.00	42.86	0.01	3.54	176.22
		16.00	45.71	0.01	2.58	168.29
		18.00	51.43	0.00	1.38	153.50
		20.00	57.14	0.00	0.73	140.01
		25.00	71.43	0.00	0.15	111.24

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.38	0.19	0.25	0.67	0.76	420.60	399.48
		0.50	1.33	0.71	390.86	395.21
		0.75	2.00	0.66	363.22	390.98
		1.00	2.67	0.61	337.54	386.80
		2.00	5.33	0.46	251.73	370.52
		3.00	8.00	0.34	187.73	354.93
		4.00	10.67	0.25	140.01	339.99
		5.00	13.33	0.19	104.41	325.68
		6.00	16.00	0.14	77.87	311.97
		8.00	21.33	0.08	43.31	286.26
		10.00	26.67	0.04	24.09	262.67
		12.00	32.00	0.02	13.40	241.03
		14.00	37.33	0.01	7.45	221.17
		15.00	40.00	0.01	5.56	211.86
		16.00	42.67	0.01	4.14	202.94
		18.00	48.00	0.00	2.30	186.22
		20.00	53.33	0.00	1.28	170.87
		25.00	66.67	0.00	0.30	137.82

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.53	0.27	0.25	0.47	0.78	858.36	803.27
		0.50	0.94	0.74	814.96	797.07
		0.75	1.42	0.70	773.75	790.92
		1.00	1.89	0.67	734.63	784.81
		2.00	3.77	0.54	596.94	760.85
		3.00	5.66	0.44	485.06	737.63
		4.00	7.55	0.36	394.15	715.11
		5.00	9.43	0.29	320.27	693.28
		6.00	11.32	0.24	260.25	672.12
		8.00	15.09	0.16	171.84	631.72
		10.00	18.87	0.10	113.46	593.74
		12.00	22.64	0.07	74.91	558.05
		14.00	26.42	0.04	49.46	524.50
		15.00	28.30	0.04	40.19	508.49
		16.00	30.19	0.03	32.66	492.97
		18.00	33.96	0.02	21.56	463.33
		20.00	37.74	0.01	14.24	435.48
		25.00	47.17	0.00	5.04	372.95

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.65	0.33	0.25	0.38	0.79	1303.49	1211.10
		0.50	0.77	0.75	1249.49	1203.56
		0.75	1.15	0.72	1197.73	1196.06
		1.00	1.54	0.69	1148.11	1188.60
		2.00	3.08	0.58	969.37	1159.26
		3.00	4.62	0.49	818.45	1130.64
		4.00	6.15	0.42	691.03	1102.72
		5.00	7.69	0.35	583.45	1075.49
		6.00	9.23	0.30	492.61	1048.94
		8.00	12.31	0.21	351.17	997.78
		10.00	15.38	0.15	250.33	949.12
		12.00	18.46	0.11	178.45	902.83
		14.00	21.54	0.08	127.21	858.80
		15.00	23.08	0.06	107.41	837.60
		16.00	24.62	0.05	90.69	816.92
		18.00	27.69	0.04	64.65	777.07
		20.00	30.77	0.03	46.09	739.18
		25.00	38.46	0.01	19.77	652.32
Pipe Diameter (m)	**Pipe Radius (m)**	**Pipe Length (m)**	**Pipe Aspect Ratio**	**τ**	**FLUX (lm) calculated with the Luxplot method**	**FLUX (lm) calculated with the TTE method**
0.90	0.45	0.25	0.28	0.80	2528.53	2331.67
		0.50	0.56	0.77	2452.44	2320.62
		0.75	0.83	0.75	2378.64	2309.62
		1.00	1.11	0.73	2307.06	2298.67
		2.00	2.22	0.64	2041.63	2255.41
		3.00	3.33	0.57	1806.75	2212.96
		4.00	4.44	0.50	1598.88	2171.31
		5.00	5.56	0.45	1414.93	2130.45
		6.00	6.67	0.39	1252.15	2090.35
		8.00	8.89	0.31	980.61	2012.41
		10.00	11.11	0.24	767.95	1937.37
		12.00	13.33	0.19	601.41	1865.13
		14.00	15.56	0.15	470.99	1795.59
		15.00	16.67	0.13	416.80	1761.79
		16.00	17.78	0.12	368.85	1728.64
		18.00	20.00	0.09	288.86	1664.18
		20.00	22.22	0.07	226.22	1602.13
		25.00	27.78	0.04	122.78	1456.93

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.25	0.13	0.25	1.00	0.73	180.20	174.95
		0.50	2.00	0.66	161.43	172.22
		0.75	3.00	0.59	144.62	169.53
		1.00	4.00	0.53	129.55	166.88
		2.00	8.00	0.34	83.44	156.69
		3.00	12.00	0.22	53.74	147.12
		4.00	16.00	0.14	34.61	138.14
		5.00	20.00	0.09	22.29	129.70
		6.00	24.00	0.06	14.35	121.78
		8.00	32.00	0.02	5.95	107.37
		10.00	40.00	0.01	2.47	94.66
		12.00	48.00	0.00	1.02	83.45
		14.00	56.00	0.00	0.42	73.57
		15.00	60.00	0.00	0.27	69.08
		16.00	64.00	0.00	0.18	64.86
		18.00	72.00	0.00	0.07	57.18
		20.00	80.00	0.00	0.03	50.41
		25.00	100.00	0.00	0.00	36.79
Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.35	0.18	0.25	0.71	0.76	364.47	347.31
		0.50	1.43	0.70	336.93	343.34
		0.75	2.14	0.65	311.47	339.41
		1.00	2.86	0.60	287.94	335.53
		2.00	5.71	0.44	210.28	320.45
		3.00	8.57	0.32	153.57	306.04
		4.00	11.43	0.23	112.16	292.28
		5.00	14.29	0.17	81.91	279.14
		6.00	17.14	0.12	59.82	266.59
		8.00	22.86	0.07	31.90	243.16
		10.00	28.57	0.04	17.02	221.79
		12.00	34.29	0.02	9.08	202.29
		14.00	40.00	0.01	4.84	184.51
		15.00	42.86	0.01	3.54	176.22
		16.00	45.71	0.01	2.58	168.29
		18.00	51.43	0.00	1.38	153.50
		20.00	57.14	0.00	0.73	140.01
		25.00	71.43	0.00	0.15	111.24

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.38	0.19	0.25	0.67	0.76	420.60	399.48
		0.50	1.33	0.71	390.86	395.21
		0.75	2.00	0.66	363.22	390.98
		1.00	2.67	0.61	337.54	386.80
		2.00	5.33	0.46	251.73	370.52
		3.00	8.00	0.34	187.73	354.93
		4.00	10.67	0.25	140.01	339.99
		5.00	13.33	0.19	104.41	325.68
		6.00	16.00	0.14	77.87	311.97
		8.00	21.33	0.08	43.31	286.26
		10.00	26.67	0.04	24.09	262.67
		12.00	32.00	0.02	13.40	241.03
		14.00	37.33	0.01	7.45	221.17
		15.00	40.00	0.01	5.56	211.86
		16.00	42.67	0.01	4.14	202.94
		18.00	48.00	0.00	2.30	186.22
		20.00	53.33	0.00	1.28	170.87
		25.00	66.67	0.00	0.30	137.82
Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.53	0.27	0.25	0.47	0.78	858.36	803.27
		0.50	0.94	0.74	814.96	797.07
		0.75	1.42	0.70	773.75	790.92
		1.00	1.89	0.67	734.63	784.81
		2.00	3.77	0.54	596.94	760.85
		3.00	5.66	0.44	485.06	737.63
		4.00	7.55	0.36	394.15	715.11
		5.00	9.43	0.29	320.27	693.28
		6.00	11.32	0.24	260.25	672.12
		8.00	15.09	0.16	171.84	631.72
		10.00	18.87	0.10	113.46	593.74
		12.00	22.64	0.07	74.91	558.05
		14.00	26.42	0.04	49.46	524.50
		15.00	28.30	0.04	40.19	508.49
		16.00	30.19	0.03	32.66	492.97
		18.00	33.96	0.02	21.56	463.33
		20.00	37.74	0.01	14.24	435.48
		25.00	47.17	0.00	5.04	372.95

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.65	0.33	0.25	0.38	0.79	1303.49	1211.10
		0.50	0.77	0.75	1249.49	1203.56
		0.75	1.15	0.72	1197.73	1196.06
		1.00	1.54	0.69	1148.11	1188.60
		2.00	3.08	0.58	969.37	1159.26
		3.00	4.62	0.49	818.45	1130.64
		4.00	6.15	0.42	691.03	1102.72
		5.00	7.69	0.35	583.45	1075.49
		6.00	9.23	0.30	492.61	1048.94
		8.00	12.31	0.21	351.17	997.78
		10.00	15.38	0.15	250.33	949.12
		12.00	18.46	0.11	178.45	902.83
		14.00	21.54	0.08	127.21	858.80
		15.00	23.08	0.06	107.41	837.60
		16.00	24.62	0.05	90.69	816.92
		18.00	27.69	0.04	64.65	777.07
		20.00	30.77	0.03	46.09	739.18
		25.00	38.46	0.01	19.77	652.32
Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.90	0.45	0.25	0.28	0.80	2528.53	2331.67
		0.50	0.56	0.77	2452.44	2320.62
		0.75	0.83	0.75	2378.64	2309.62
		1.00	1.11	0.73	2307.06	2298.67
		2.00	2.22	0.64	2041.63	2255.41
		3.00	3.33	0.57	1806.75	2212.96
		4.00	4.44	0.50	1598.88	2171.31
		5.00	5.56	0.45	1414.93	2130.45
		6.00	6.67	0.39	1252.15	2090.35
		8.00	8.89	0.31	980.61	2012.41
		10.00	11.11	0.24	767.95	1937.37
		12.00	13.33	0.19	601.41	1865.13
		14.00	15.56	0.15	470.99	1795.59
		15.00	16.67	0.13	416.80	1761.79
		16.00	17.78	0.12	368.85	1728.64
		18.00	20.00	0.09	288.86	1664.18
		20.00	22.22	0.07	226.22	1602.13
		25.00	27.78	0.04	122.78	1456.93

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.25	0.13	0.25	1.00	0.73	180.20	174.95
		0.50	2.00	0.66	161.43	172.22
		0.75	3.00	0.59	144.62	169.53
		1.00	4.00	0.53	129.55	166.88
		2.00	8.00	0.34	83.44	156.69
		3.00	12.00	0.22	53.74	147.12
		4.00	16.00	0.14	34.61	138.14
		5.00	20.00	0.09	22.29	129.70
		6.00	24.00	0.06	14.35	121.78
		8.00	32.00	0.02	5.95	107.37
		10.00	40.00	0.01	2.47	94.66
		12.00	48.00	0.00	1.02	83.45
		14.00	56.00	0.00	0.42	73.57
		15.00	60.00	0.00	0.27	69.08
		16.00	64.00	0.00	0.18	64.86
		18.00	72.00	0.00	0.07	57.18
		20.00	80.00	0.00	0.03	50.41
		25.00	100.00	0.00	0.00	36.79

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.35	0.18	0.25	0.71	0.76	364.47	347.31
		0.50	1.43	0.70	336.93	343.34
		0.75	2.14	0.65	311.47	339.41
		1.00	2.86	0.60	287.94	335.53
		2.00	5.71	0.44	210.28	320.45
		3.00	8.57	0.32	153.57	306.04
		4.00	11.43	0.23	112.16	292.28
		5.00	14.29	0.17	81.91	279.14
		6.00	17.14	0.12	59.82	266.59
		8.00	22.86	0.07	31.90	243.16
		10.00	28.57	0.04	17.02	221.79
		12.00	34.29	0.02	9.08	202.29
		14.00	40.00	0.01	4.84	184.51
		15.00	42.86	0.01	3.54	176.22
		16.00	45.71	0.01	2.58	168.29
		18.00	51.43	0.00	1.38	153.50
		20.00	57.14	0.00	0.73	140.01
		25.00	71.43	0.00	0.15	111.24

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.38	0.19	0.25	0.67	0.76	420.60	399.48
		0.50	1.33	0.71	390.86	395.21
		0.75	2.00	0.66	363.22	390.98
		1.00	2.67	0.61	337.54	386.80
		2.00	5.33	0.46	251.73	370.52
		3.00	8.00	0.34	187.73	354.93
		4.00	10.67	0.25	140.01	339.99
		5.00	13.33	0.19	104.41	325.68
		6.00	16.00	0.14	77.87	311.97
		8.00	21.33	0.08	43.31	286.26
		10.00	26.67	0.04	24.09	262.67
		12.00	32.00	0.02	13.40	241.03
		14.00	37.33	0.01	7.45	221.17
		15.00	40.00	0.01	5.56	211.86
		16.00	42.67	0.01	4.14	202.94
		18.00	48.00	0.00	2.30	186.22
		20.00	53.33	0.00	1.28	170.87
		25.00	66.67	0.00	0.30	137.82
Pipe Diameter (m)	**Pipe Radius (m)**	**Pipe Length (m)**	**Pipe Aspect Ratio**	**τ**	**FLUX (lm) calculated with the Luxplot method**	**FLUX (lm) calculated with the TTE method**
0.53	0.27	0.25	0.47	0.78	858.36	803.27
		0.50	0.94	0.74	814.96	797.07
		0.75	1.42	0.70	773.75	790.92
		1.00	1.89	0.67	734.63	784.81
		2.00	3.77	0.54	596.94	760.85
		3.00	5.66	0.44	485.06	737.63
		4.00	7.55	0.36	394.15	715.11
		5.00	9.43	0.29	320.27	693.28
		6.00	11.32	0.24	260.25	672.12
		8.00	15.09	0.16	171.84	631.72
		10.00	18.87	0.10	113.46	593.74
		12.00	22.64	0.07	74.91	558.05
		14.00	26.42	0.04	49.46	524.50
		15.00	28.30	0.04	40.19	508.49
		16.00	30.19	0.03	32.66	492.97
		18.00	33.96	0.02	21.56	463.33
		20.00	37.74	0.01	14.24	435.48
		25.00	47.17	0.00	5.04	372.95

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.65	0.33	0.25	0.38	0.79	1303.49	1211.10
		0.50	0.77	0.75	1249.49	1203.56
		0.75	1.15	0.72	1197.73	1196.06
		1.00	1.54	0.69	1148.11	1188.60
		2.00	3.08	0.58	969.37	1159.26
		3.00	4.62	0.49	818.45	1130.64
		4.00	6.15	0.42	691.03	1102.72
		5.00	7.69	0.35	583.45	1075.49
		6.00	9.23	0.30	492.61	1048.94
		8.00	12.31	0.21	351.17	997.78
		10.00	15.38	0.15	250.33	949.12
		12.00	18.46	0.11	178.45	902.83
		14.00	21.54	0.08	127.21	858.80
		15.00	23.08	0.06	107.41	837.60
		16.00	24.62	0.05	90.69	816.92
		18.00	27.69	0.04	64.65	777.07
		20.00	30.77	0.03	46.09	739.18
		25.00	38.46	0.01	19.77	652.32

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.90	0.45	0.25	0.28	0.80	2528.53	2331.67
		0.50	0.56	0.77	2452.44	2320.62
		0.75	0.83	0.75	2378.64	2309.62
		1.00	1.11	0.73	2307.06	2298.67
		2.00	2.22	0.64	2041.63	2255.41
		3.00	3.33	0.57	1806.75	2212.96
		4.00	4.44	0.50	1598.88	2171.31
		5.00	5.56	0.45	1414.93	2130.45
		6.00	6.67	0.39	1252.15	2090.35
		8.00	8.89	0.31	980.61	2012.41
		10.00	11.11	0.24	767.95	1937.37
		12.00	13.33	0.19	601.41	1865.13
		14.00	15.56	0.15	470.99	1795.59
		15.00	16.67	0.13	416.80	1761.79
		16.00	17.78	0.12	368.85	1728.64
		18.00	20.00	0.09	288.86	1664.18
		20.00	22.22	0.07	226.22	1602.13
		25.00	27.78	0.04	122.78	1456.93

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.25	0.13	0.25	1.00	0.73	180.20	174.95
		0.50	2.00	0.66	161.43	172.22
		0.75	3.00	0.59	144.62	169.53
		1.00	4.00	0.53	129.55	166.88
		2.00	8.00	0.34	83.44	156.69
		3.00	12.00	0.22	53.74	147.12
		4.00	16.00	0.14	34.61	138.14
		5.00	20.00	0.09	22.29	129.70
		6.00	24.00	0.06	14.35	121.78
		8.00	32.00	0.02	5.95	107.37
		10.00	40.00	0.01	2.47	94.66
		12.00	48.00	0.00	1.02	83.45
		14.00	56.00	0.00	0.42	73.57
		15.00	60.00	0.00	0.27	69.08
		16.00	64.00	0.00	0.18	64.86
		18.00	72.00	0.00	0.07	57.18
		20.00	80.00	0.00	0.03	50.41
		25.00	100.00	0.00	0.00	36.79

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.35	0.18	0.25	0.71	0.76	364.47	347.31
		0.50	1.43	0.70	336.93	343.34
		0.75	2.14	0.65	311.47	339.41
		1.00	2.86	0.60	287.94	335.53
		2.00	5.71	0.44	210.28	320.45
		3.00	8.57	0.32	153.57	306.04
		4.00	11.43	0.23	112.16	292.28
		5.00	14.29	0.17	81.91	279.14
		6.00	17.14	0.12	59.82	266.59
		8.00	22.86	0.07	31.90	243.16
		10.00	28.57	0.04	17.02	221.79
		12.00	34.29	0.02	9.08	202.29
		14.00	40.00	0.01	4.84	184.51
		15.00	42.86	0.01	3.54	176.22
		16.00	45.71	0.01	2.58	168.29
		18.00	51.43	0.00	1.38	153.50
		20.00	57.14	0.00	0.73	140.01
		25.00	71.43	0.00	0.15	111.24

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.38	0.19	0.25	0.67	0.76	420.60	399.48
		0.50	1.33	0.71	390.86	395.21
		0.75	2.00	0.66	363.22	390.98
		1.00	2.67	0.61	337.54	386.80
		2.00	5.33	0.46	251.73	370.52
		3.00	8.00	0.34	187.73	354.93
		4.00	10.67	0.25	140.01	339.99
		5.00	13.33	0.19	104.41	325.68
		6.00	16.00	0.14	77.87	311.97
		8.00	21.33	0.08	43.31	286.26
		10.00	26.67	0.04	24.09	262.67
		12.00	32.00	0.02	13.40	241.03
		14.00	37.33	0.01	7.45	221.17
		15.00	40.00	0.01	5.56	211.86
		16.00	42.67	0.01	4.14	202.94
		18.00	48.00	0.00	2.30	186.22
		20.00	53.33	0.00	1.28	170.87
		25.00	66.67	0.00	0.30	137.82
Pipe Diameter (m)	**Pipe Radius (m)**	**Pipe Length (m)**	**Pipe Aspect Ratio**	**τ**	**FLUX (lm) calculated with the Luxplot method**	**FLUX (lm) calculated with the TTE method**
0.53	0.27	0.25	0.47	0.78	858.36	803.27
		0.50	0.94	0.74	814.96	797.07
		0.75	1.42	0.70	773.75	790.92
		1.00	1.89	0.67	734.63	784.81
		2.00	3.77	0.54	596.94	760.85
		3.00	5.66	0.44	485.06	737.63
		4.00	7.55	0.36	394.15	715.11
		5.00	9.43	0.29	320.27	693.28
		6.00	11.32	0.24	260.25	672.12
		8.00	15.09	0.16	171.84	631.72
		10.00	18.87	0.10	113.46	593.74
		12.00	22.64	0.07	74.91	558.05
		14.00	26.42	0.04	49.46	524.50
		15.00	28.30	0.04	40.19	508.49
		16.00	30.19	0.03	32.66	492.97
		18.00	33.96	0.02	21.56	463.33
		20.00	37.74	0.01	14.24	435.48
		25.00	47.17	0.00	5.04	372.95

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.65	0.33	0.25	0.38	0.79	1303.49	1211.10
		0.50	0.77	0.75	1249.49	1203.56
		0.75	1.15	0.72	1197.73	1196.06
		1.00	1.54	0.69	1148.11	1188.60
		2.00	3.08	0.58	969.37	1159.26
		3.00	4.62	0.49	818.45	1130.64
		4.00	6.15	0.42	691.03	1102.72
		5.00	7.69	0.35	583.45	1075.49
		6.00	9.23	0.30	492.61	1048.94
		8.00	12.31	0.21	351.17	997.78
		10.00	15.38	0.15	250.33	949.12
		12.00	18.46	0.11	178.45	902.83
		14.00	21.54	0.08	127.21	858.80
		15.00	23.08	0.06	107.41	837.60
		16.00	24.62	0.05	90.69	816.92
		18.00	27.69	0.04	64.65	777.07
		20.00	30.77	0.03	46.09	739.18
		25.00	38.46	0.01	19.77	652.32
Pipe Diameter (m)	**Pipe Radius (m)**	**Pipe Length (m)**	**Pipe Aspect Ratio**	**τ**	**FLUX (lm) calculated with the Luxplot method**	**FLUX (lm) calculated with the TTE method**
0.90	0.45	0.25	0.28	0.80	2528.53	2331.67
		0.50	0.56	0.77	2452.44	2320.62
		0.75	0.83	0.75	2378.64	2309.62
		1.00	1.11	0.73	2307.06	2298.67
		2.00	2.22	0.64	2041.63	2255.41
		3.00	3.33	0.57	1806.75	2212.96
		4.00	4.44	0.50	1598.88	2171.31
		5.00	5.56	0.45	1414.93	2130.45
		6.00	6.67	0.39	1252.15	2090.35
		8.00	8.89	0.31	980.61	2012.41
		10.00	11.11	0.24	767.95	1937.37
		12.00	13.33	0.19	601.41	1865.13
		14.00	15.56	0.15	470.99	1795.59
		15.00	16.67	0.13	416.80	1761.79
		16.00	17.78	0.12	368.85	1728.64
		18.00	20.00	0.09	288.86	1664.18
		20.00	22.22	0.07	226.22	1602.13
		25.00	27.78	0.04	122.78	1456.93

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.25	0.13	0.25	1.00	0.73	180.20	174.95
		0.50	2.00	0.66	161.43	172.22
		0.75	3.00	0.59	144.62	169.53
		1.00	4.00	0.53	129.55	166.88
		2.00	8.00	0.34	83.44	156.69
		3.00	12.00	0.22	53.74	147.12
		4.00	16.00	0.14	34.61	138.14
		5.00	20.00	0.09	22.29	129.70
		6.00	24.00	0.06	14.35	121.78
		8.00	32.00	0.02	5.95	107.37
		10.00	40.00	0.01	2.47	94.66
		12.00	48.00	0.00	1.02	83.45
		14.00	56.00	0.00	0.42	73.57
		15.00	60.00	0.00	0.27	69.08
		16.00	64.00	0.00	0.18	64.86
		18.00	72.00	0.00	0.07	57.18
		20.00	80.00	0.00	0.03	50.41
		25.00	100.00	0.00	0.00	36.79
Pipe Diameter (m)	**Pipe Radius (m)**	**Pipe Length (m)**	**Pipe Aspect Ratio**	**τ**	**FLUX (lm) calculated with the Luxplot method**	**FLUX (lm) calculated with the TTE method**
0.35	0.18	0.25	0.71	0.76	364.47	347.31
		0.50	1.43	0.70	336.93	343.34
		0.75	2.14	0.65	311.47	339.41
		1.00	2.86	0.60	287.94	335.53
		2.00	5.71	0.44	210.28	320.45
		3.00	8.57	0.32	153.57	306.04
		4.00	11.43	0.23	112.16	292.28
		5.00	14.29	0.17	81.91	279.14
		6.00	17.14	0.12	59.82	266.59
		8.00	22.86	0.07	31.90	243.16
		10.00	28.57	0.04	17.02	221.79
		12.00	34.29	0.02	9.08	202.29
		14.00	40.00	0.01	4.84	184.51
		15.00	42.86	0.01	3.54	176.22
		16.00	45.71	0.01	2.58	168.29
		18.00	51.43	0.00	1.38	153.50
		20.00	57.14	0.00	0.73	140.01
		25.00	71.43	0.00	0.15	111.24

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.38	0.19	0.25	0.67	0.76	420.60	399.48
		0.50	1.33	0.71	390.86	395.21
		0.75	2.00	0.66	363.22	390.98
		1.00	2.67	0.61	337.54	386.80
		2.00	5.33	0.46	251.73	370.52
		3.00	8.00	0.34	187.73	354.93
		4.00	10.67	0.25	140.01	339.99
		5.00	13.33	0.19	104.41	325.68
		6.00	16.00	0.14	77.87	311.97
		8.00	21.33	0.08	43.31	286.26
		10.00	26.67	0.04	24.09	262.67
		12.00	32.00	0.02	13.40	241.03
		14.00	37.33	0.01	7.45	221.17
		15.00	40.00	0.01	5.56	211.86
		16.00	42.67	0.01	4.14	202.94
		18.00	48.00	0.00	2.30	186.22
		20.00	53.33	0.00	1.28	170.87
		25.00	66.67	0.00	0.30	137.82

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.53	0.27	0.25	0.47	0.78	858.36	803.27
		0.50	0.94	0.74	814.96	797.07
		0.75	1.42	0.70	773.75	790.92
		1.00	1.89	0.67	734.63	784.81
		2.00	3.77	0.54	596.94	760.85
		3.00	5.66	0.44	485.06	737.63
		4.00	7.55	0.36	394.15	715.11
		5.00	9.43	0.29	320.27	693.28
		6.00	11.32	0.24	260.25	672.12
		8.00	15.09	0.16	171.84	631.72
		10.00	18.87	0.10	113.46	593.74
		12.00	22.64	0.07	74.91	558.05
		14.00	26.42	0.04	49.46	524.50
		15.00	28.30	0.04	40.19	508.49
		16.00	30.19	0.03	32.66	492.97
		18.00	33.96	0.02	21.56	463.33
		20.00	37.74	0.01	14.24	435.48
		25.00	47.17	0.00	5.04	372.95

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.65	0.33	0.25	0.38	0.79	1303.49	1211.10
		0.50	0.77	0.75	1249.49	1203.56
		0.75	1.15	0.72	1197.73	1196.06
		1.00	1.54	0.69	1148.11	1188.60
		2.00	3.08	0.58	969.37	1159.26
		3.00	4.62	0.49	818.45	1130.64
		4.00	6.15	0.42	691.03	1102.72
		5.00	7.69	0.35	583.45	1075.49
		6.00	9.23	0.30	492.61	1048.94
		8.00	12.31	0.21	351.17	997.78
		10.00	15.38	0.15	250.33	949.12
		12.00	18.46	0.11	178.45	902.83
		14.00	21.54	0.08	127.21	858.80
		15.00	23.08	0.06	107.41	837.60
		16.00	24.62	0.05	90.69	816.92
		18.00	27.69	0.04	64.65	777.07
		20.00	30.77	0.03	46.09	739.18
		25.00	38.46	0.01	19.77	652.32
Pipe Diameter (m)	**Pipe Radius (m)**	**Pipe Length (m)**	**Pipe Aspect Ratio**	**τ**	**FLUX (lm) calculated with the Luxplot method**	**FLUX (lm) calculated with the TTE method**
0.90	0.45	0.25	0.28	0.80	2528.53	2331.67
		0.50	0.56	0.77	2452.44	2320.62
		0.75	0.83	0.75	2378.64	2309.62
		1.00	1.11	0.73	2307.06	2298.67
		2.00	2.22	0.64	2041.63	2255.41
		3.00	3.33	0.57	1806.75	2212.96
		4.00	4.44	0.50	1598.88	2171.31
		5.00	5.56	0.45	1414.93	2130.45
		6.00	6.67	0.39	1252.15	2090.35
		8.00	8.89	0.31	980.61	2012.41
		10.00	11.11	0.24	767.95	1937.37
		12.00	13.33	0.19	601.41	1865.13
		14.00	15.56	0.15	470.99	1795.59
		15.00	16.67	0.13	416.80	1761.79
		16.00	17.78	0.12	368.85	1728.64
		18.00	20.00	0.09	288.86	1664.18
		20.00	22.22	0.07	226.22	1602.13
		25.00	27.78	0.04	122.78	1456.93

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.25	0.13	0.25	1.00	0.73	180.20	174.95
		0.50	2.00	0.66	161.43	172.22
		0.75	3.00	0.59	144.62	169.53
		1.00	4.00	0.53	129.55	166.88
		2.00	8.00	0.34	83.44	156.69
		3.00	12.00	0.22	53.74	147.12
		4.00	16.00	0.14	34.61	138.14
		5.00	20.00	0.09	22.29	129.70
		6.00	24.00	0.06	14.35	121.78
		8.00	32.00	0.02	5.95	107.37
		10.00	40.00	0.01	2.47	94.66
		12.00	48.00	0.00	1.02	83.45
		14.00	56.00	0.00	0.42	73.57
		15.00	60.00	0.00	0.27	69.08
		16.00	64.00	0.00	0.18	64.86
		18.00	72.00	0.00	0.07	57.18
		20.00	80.00	0.00	0.03	50.41
		25.00	100.00	0.00	0.00	36.79
Pipe Diameter (m)	**Pipe Radius (m)**	**Pipe Length (m)**	**Pipe Aspect Ratio**	**τ**	**FLUX (lm) calculated with the Luxplot method**	**FLUX (lm) calculated with the TTE method**
0.35	0.18	0.25	0.71	0.76	364.47	347.31
		0.50	1.43	0.70	336.93	343.34
		0.75	2.14	0.65	311.47	339.41
		1.00	2.86	0.60	287.94	335.53
		2.00	5.71	0.44	210.28	320.45
		3.00	8.57	0.32	153.57	306.04
		4.00	11.43	0.23	112.16	292.28
		5.00	14.29	0.17	81.91	279.14
		6.00	17.14	0.12	59.82	266.59
		8.00	22.86	0.07	31.90	243.16
		10.00	28.57	0.04	17.02	221.79
		12.00	34.29	0.02	9.08	202.29
		14.00	40.00	0.01	4.84	184.51
		15.00	42.86	0.01	3.54	176.22
		16.00	45.71	0.01	2.58	168.29
		18.00	51.43	0.00	1.38	153.50
		20.00	57.14	0.00	0.73	140.01
		25.00	71.43	0.00	0.15	111.24

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.38	0.19	0.25	0.67	0.76	420.60	399.48
		0.50	1.33	0.71	390.86	395.21
		0.75	2.00	0.66	363.22	390.98
		1.00	2.67	0.61	337.54	386.80
		2.00	5.33	0.46	251.73	370.52
		3.00	8.00	0.34	187.73	354.93
		4.00	10.67	0.25	140.01	339.99
		5.00	13.33	0.19	104.41	325.68
		6.00	16.00	0.14	77.87	311.97
		8.00	21.33	0.08	43.31	286.26
		10.00	26.67	0.04	24.09	262.67
		12.00	32.00	0.02	13.40	241.03
		14.00	37.33	0.01	7.45	221.17
		15.00	40.00	0.01	5.56	211.86
		16.00	42.67	0.01	4.14	202.94
		18.00	48.00	0.00	2.30	186.22
		20.00	53.33	0.00	1.28	170.87
		25.00	66.67	0.00	0.30	137.82

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.53	0.27	0.25	0.47	0.78	858.36	803.27
		0.50	0.94	0.74	814.96	797.07
		0.75	1.42	0.70	773.75	790.92
		1.00	1.89	0.67	734.63	784.81
		2.00	3.77	0.54	596.94	760.85
		3.00	5.66	0.44	485.06	737.63
		4.00	7.55	0.36	394.15	715.11
		5.00	9.43	0.29	320.27	693.28
		6.00	11.32	0.24	260.25	672.12
		8.00	15.09	0.16	171.84	631.72
		10.00	18.87	0.10	113.46	593.74
		12.00	22.64	0.07	74.91	558.05
		14.00	26.42	0.04	49.46	524.50
		15.00	28.30	0.04	40.19	508.49
		16.00	30.19	0.03	32.66	492.97
		18.00	33.96	0.02	21.56	463.33
		20.00	37.74	0.01	14.24	435.48
		25.00	47.17	0.00	5.04	372.95

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.65	0.33	0.25	0.38	0.79	1303.49	1211.10
		0.50	0.77	0.75	1249.49	1203.56
		0.75	1.15	0.72	1197.73	1196.06
		1.00	1.54	0.69	1148.11	1188.60
		2.00	3.08	0.58	969.37	1159.26
		3.00	4.62	0.49	818.45	1130.64
		4.00	6.15	0.42	691.03	1102.72
		5.00	7.69	0.35	583.45	1075.49
		6.00	9.23	0.30	492.61	1048.94
		8.00	12.31	0.21	351.17	997.78
		10.00	15.38	0.15	250.33	949.12
		12.00	18.46	0.11	178.45	902.83
		14.00	21.54	0.08	127.21	858.80
		15.00	23.08	0.06	107.41	837.60
		16.00	24.62	0.05	90.69	816.92
		18.00	27.69	0.04	64.65	777.07
		20.00	30.77	0.03	46.09	739.18
		25.00	38.46	0.01	19.77	652.32
Pipe Diameter (m)	**Pipe Radius (m)**	**Pipe Length (m)**	**Pipe Aspect Ratio**	**τ**	**FLUX (lm) calculated with the Luxplot method**	**FLUX (lm) calculated with the TTE method**
0.90	0.45	0.25	0.28	0.80	2528.53	2331.67
		0.50	0.56	0.77	2452.44	2320.62
		0.75	0.83	0.75	2378.64	2309.62
		1.00	1.11	0.73	2307.06	2298.67
		2.00	2.22	0.64	2041.63	2255.41
		3.00	3.33	0.57	1806.75	2212.96
		4.00	4.44	0.50	1598.88	2171.31
		5.00	5.56	0.45	1414.93	2130.45
		6.00	6.67	0.39	1252.15	2090.35
		8.00	8.89	0.31	980.61	2012.41
		10.00	11.11	0.24	767.95	1937.37
		12.00	13.33	0.19	601.41	1865.13
		14.00	15.56	0.15	470.99	1795.59
		15.00	16.67	0.13	416.80	1761.79
		16.00	17.78	0.12	368.85	1728.64
		18.00	20.00	0.09	288.86	1664.18
		20.00	22.22	0.07	226.22	1602.13
		25.00	27.78	0.04	122.78	1456.93

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.25	0.13	0.25	1.00	0.73	180.20	174.95
		0.50	2.00	0.66	161.43	172.22
		0.75	3.00	0.59	144.62	169.53
		1.00	4.00	0.53	129.55	166.88
		2.00	8.00	0.34	83.44	156.69
		3.00	12.00	0.22	53.74	147.12
		4.00	16.00	0.14	34.61	138.14
		5.00	20.00	0.09	22.29	129.70
		6.00	24.00	0.06	14.35	121.78
		8.00	32.00	0.02	5.95	107.37
		10.00	40.00	0.01	2.47	94.66
		12.00	48.00	0.00	1.02	83.45
		14.00	56.00	0.00	0.42	73.57
		15.00	60.00	0.00	0.27	69.08
		16.00	64.00	0.00	0.18	64.86
		18.00	72.00	0.00	0.07	57.18
		20.00	80.00	0.00	0.03	50.41
		25.00	100.00	0.00	0.00	36.79
Pipe Diameter (m)	**Pipe Radius (m)**	**Pipe Length (m)**	**Pipe Aspect Ratio**	**τ**	**FLUX (lm) calculated with the Luxplot method**	**FLUX (lm) calculated with the TTE method**
0.35	0.18	0.25	0.71	0.76	364.47	347.31
		0.50	1.43	0.70	336.93	343.34
		0.75	2.14	0.65	311.47	339.41
		1.00	2.86	0.60	287.94	335.53
		2.00	5.71	0.44	210.28	320.45
		3.00	8.57	0.32	153.57	306.04
		4.00	11.43	0.23	112.16	292.28
		5.00	14.29	0.17	81.91	279.14
		6.00	17.14	0.12	59.82	266.59
		8.00	22.86	0.07	31.90	243.16
		10.00	28.57	0.04	17.02	221.79
		12.00	34.29	0.02	9.08	202.29
		14.00	40.00	0.01	4.84	184.51
		15.00	42.86	0.01	3.54	176.22
		16.00	45.71	0.01	2.58	168.29
		18.00	51.43	0.00	1.38	153.50
		20.00	57.14	0.00	0.73	140.01
		25.00	71.43	0.00	0.15	111.24

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.38	0.19	0.25	0.67	0.76	420.60	399.48
		0.50	1.33	0.71	390.86	395.21
		0.75	2.00	0.66	363.22	390.98
		1.00	2.67	0.61	337.54	386.80
		2.00	5.33	0.46	251.73	370.52
		3.00	8.00	0.34	187.73	354.93
		4.00	10.67	0.25	140.01	339.99
		5.00	13.33	0.19	104.41	325.68
		6.00	16.00	0.14	77.87	311.97
		8.00	21.33	0.08	43.31	286.26
		10.00	26.67	0.04	24.09	262.67
		12.00	32.00	0.02	13.40	241.03
		14.00	37.33	0.01	7.45	221.17
		15.00	40.00	0.01	5.56	211.86
		16.00	42.67	0.01	4.14	202.94
		18.00	48.00	0.00	2.30	186.22
		20.00	53.33	0.00	1.28	170.87
		25.00	66.67	0.00	0.30	137.82
Pipe Diameter (m)	**Pipe Radius (m)**	**Pipe Length (m)**	**Pipe Aspect Ratio**	**τ**	**FLUX (lm) calculated with the Luxplot method**	**FLUX (lm) calculated with the TTE method**
0.53	0.27	0.25	0.47	0.78	858.36	803.27
		0.50	0.94	0.74	814.96	797.07
		0.75	1.42	0.70	773.75	790.92
		1.00	1.89	0.67	734.63	784.81
		2.00	3.77	0.54	596.94	760.85
		3.00	5.66	0.44	485.06	737.63
		4.00	7.55	0.36	394.15	715.11
		5.00	9.43	0.29	320.27	693.28
		6.00	11.32	0.24	260.25	672.12
		8.00	15.09	0.16	171.84	631.72
		10.00	18.87	0.10	113.46	593.74
		12.00	22.64	0.07	74.91	558.05
		14.00	26.42	0.04	49.46	524.50
		15.00	28.30	0.04	40.19	508.49
		16.00	30.19	0.03	32.66	492.97
		18.00	33.96	0.02	21.56	463.33
		20.00	37.74	0.01	14.24	435.48
		25.00	47.17	0.00	5.04	372.95

Pipe Diameter (m)	Pipe Radius (m)	Pipe Length (m)	Pipe Aspect Ratio	τ	FLUX (lm) calculated with the Luxplot method	FLUX (lm) calculated with the TTE method
0.65	0.33	0.25	0.38	0.79	1303.49	1211.10
		0.50	0.77	0.75	1249.49	1203.56
		0.75	1.15	0.72	1197.73	1196.06
		1.00	1.54	0.69	1148.11	1188.60
		2.00	3.08	0.58	969.37	1159.26
		3.00	4.62	0.49	818.45	1130.64
		4.00	6.15	0.42	691.03	1102.72
		5.00	7.69	0.35	583.45	1075.49
		6.00	9.23	0.30	492.61	1048.94
		8.00	12.31	0.21	351.17	997.78
		10.00	15.38	0.15	250.33	949.12
		12.00	18.46	0.11	178.45	902.83
		14.00	21.54	0.08	127.21	858.80
		15.00	23.08	0.06	107.41	837.60
		16.00	24.62	0.05	90.69	816.92
		18.00	27.69	0.04	64.65	777.07
		20.00	30.77	0.03	46.09	739.18
		25.00	38.46	0.01	19.77	652.32
Pipe Diameter (m)	**Pipe Radius (m)**	**Pipe Length (m)**	**Pipe Aspect Ratio**	**τ**	**FLUX (lm) calculated with the Luxplot method**	**FLUX (lm) calculated with the TTE method**
0.90	0.45	0.25	0.28	0.80	2528.53	2331.67
		0.50	0.56	0.77	2452.44	2320.62
		0.75	0.83	0.75	2378.64	2309.62
		1.00	1.11	0.73	2307.06	2298.67
		2.00	2.22	0.64	2041.63	2255.41
		3.00	3.33	0.57	1806.75	2212.96
		4.00	4.44	0.50	1598.88	2171.31
		5.00	5.56	0.45	1414.93	2130.45
		6.00	6.67	0.39	1252.15	2090.35
		8.00	8.89	0.31	980.61	2012.41
		10.00	11.11	0.24	767.95	1937.37
		12.00	13.33	0.19	601.41	1865.13
		14.00	15.56	0.15	470.99	1795.59
		15.00	16.67	0.13	416.80	1761.79
		16.00	17.78	0.12	368.85	1728.64
		18.00	20.00	0.09	288.86	1664.18
		20.00	22.22	0.07	226.22	1602.13
		25.00	27.78	0.04	122.78	1456.93

Appendix IV

Results of the application of the Luxplot method and of the equations produced by the Luxplot method (Table 13) for the calculation of the average illuminance E_{pipe} on the reference plane. Each table of results is followed by the respective graph giving the correlation of the illuminance calculated with the two methods.

Room surface reflectances (%): Walls/Ceiling/Floor-Reference Plane=50/70/30

Reference plane: 0.85m above the floor and 0.50m offset from the walls

τ_{dome} x τ_{dif}=0.82, ρ=0.98, MF=0.9

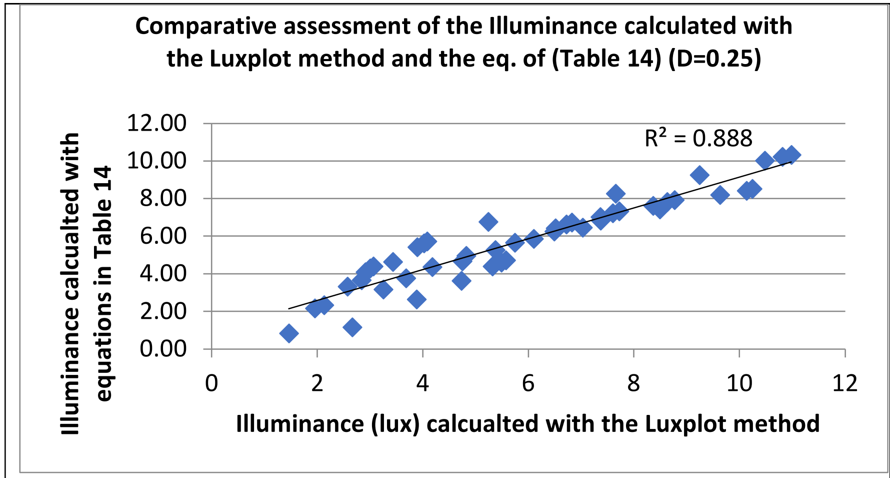
E_{ex}=5,000lux

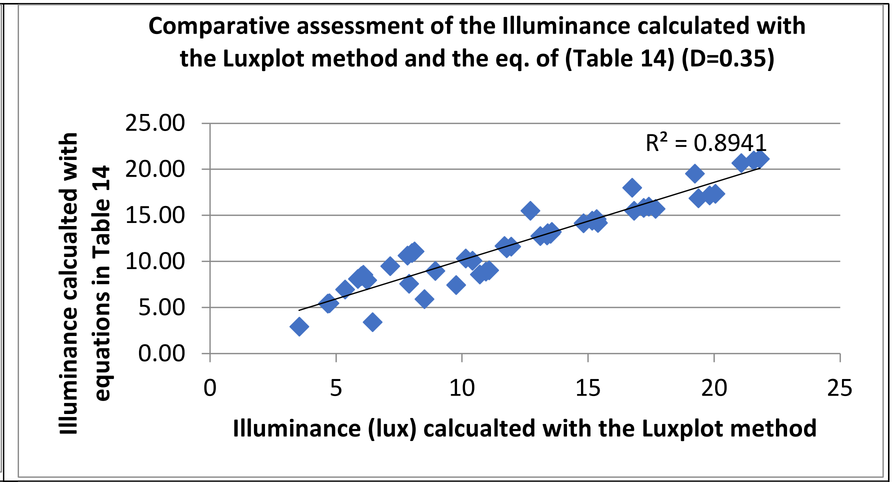
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	FLUX (lm) calculated with the TTE method	ILLUMINANCE (lux) calculated with the Luxplot method	ILLUMINANCE (lux) calculated with relationships included in Table 13
4	4	3	0.25	0.25	174.95	10.24	8.53
				0.5	172.22	10.13	8.42
				1	166.88	9.63	8.21
				3	147.12	8.49	7.44
				6	121.78	7.03	6.46
				12	83.45	4.82	4.97
4	4	5		0.25	174.95	4.08	5.73
				0.5	172.22	4.02	5.63
				1	166.88	3.89	5.42
				3	147.12	3.43	4.65
				6	121.78	2.84	3.66
				12	83.45	1.95	2.17
6	4	3		0.25	174.95	7.72	7.34
				0.5	172.22	7.60	7.23
				1	166.88	7.36	7.02
				3	147.12	6.49	6.25
				6	121.78	5.37	5.27
				12	83.45	3.68	3.78
7	4	3		0.25	174.95	6.82	6.74
				0.5	172.22	6.72	6.64
				1	166.88	6.51	6.43
				3	147.12	5.74	5.66
				6	121.78	4.75	4.67
				12	83.45	3.25	3.18
5	5	4		0.25	174.95	5.57	4.72
				0.5	172.22	5.49	4.62
				1	166.88	5.32	4.41
				3	147.12	4.73	3.64
				6	121.78	3.88	2.65
				12	83.45	2.66	1.16
6	6	2.5		0.25	174.95	3.06	4.41
				0.5	172.22	3.00	4.30
				1	166.88	2.91	4.10
				3	147.12	2.57	3.33
				6	121.78	2.13	2.34
				12	83.45	1.46	0.85
4	3	3		0.25	174.95	10.98	10.34
				0.5	172.22	10.81	10.23
				1	166.88	10.48	10.02
				3	147.12	9.24	9.26
				6	121.78	7.65	8.27
				12	83.45	5.24	6.78
5	4	3		0.25	174.95	8.77	7.93
				0.5	172.22	8.63	7.82
				1	166.88	8.36	7.62
				3	147.12	7.37	6.85
				6	121.78	6.10	5.86
				12	83.45	4.18	4.37

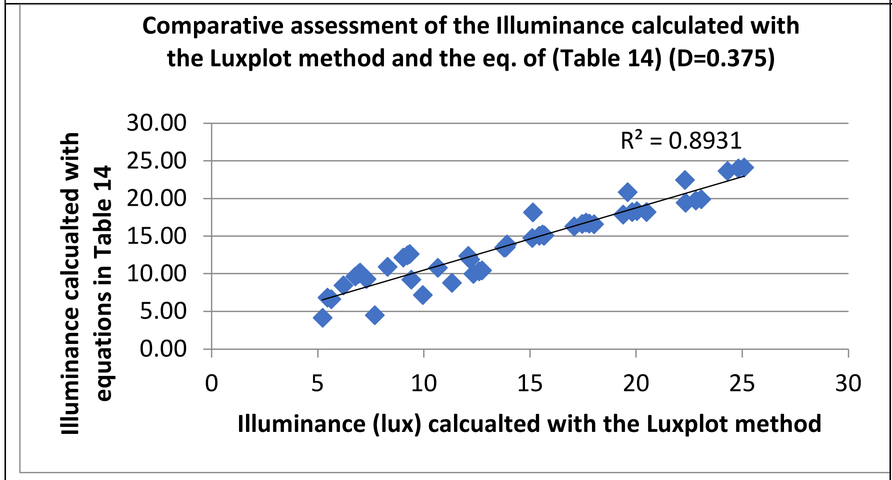
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	FLUX (lm) calculated with the TTE method	ILLUMINANCE (lux) calculated with the Luxplot method	ILLUMINANCE (lux) calculated with relationships included in Table 13
4	4	3	0.35	0.25	347.31	20.04	17.35
				0.5	343.34	19.81	17.20
				1	335.53	19.36	16.89
				3	306.04	17.66	15.75
				6	266.59	15.38	14.21
				12	202.29	11.67	11.72
4	4	5		0.25	347.31	8.10	11.10
				0.5	343.34	8.00	10.95
				1	335.53	7.82	10.65
				3	306.04	7.14	9.50
				6	266.59	6.22	7.97
				12	202.29	4.72	5.47
6	4	3		0.25	347.31	15.33	14.61
				0.5	343.34	15.15	14.46
				1	335.53	14.81	14.15
				3	306.04	13.50	13.01
				6	266.59	11.76	11.48
				12	202.29	8.93	8.98
7	4	3		0.25	347.31	13.55	13.24
				0.5	343.34	13.39	13.09
				1	335.53	13.09	12.78
				3	306.04	11.94	11.64
				6	266.59	10.40	10.11
				12	202.29	7.89	7.61
5	5	4		0.25	347.31	11.06	9.06
				0.5	343.34	10.94	8.91
				1	335.53	10.69	8.60
				3	306.04	9.75	7.46
				6	266.59	8.49	5.93
				12	202.29	6.44	3.43
6	6	2.5		0.25	347.31	6.07	8.58
				0.5	343.34	6.00	8.43
				1	335.53	5.86	8.12
				3	306.04	5.35	6.98
				6	266.59	4.66	5.45
				12	202.29	3.53	2.95
4	3	3		0.25	347.31	21.81	21.14
				0.5	343.34	21.56	20.99
				1	335.53	21.07	20.69
				3	306.04	19.22	19.54
				6	266.59	16.74	18.01
				12	202.29	12.70	15.51
5	4	3		0.25	347.31	17.40	15.98
				0.5	343.34	17.20	15.83
				1	335.53	16.81	15.52
				3	306.04	15.33	14.38
				6	266.59	13.36	12.85
				12	202.29	10.14	10.35

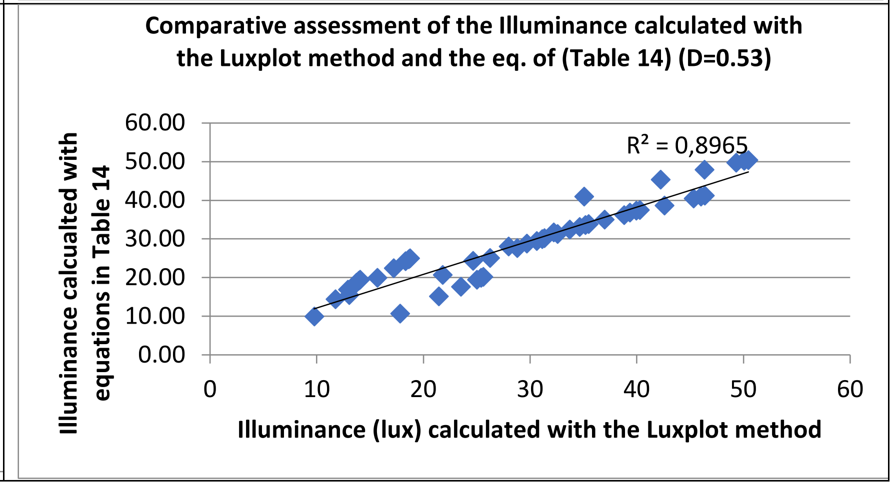
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	FLUX (lm) calculated with the TTE method	ILLUMINANCE (lux) calculated with the Luxplot method	ILLUMINANCE (lux) calculated with relationships included in Table 13
4	4	3	0.375	0.25	399.48	23.05	19.90
				0.5	395.21	22.8	19.73
				1	386.80	22.32	19.42
				3	354.93	20.48	18.21
				6	311.97	18	16.58
				12	241.03	13.9	13.90
4	4	5		0.25	399.48	9.32	12.61
				0.5	395.21	9.22	12.45
				1	386.80	9.02	12.13
				3	354.93	8.28	10.92
				6	311.97	7.28	9.30
				12	241.03	5.62	6.61
6	4	3		0.25	399.48	17.63	16.77
				0.5	395.21	17.44	16.61
				1	386.80	17.07	16.29
				3	354.93	15.66	15.09
				6	311.97	13.77	13.46
				12	241.03	10.64	10.78
7	4	3		0.25	399.48	15.58	15.21
				0.5	395.21	15.42	15.05
				1	386.80	15.09	14.73
				3	354.93	13.84	13.52
				6	311.97	12.17	11.90
				12	241.03	9.40	9.21
5	5	4		0.25	399.48	12.73	10.46
				0.5	395.21	12.59	10.30
				1	386.80	12.32	9.98
				3	354.93	11.31	8.77
				6	311.97	9.94	7.15
				12	241.03	7.68	4.46
6	6	2.5		0.25	399.48	6.98	10.13
				0.5	395.21	6.90	9.96
				1	386.80	6.76	9.65
				3	354.93	6.20	8.44
				6	311.97	5.45	6.81
				12	241.03	5.21	4.13
4	3	3		0.25	399.48	25.08	24.13
				0.5	395.21	24.81	23.97
				1	386.80	24.29	23.65
				3	354.93	22.29	22.44
				6	311.97	19.59	20.82
				12	241.03	15.13	18.13
5	4	3		0.25	399.48	20.02	18.33
				0.5	395.21	19.80	18.17
				1	386.80	19.38	17.85
				3	354.93	17.78	16.65
				6	311.97	15.63	15.02
				12	241.03	12.08	12.34

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	FLUX (lm) calculated with the TTE method	ILLUMINANCE (lux) calculated with the Luxplot method	ILLUMINANCE (lux) calculated with relationships included in Table 13
4	4	3	0.53	0.25	803.27	46.35	41.19
				0.5	797.07	45.99	40.95
				1	784.81	45.29	40.47
				3	737.63	42.56	38.65
				6	672.12	38.78	36.12
				12	558.05	32.2	31.70
4	4	5		0.25	803.27	18.73	24.98
				0.5	797.07	18.59	24.74
				1	784.81	18.30	24.27
				3	737.63	17.20	22.44
				6	672.12	15.67	19.91
				12	558.05	13.01	15.50
6	4	3		0.25	803.27	35.45	33.85
				0.5	797.07	35.17	33.61
				1	784.81	34.63	33.13
				3	737.63	32.55	31.31
				6	672.12	29.66	28.77
				12	558.05	24.63	24.36
7	4	3		0.25	803.27	31.33	30.17
				0.5	797.07	31.10	29.93
				1	784.81	30.61	29.46
				3	737.63	28.77	27.63
				6	672.12	26.22	25.10
				12	558.05	21.77	20.69
5	5	4		0.25	803.27	25.60	20.18
				0.5	797.07	25.39	19.94
				1	784.81	25.00	19.47
				3	737.63	23.50	17.64
				6	672.12	21.41	15.11
				12	558.05	17.78	10.70
6	6	2.5		0.25	803.27	14.03	19.44
				0.5	797.07	13.92	19.20
				1	784.81	13.71	18.72
				3	737.63	12.89	16.90
				6	672.12	11.74	14.36
				12	558.05	9.75	9.95
4	3	3		0.25	803.27	50.44	50.42
				0.5	797.07	50.05	50.18
				1	784.81	49.28	49.71
				3	737.63	46.32	47.88
				6	672.12	42.20	45.35
				12	558.05	35.04	40.93
5	4	3		0.25	803.27	40.25	37.52
				0.5	797.07	39.94	37.28
				1	784.81	39.32	36.80
				3	737.63	36.96	34.98
				6	672.12	33.68	32.44
				12	558.05	27.96	28.03


Comparative assessment of the Illuminance calculated with the Luxplot method and the eq. of (Table 14) (D=0.25)
R² = 0.888
Illuminance calcualted with equations in Table 14
Illuminance (lux) calcualted with the Luxplot method
12.00
10.00
8.00
6.00
4.00
2.00
0.00
0
2
4
6
8
10
12

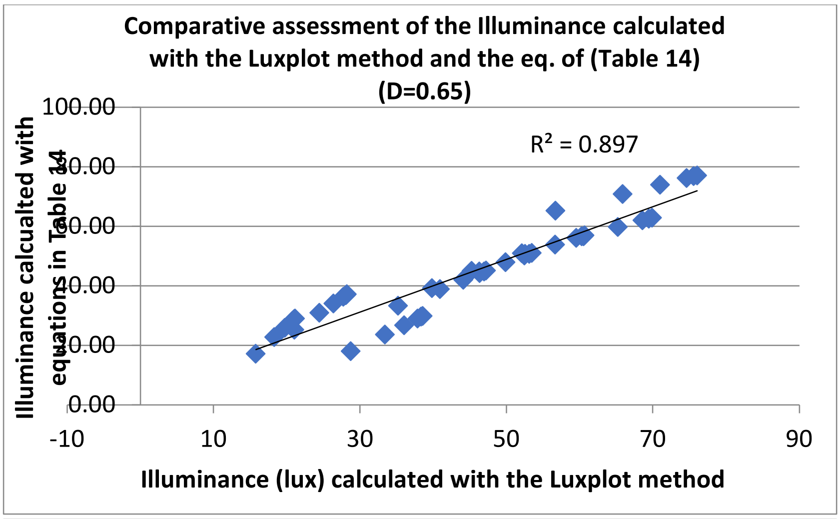

Comparative assessment of the Illuminance calculated with the Luxplot method and the eq. of (Table 14) (D=0.35)
R² = 0.8941
Illuminance calcualted with equations in Table 14
Illuminance (lux) calcualted with the Luxplot method
25.00
20.00
15.00
10.00
5.00
0.00
0
5
10
15
20
25

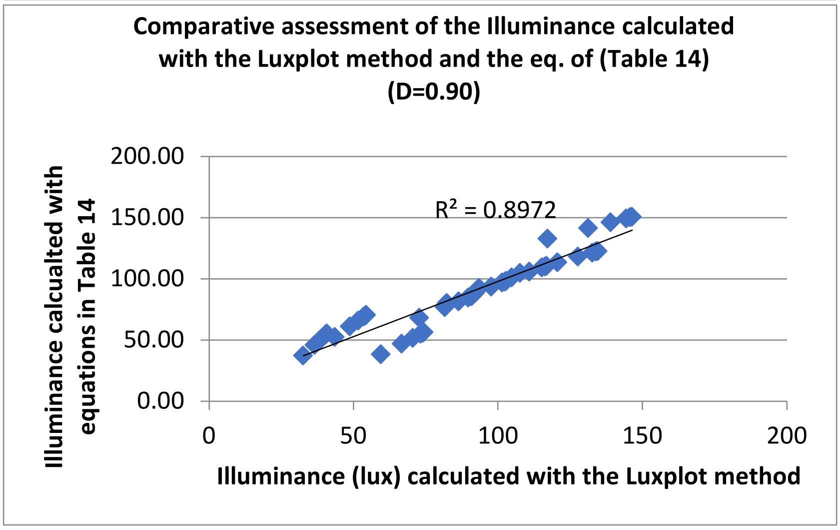

Comparative assessment of the Illuminance calculated with the Luxplot method and the eq. of (Table 14) (D=0.375)
R² = 0.8931
Illuminance calcualted with equations in Table 14
Illuminance (lux) calcualted with the Luxplot method
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0
5
10
15
20
25
30


Comparative assessment of the Illuminance calculated with the Luxplot method and the eq. of (Table 14) (D=0.53)
R² = 0,8965
Illuminance calcualted with equations in Table 14
Illuminance (lux) calculated with the Luxplot method
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0
10
20
30
40
50
60

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	FLUX (lm) calculated with the TTE method	ILLUMINANCE (lux) calculated with the Luxplot method	ILLUMINANCE (lux) calculated with relationships included in Table 13
4	4	3	0.65	0.25	1211.10	69.89	62.87
				0.5	1203.56	69.45	62.58
				1	1188.60	68.59	62.01
				3	1130.64	65.24	59.77
				6	1048.94	60.53	56.62
				12	902.83	52.1	50.98
4	4	5		0.25	1211.10	28.24	37.17
				0.5	1203.56	28.07	36.88
				1	1188.60	27.72	36.30
				3	1130.64	26.37	34.06
				6	1048.94	24.46	30.91
				12	902.83	21.05	25.27
6	4	3		0.25	1211.10	53.45	51.05
				0.5	1203.56	53.11	50.76
				1	1188.60	52.45	50.19
				3	1130.64	49.90	47.95
				6	1048.94	46.29	44.80
				12	902.83	39.84	39.16
7	4	3		0.25	1211.10	47.24	45.14
				0.5	1203.56	46.95	44.85
				1	1188.60	46.36	44.28
				3	1130.64	44.10	42.04
				6	1048.94	40.92	38.89
				12	902.83	35.22	33.25
5	5	4		0.25	1211.10	38.58	29.89
				0.5	1203.56	38.34	29.59
				1	1188.60	37.87	29.02
				3	1130.64	36.02	26.78
				6	1048.94	33.42	23.63
				12	902.83	28.76	17.99
6	6	2.5		0.25	1211.10	21.16	29.03
				0.5	1203.56	21.02	28.74
				1	1188.60	20.76	28.16
				3	1130.64	19.75	25.92
				6	1048.94	18.32	22.77
				12	902.83	15.77	17.13
4	3	3		0.25	1211.10	76.05	77.10
				0.5	1203.56	75.57	76.81
				1	1188.60	74.63	76.23
				3	1130.64	70.99	74.00
				6	1048.94	65.86	70.84
				12	902.83	56.69	65.21
5	4	3		0.25	1211.10	60.68	56.96
				0.5	1203.56	60.30	56.67
				1	1188.60	59.55	56.10
				3	1130.64	56.65	53.86
				6	1048.94	52.56	50.71
				12	902.83	45.24	45.07

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	FLUX (lm) calculated with the TTE method	ILLUMINANCE (lux) calculated with the Luxplot method	ILLUMINANCE (lux) calculated with relationships included in Table 13
4	4	3	0.9	0.25	2331.67	134.55	122.74
				0.5	2320.62	133.91	122.32
				1	2298.67	132.64	121.47
				3	2212.96	127.7	118.18
				6	2090.35	120.62	113.46
				12	1432.97	107.63	104.80
4	4	5		0.25	2331.67	54.38	70.53
				0.5	2320.62	54.12	70.10
				1	2298.67	53.61	69.26
				3	2212.96	51.61	65.96
				6	2090.35	48.75	61.25
				12	1865.13	43.50	52.59
6	4	3		0.25	2331.67	102.90	98.31
				0.5	2320.62	102.41	97.89
				1	2298.67	101.44	97.05
				3	2212.96	97.66	93.75
				6	2090.35	92.25	89.04
				12	1865.13	82.31	80.38
7	4	3		0.25	2331.67	90.95	86.10
				0.5	2320.62	90.52	85.68
				1	2298.67	89.66	84.83
				3	2212.96	86.32	81.54
				6	2090.35	81.54	76.82
				12	1865.13	72.75	68.16
5	5	4		0.25	2331.67	74.28	56.41
				0.5	2320.62	73.93	55.98
				1	2298.67	73.23	55.14
				3	2212.96	70.50	51.84
				6	2090.35	66.59	47.13
				12	1865.13	59.42	38.47
6	6	2.5		0.25	2331.67	40.73	55.34
				0.5	2320.62	40.54	54.92
				1	2298.67	40.15	54.08
				3	2212.96	38.66	50.78
				6	2090.35	36.52	46.07
				12	1865.13	32.58	37.41
4	3	3		0.25	2331.67	146.41	150.75
				0.5	2320.62	145.71	150.33
				1	2298.67	144.33	149.49
				3	2212.96	138.95	146.19
				6	2090.35	131.25	141.48
				12	1865.13	117.11	132.82
5	4	3		0.25	2331.67	116.83	110.53
				0.5	2320.62	116.27	110.10
				1	2298.67	115.17	109.26
				3	2212.96	110.88	105.96
				6	2090.35	104.74	101.25
				12	1865.13	93.45	92.59


Comparative assessment of the Illuminance calculated with the Luxplot method and the eq. of (Table 14) (D=0.65)
Illuminance calcualted with equations in Table 14
Illuminance (lux) calculated with the Luxplot method
R² = 0.897
100.00
0.00
-10
10
30
50
70
90


Comparative assessment of the Illuminance calculated with the Luxplot method and the eq. of (Table 14) (D=0.90)
Illuminance calcualted with equations in Table 14
Illuminance (lux) calculated with the Luxplot method
R² = 0.8972
200.00
150.00
100.00
50.00
0.00
0
50
100
150
200

Appendix V

Illuminance values for various light pipes that resulted from simulations with IES VE pro software.
External illuminance: 5,000lux.

Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with eq. (36)
4	4	3		35.10	54.01
4	4	5		9.47	0.41
6	4	3		25.56	28.69
7	4	3		21.57	16.03
5	5	4		18.19	4.89
6	6	2.5		22.53	22.77
4	3	3		39.34	63.67
5	4	3	0.27	30.90	41.35
4	4	3		40.00	59.75
4	4	5		15.50	6.15
6	4	3		29.39	34.43
7	4	3		25.46	21.77
5	5	4		19.65	10.63
6	6	2.5		25.38	28.51
4	3	3		43.57	69.41
5	4	3	0.3	32.68	47.09
4	4	3		98.37	69.32
4	4	5		22.40	15.72
6	4	3		39.80	44.00
7	4	3		35.27	31.34
5	5	4		28.07	20.20
6	6	2.5		33.73	38.08
4	3	3		62.97	78.98
5	4	3	0.35	46.21	56.66
4	4	3		99.55	92.30
4	4	5		39.48	38.70
6	4	3		71.40	66.98
7	4	3		61.94	54.32
5	5	4		50.03	43.18
6	6	2.5		59.30	61.06
4	3	3		118.75	101.96
5	4	3	0.47	84.04	79.64
4	4	3		100.30	98.04
4	4	5		39.90	44.44
6	4	3		71.77	72.72
7	4	3		62.22	60.06
5	5	4		50.05	48.92
6	6	2.5		59.28	66.80
4	3	3		119.04	107.70
5	4	3	0.5	84.77	85.38
4	4	3		140.97	136.33
4	4	5		57.31	82.73
6	4	3		106.43	111.01
7	4	3		97.38	98.35
5	5	4		78.75	87.21
6	6	2.5		92.68	105.09
4	3	3		173.13	145.99
5	4	3	0.7	126.56	123.67

Illuminance values for various window areas that resulted from simulations with IES VE pro software. External illuminance: 5,000lux.

Room Length (m)	Room Width (m)	Room Height (m)	Window Area (m2)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with eq. (37)
			1	83.82	126.72
			2	137.00	173.97
			3	216.80	221.22
4	4	3	4	220.20	268.47
			1	80.24	104.70
			2	141.66	151.95
			3	220.84	199.20
4	4	5	4	263.92	246.45
			1	58.98	58.64
			2	100.42	105.89
			3	159.96	153.14
6	4	3	4	194.88	200.39
			1	51.43	24.60
			2	81.79	71.85
			3	130.25	119.10
7	4	3	4	135.86	166.35
			1	54.32	49.37
			2	90.16	96.62
			3	145.84	143.87
5	5	4	4	176.96	191.12
			1	38.04	-0.46
			2	64.40	46.79
			3	105.04	94.04
6	6	2.5	4	107.22	141.29
			1	114.30	159.02
			2	203.64	206.27
			3	308.92	253.52
4	3	3	4	364.64	300.77
			1	66.58	92.68
			2	114.78	139.93
			3	184.45	187.18
5	4	3	4	245.12	234.43

Appendix VI

Results of the simulations and of the algorithms produced by the simulations (Table 17) for the calculation of the average illuminance E_{pipe} on the reference plane. Each table of results is followed by the respective graph giving the correlation of the illuminance calculated with the two methods.

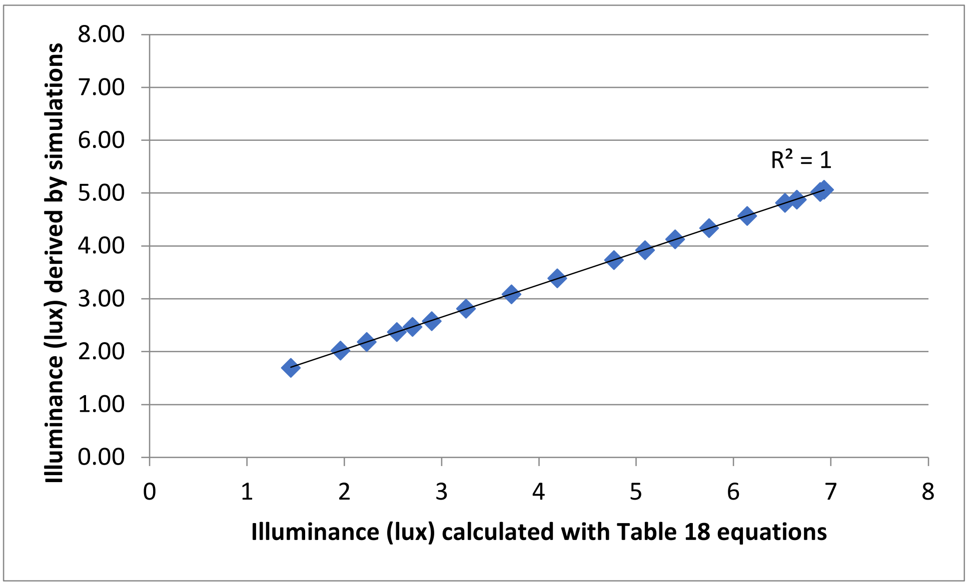
Room surface reflectances (%): Walls/Ceiling/Floor-Reference Plane=50/70/30

Reference plane: 0.85m above the floor and 0.50m offset from the walls

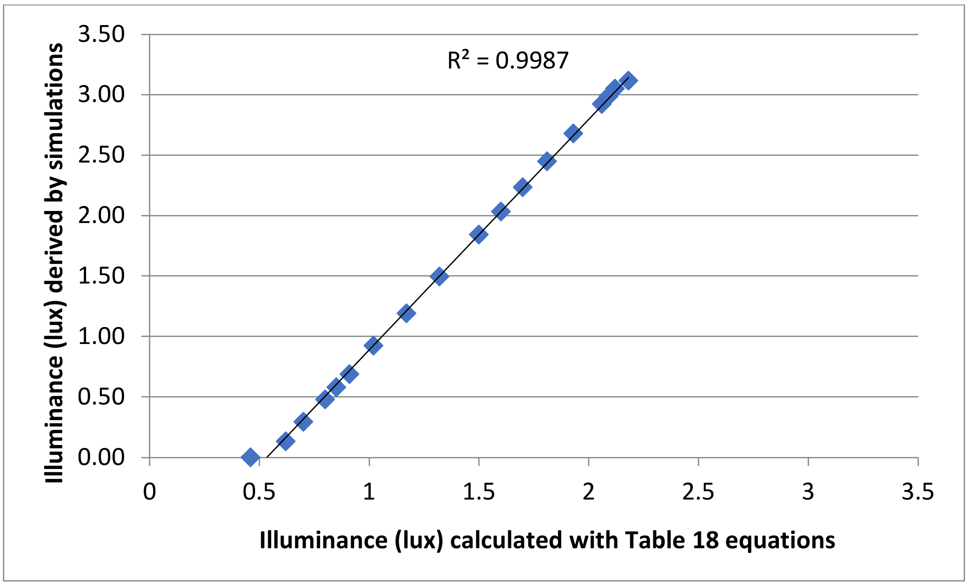
$\tau_{dome} \times \tau_{dif}$=0.82, ρ_{pipe}=0.98, MF=0.9

E_{ex}=5,000lux

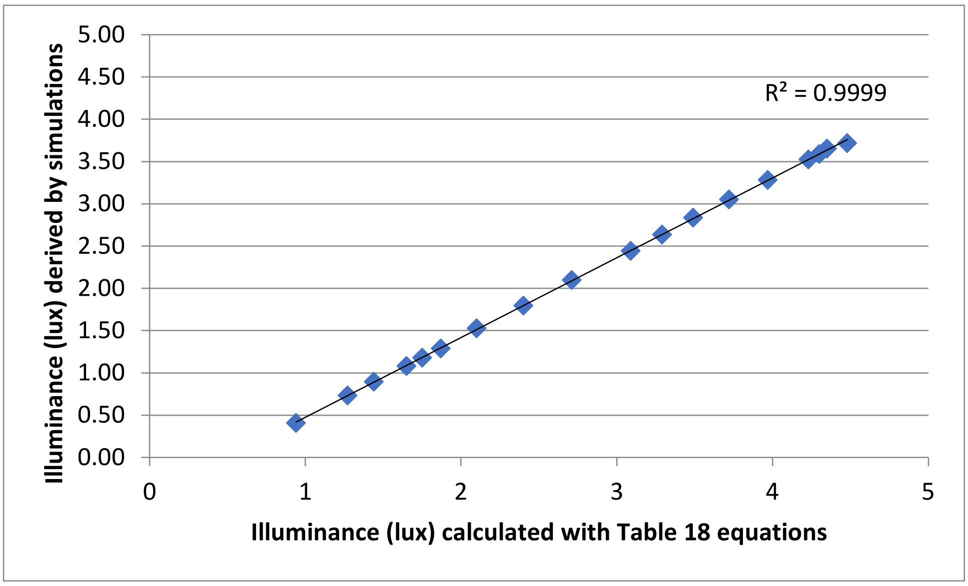
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
4	4	3	0.25	0.25	6.93	5.07
				0.5	6.89	5.03
				0.75	6.65	4.88
				1	6.53	4.82
				2	6.14	4.57
				3	5.75	4.35
				4	5.4	4.13
				5	5.09	3.93
				6	4.77	3.74
				8	4.19	3.39
				10	3.72	3.09
				12	3.25	2.82
				14	2.9	2.58
				15	2.7	2.48
				16	2.54	2.37
				18	2.23	2.19
				20	1.96	2.03
				25	1.45	1.70



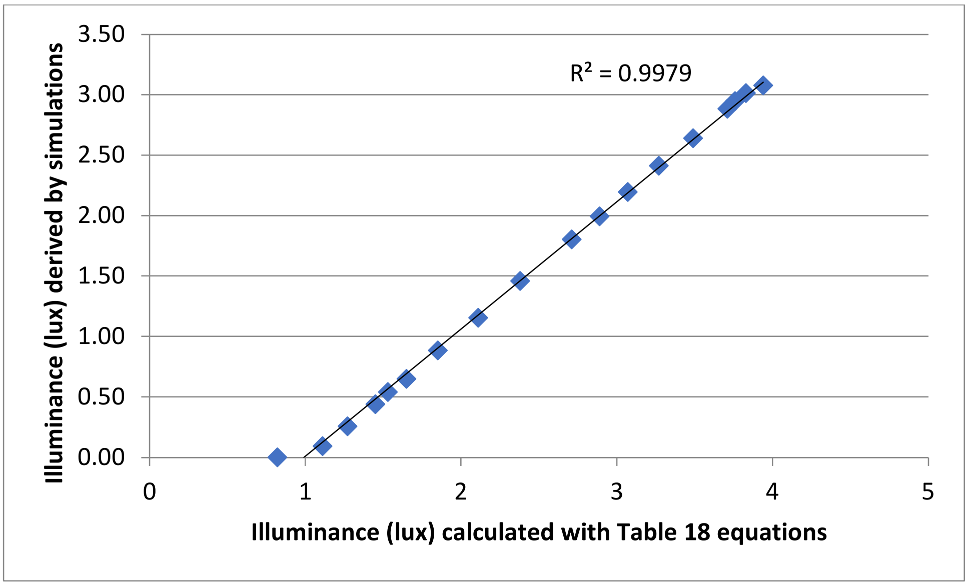
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
4	4	5	0.25	0.25	2.18	3.12
				0.5	2.12	3.05
				0.75	2.09	2.99
				1	2.06	2.92
				2	1.93	2.68
				3	1.81	2.45
				4	1.7	2.23
				5	1.6	2.03
				6	1.5	1.84
				8	1.32	1.50
				10	1.17	1.19
				12	1.02	0.92
				14	0.91	0.69
				15	0.85	0.58
				16	0.8	0.48
				18	0.7	0.29
				20	0.62	0.13
				25	0.46	0.00



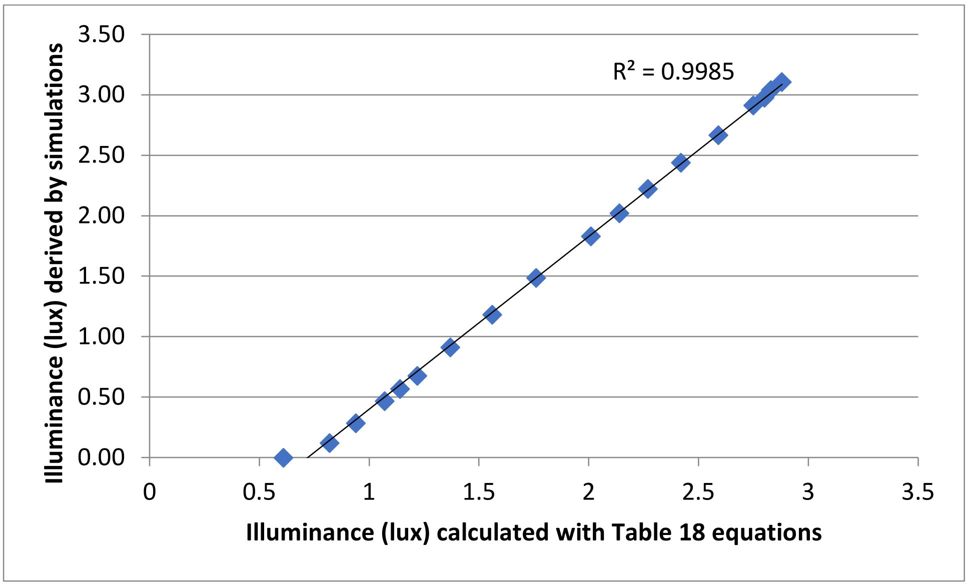
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
6	4	3	0.25	0.25	4.48	3.72
				0.5	4.35	3.66
				0.75	4.3	3.59
				1	4.23	3.53
				2	3.97	3.29
				3	3.72	3.06
				4	3.49	2.84
				5	3.29	2.64
				6	3.09	2.45
				8	2.71	2.10
				10	2.4	1.80
				12	2.1	1.53
				14	1.87	1.29
				15	1.75	1.19
				16	1.65	1.08
				18	1.44	0.90
				20	1.27	0.74
				25	0.94	0.41



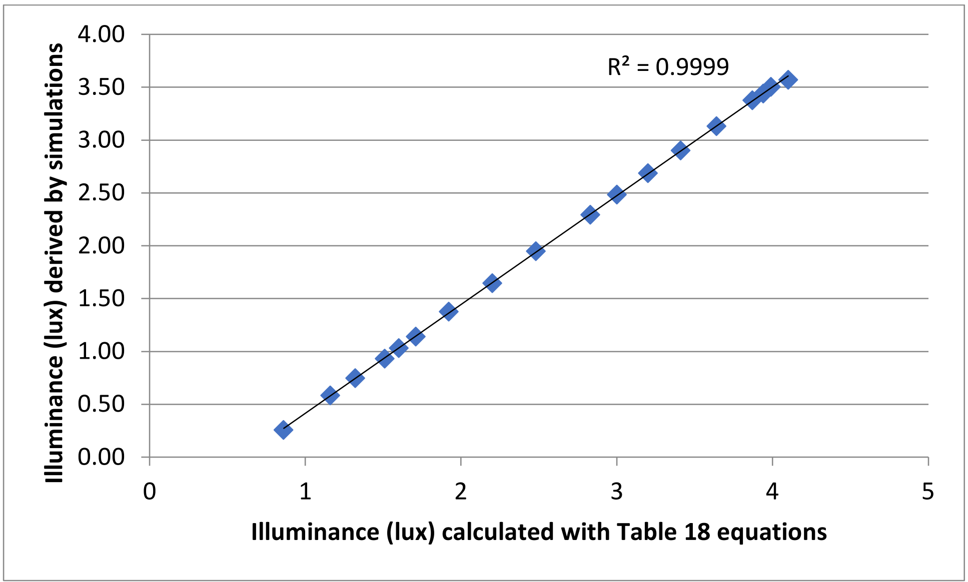
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
7	4	3	0.25	0.25	3.94	3.08
				0.5	3.83	3.01
				0.75	3.76	2.95
				1	3.71	2.88
				2	3.49	2.64
				3	3.27	2.41
				4	3.07	2.20
				5	2.89	1.99
				6	2.71	1.80
				8	2.38	1.46
				10	2.11	1.15
				12	1.85	0.89
				14	1.65	0.65
				15	1.53	0.54
				16	1.45	0.44
				18	1.27	0.26
				20	1.11	0.09
				25	0.82	0



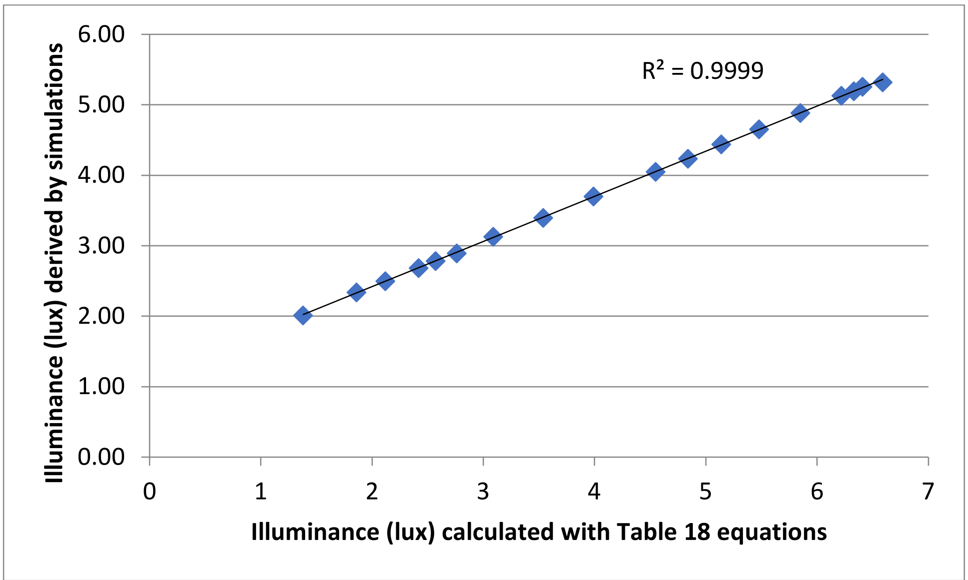
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
5	5	4	0.25	0.25	2.88	3.11
				0.5	2.83	3.04
				0.75	2.8	2.98
				1	2.75	2.91
				2	2.59	2.67
				3	2.42	2.44
				4	2.27	2.23
				5	2.14	2.02
				6	2.01	1.83
				8	1.76	1.49
				10	1.56	1.18
				12	1.37	0.91
				14	1.22	0.68
				15	1.14	0.57
				16	1.07	0.47
				18	0.94	0.29
				20	0.82	0.12
				25	0.61	0



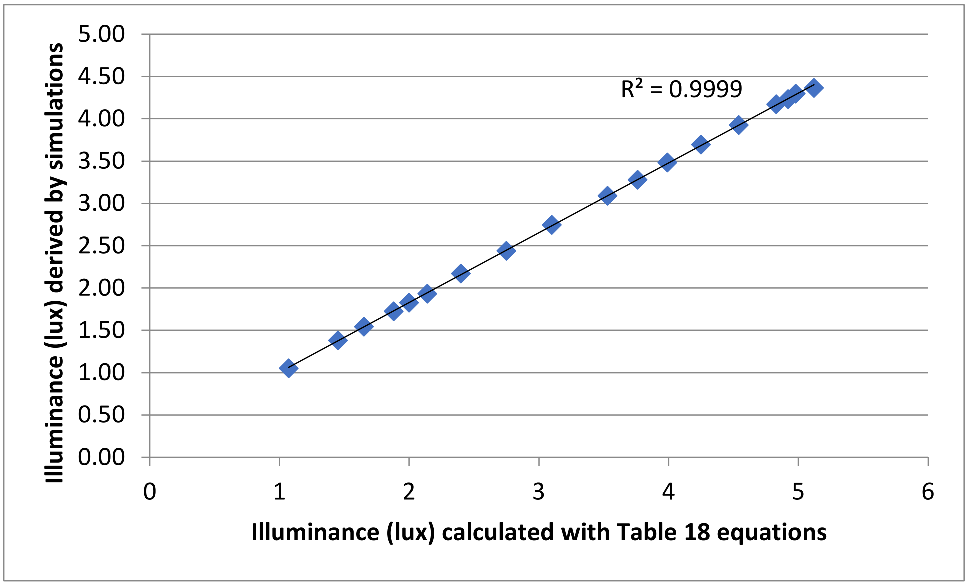
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
6	6	2.5	0.25	0.25	4.1	3.57
				0.5	3.99	3.51
				0.75	3.94	3.44
				1	3.87	3.38
				2	3.64	3.13
				3	3.41	2.91
				4	3.2	2.69
				5	3	2.49
				6	2.83	2.30
				8	2.48	1.95
				10	2.2	1.65
				12	1.92	1.38
				14	1.71	1.14
				15	1.6	1.04
				16	1.51	0.93
				18	1.32	0.75
				20	1.16	0.59
				25	0.86	0.26



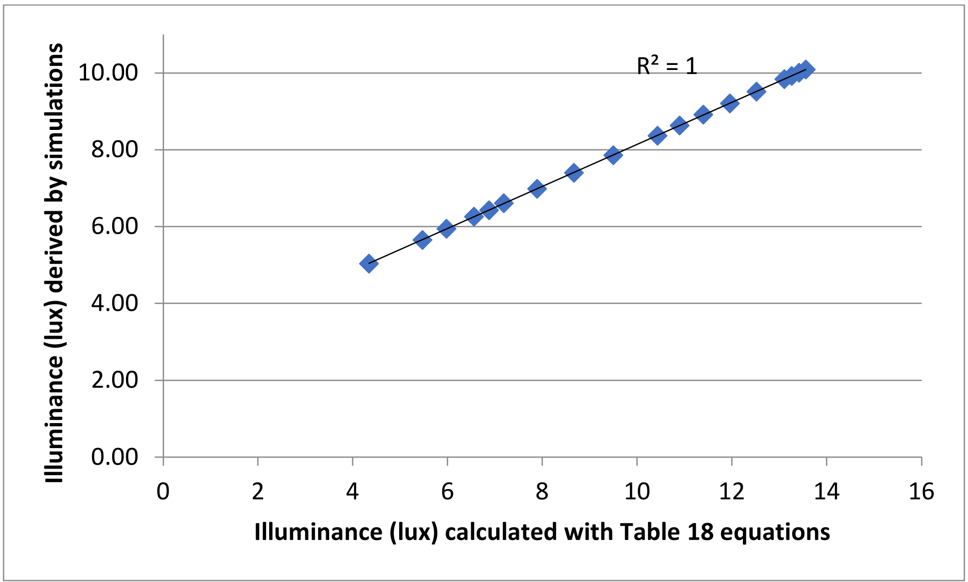
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
4	3	3	0.25	0.25	6.59	5.32
				0.5	6.41	5.26
				0.75	6.33	5.19
				1	6.22	5.13
				2	5.85	4.89
				3	5.48	4.66
				4	5.14	4.44
				5	4.84	4.24
				6	4.55	4.05
				8	3.99	3.71
				10	3.54	3.40
				12	3.09	3.13
				14	2.76	2.90
				15	2.57	2.79
				16	2.42	2.69
				18	2.12	2.50
				20	1.86	2.34
				25	1.38	2.01



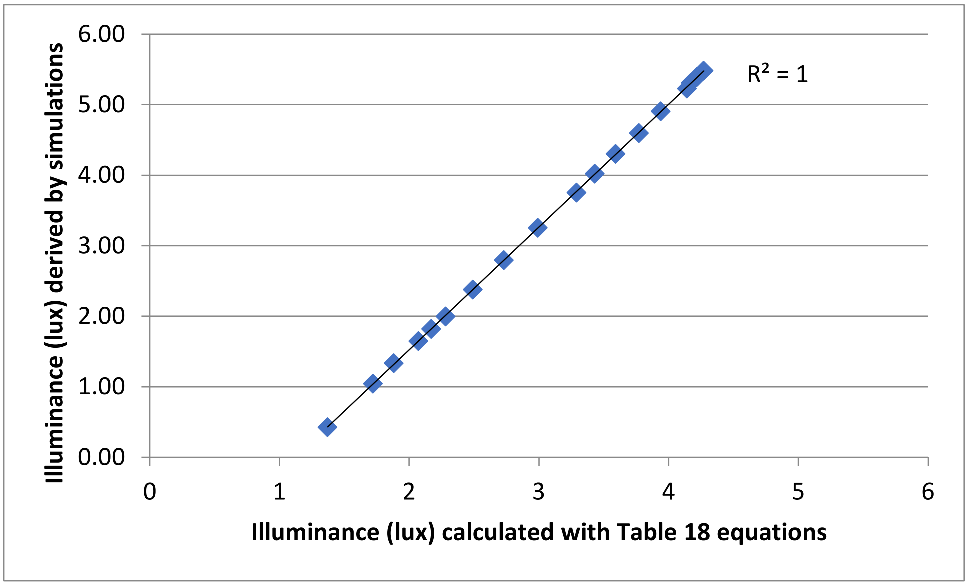
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
5	4	3	0.25	0.25	5.12	4.37
				0.5	4.98	4.30
				0.75	4.92	4.24
				1	4.83	4.17
				2	4.54	3.93
				3	4.25	3.70
				4	3.99	3.49
				5	3.76	3.28
				6	3.53	3.09
				8	3.1	2.75
				10	2.75	2.44
				12	2.4	2.17
				14	2.14	1.94
				15	2	1.83
				16	1.88	1.73
				18	1.65	1.55
				20	1.45	1.38
				25	1.07	1.06



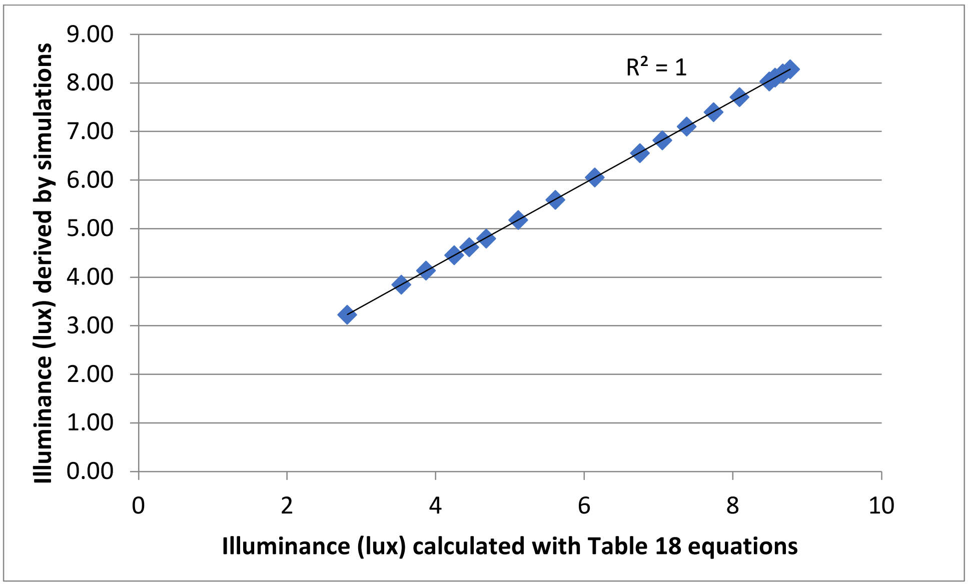
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
4	4	3	0.35	0.25	13.56	10.10
				0.5	13.42	10.01
				0.75	13.26	9.93
				1	13.11	9.84
				2	12.52	9.52
				3	11.96	9.21
				4	11.4	8.92
				5	10.9	8.64
				6	10.43	8.37
				8	9.5	7.87
				10	8.67	7.41
				12	7.89	6.99
				14	7.19	6.61
				15	6.88	6.43
				16	6.56	6.26
				18	5.98	5.95
				20	5.47	5.66
				25	4.34	5.04



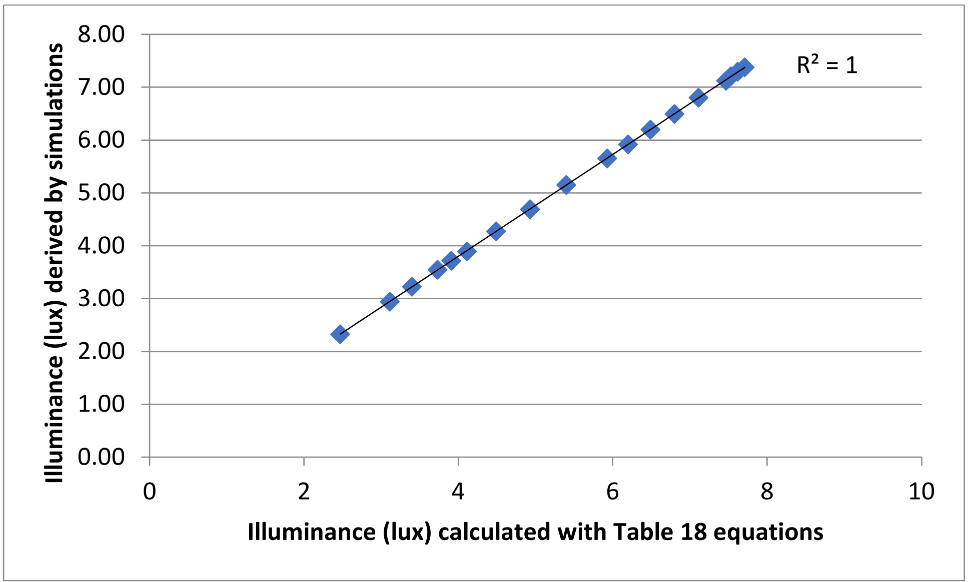
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
4	4	5	0.35	0.25	4.27	5.49
				0.5	4.22	5.40
				0.75	4.17	5.32
				1	4.14	5.23
				2	3.94	4.91
				3	3.77	4.60
				4	3.59	4.31
				5	3.43	4.03
				6	3.29	3.76
				8	2.99	3.26
				10	2.73	2.80
				12	2.49	2.38
				14	2.28	2.00
				15	2.17	1.82
				16	2.07	1.65
				18	1.88	1.34
				20	1.72	1.05
				25	1.37	0.43



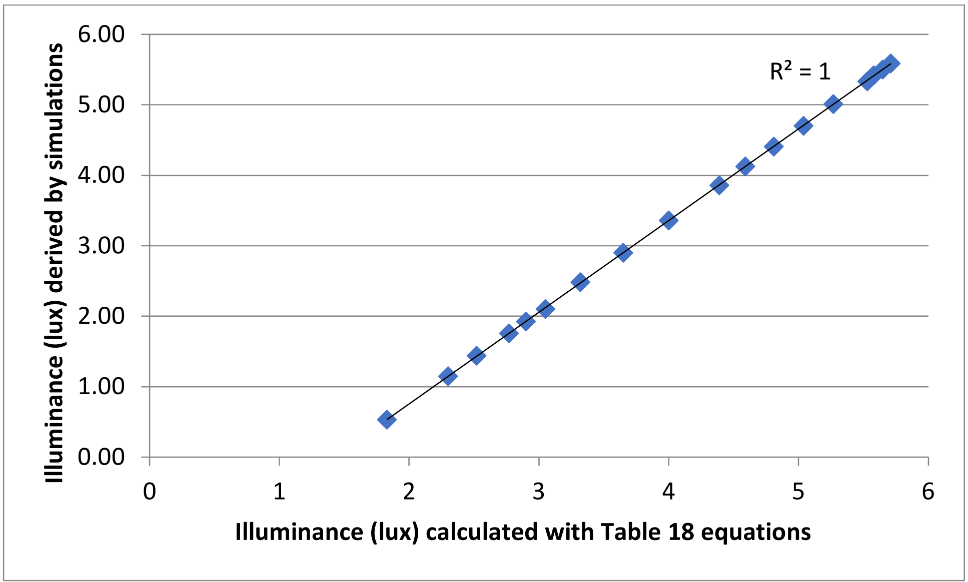
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
6	4	3	0.35	0.25	8.77	8.29
				0.5	8.67	8.20
				0.75	8.57	8.12
				1	8.49	8.04
				2	8.09	7.71
				3	7.74	7.40
				4	7.38	7.11
				5	7.05	6.83
				6	6.75	6.56
				8	6.14	6.06
				10	5.61	5.60
				12	5.11	5.18
				14	4.68	4.80
				15	4.45	4.63
				16	4.25	4.46
				18	3.87	4.14
				20	3.54	3.85
				25	2.81	3.23



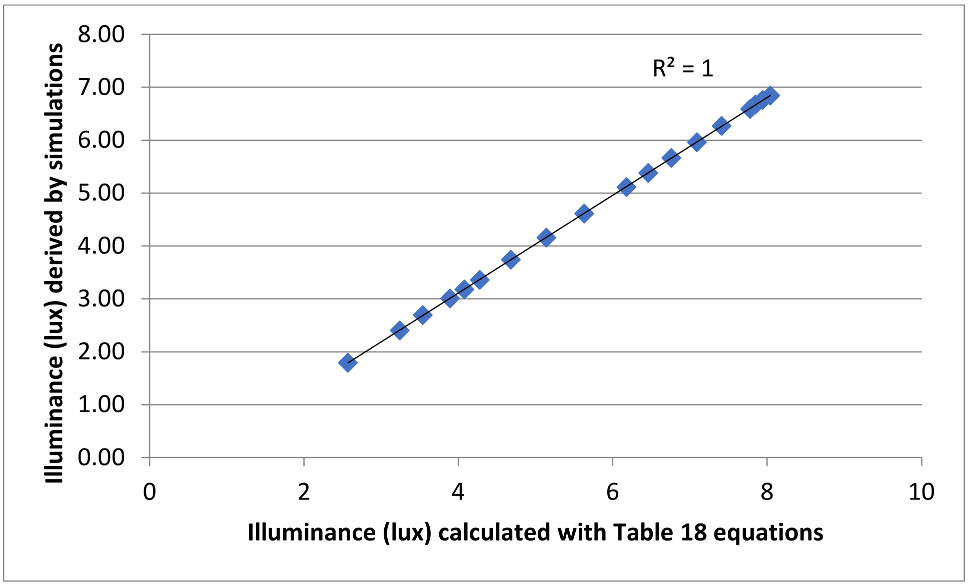
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
7	4	3	0.35	0.25	7.71	7.38
				0.5	7.62	7.30
				0.75	7.53	7.21
				1	7.47	7.13
				2	7.11	6.81
				3	6.8	6.50
				4	6.49	6.21
				5	6.2	5.92
				6	5.93	5.66
				8	5.4	5.15
				10	4.93	4.70
				12	4.49	4.28
				14	4.11	3.90
				15	3.91	3.72
				16	3.73	3.55
				18	3.4	3.23
				20	3.11	2.95
				25	2.47	2.33



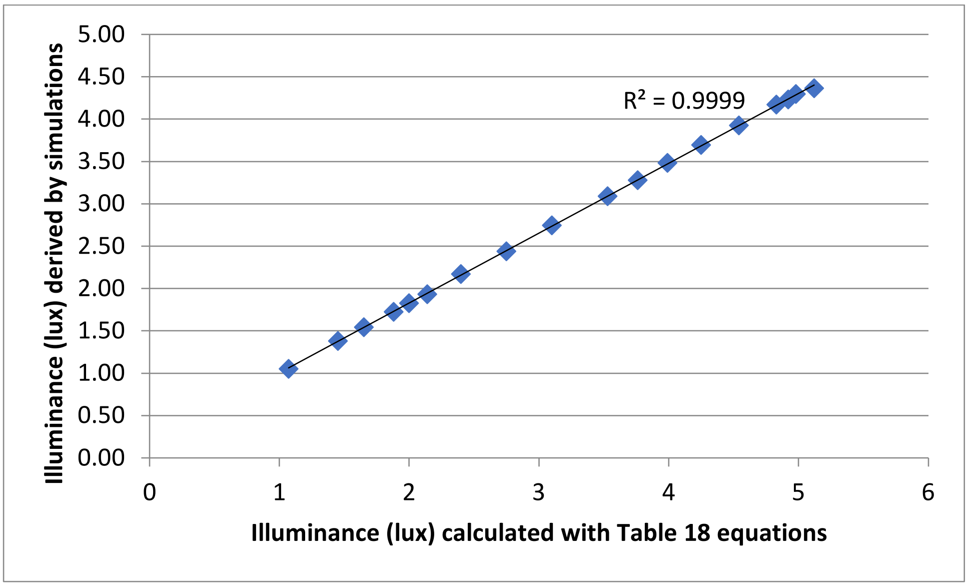
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
5	5	4	0.35	0.25	5.71	5.59
				0.5	5.65	5.51
				0.75	5.58	5.42
				1	5.53	5.34
				2	5.27	5.02
				3	5.04	4.71
				4	4.81	4.41
				5	4.59	4.13
				6	4.39	3.86
				8	4	3.36
				10	3.65	2.90
				12	3.32	2.49
				14	3.05	2.11
				15	2.9	1.93
				16	2.77	1.76
				18	2.52	1.44
				20	2.3	1.15
				25	1.83	0.54



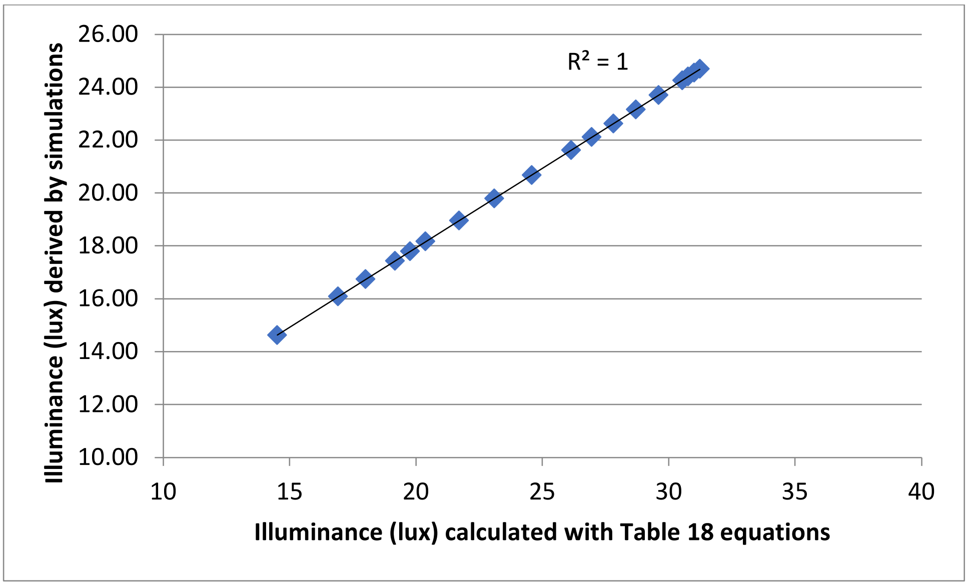
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
6	6	2.5	0.35	0.25	8.04	6.85
				0.5	7.94	6.76
				0.75	7.85	6.68
				1	7.78	6.60
				2	7.41	6.27
				3	7.09	5.96
				4	6.76	5.67
				5	6.46	5.39
				6	6.18	5.12
				8	5.63	4.62
				10	5.14	4.16
				12	4.68	3.74
				14	4.28	3.36
				15	4.08	3.19
				16	3.89	3.02
				18	3.54	2.70
				20	3.24	2.41
				25	2.57	1.79



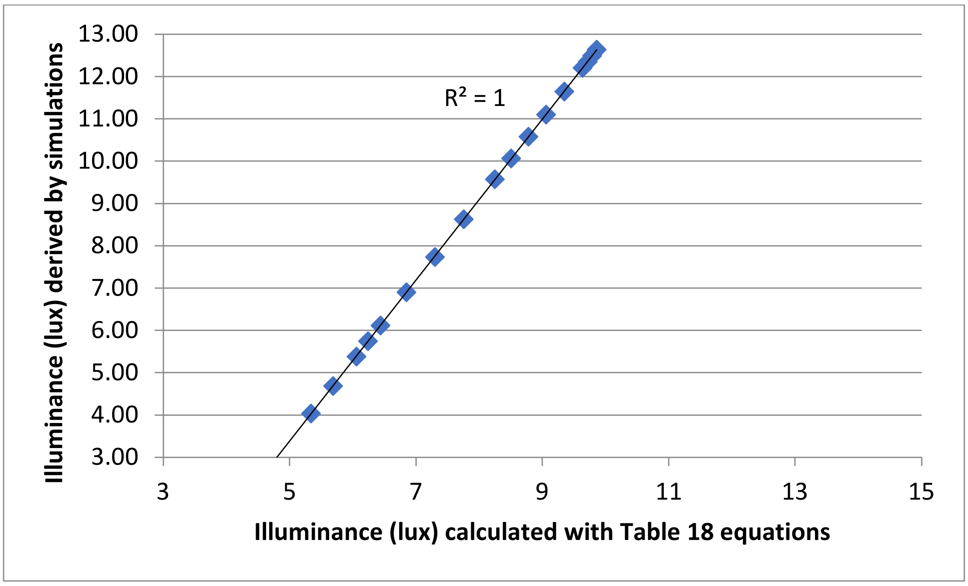
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
5	4	3	0.35	0.25	5.12	4.37
				0.5	4.98	4.30
				0.75	4.92	4.24
				1	4.83	4.17
				2	4.54	3.93
				3	4.25	3.70
				4	3.99	3.49
				5	3.76	3.28
				6	3.53	3.09
				8	3.1	2.75
				10	2.75	2.44
				12	2.4	2.17
				14	2.14	1.94
				15	2	1.83
				16	1.88	1.73
				18	1.65	1.55
				20	1.45	1.38
				25	1.07	1.06



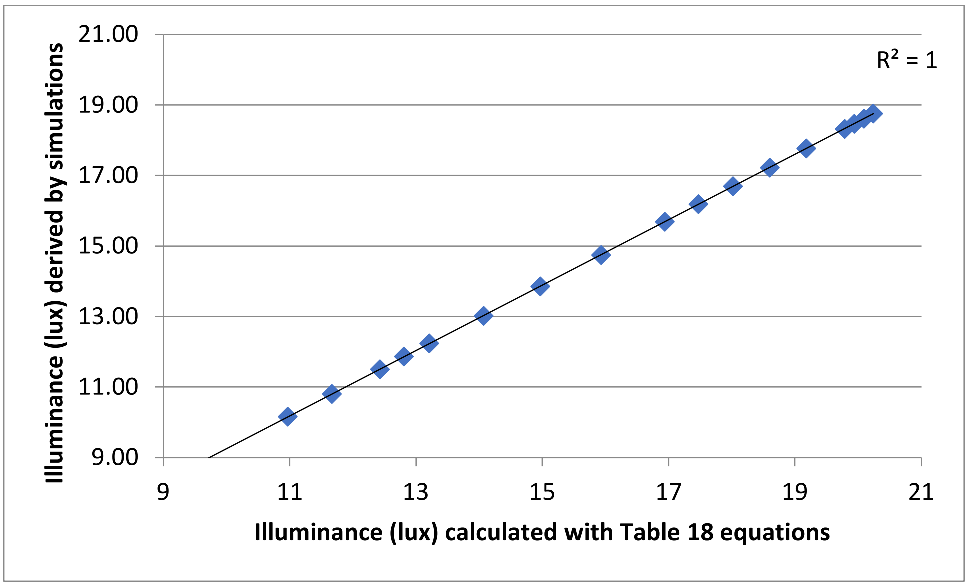
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
4	4	3	0.53	0.25	31.23	24.69
				0.5	31	24.55
				0.75	30.76	24.40
				1	30.53	24.26
				2	29.6	23.70
				3	28.7	23.16
				4	27.81	22.63
				5	26.95	22.12
				6	26.14	21.62
				8	24.58	20.68
				10	23.1	19.79
				12	21.7	18.96
				14	20.38	18.17
				15	19.76	17.80
				16	19.17	17.44
				18	18	16.74
				20	16.92	16.09
				25	14.51	14.63



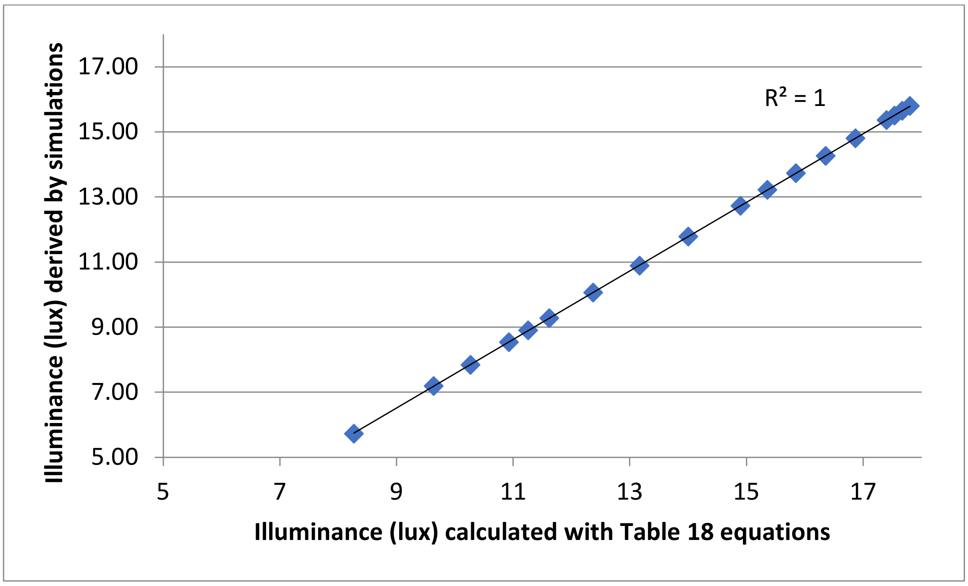
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
4	4	5	0.53	0.25	9.86	12.64
				0.5	9.79	12.50
				0.75	9.72	12.36
				1	9.64	12.21
				2	9.35	11.65
				3	9.06	11.11
				4	8.78	10.58
				5	8.51	10.07
				6	8.25	9.58
				8	7.76	8.63
				10	7.3	7.74
				12	6.85	6.91
				14	6.44	6.13
				15	6.24	5.75
				16	6.06	5.39
				18	5.69	4.70
				20	5.34	4.04
				25	4.58	2.58



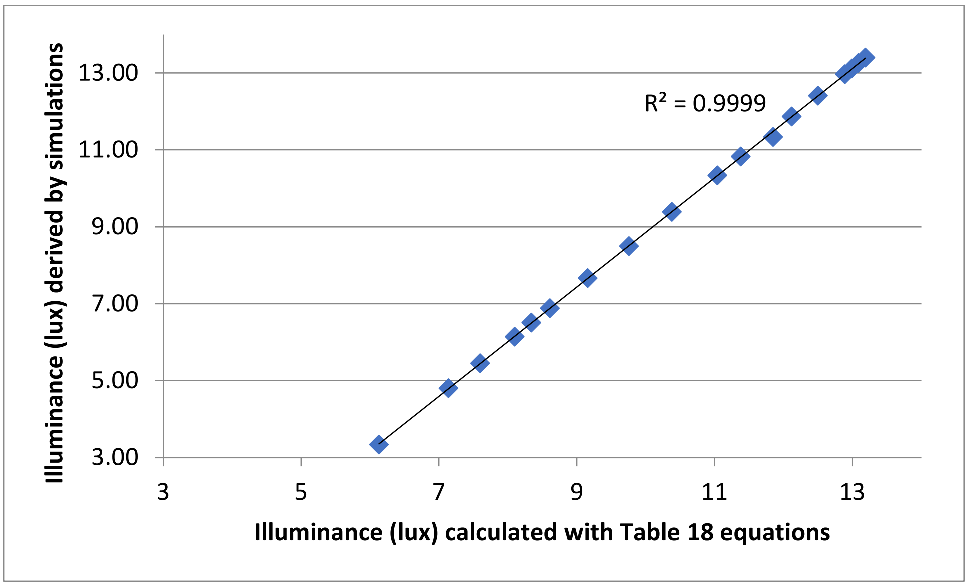
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
6	4	3	0.53	0.25	20.24	18.77
				0.5	20.09	18.62
				0.75	19.94	18.48
				1	19.79	18.33
				2	19.18	17.77
				3	18.6	17.23
				4	18.02	16.70
				5	17.47	16.19
				6	16.94	15.70
				8	15.93	14.75
				10	14.97	13.87
				12	14.07	13.03
				14	13.21	12.25
				15	12.81	11.87
				16	12.43	11.51
				18	11.67	10.82
				20	10.97	10.16
				25	9.4	8.70



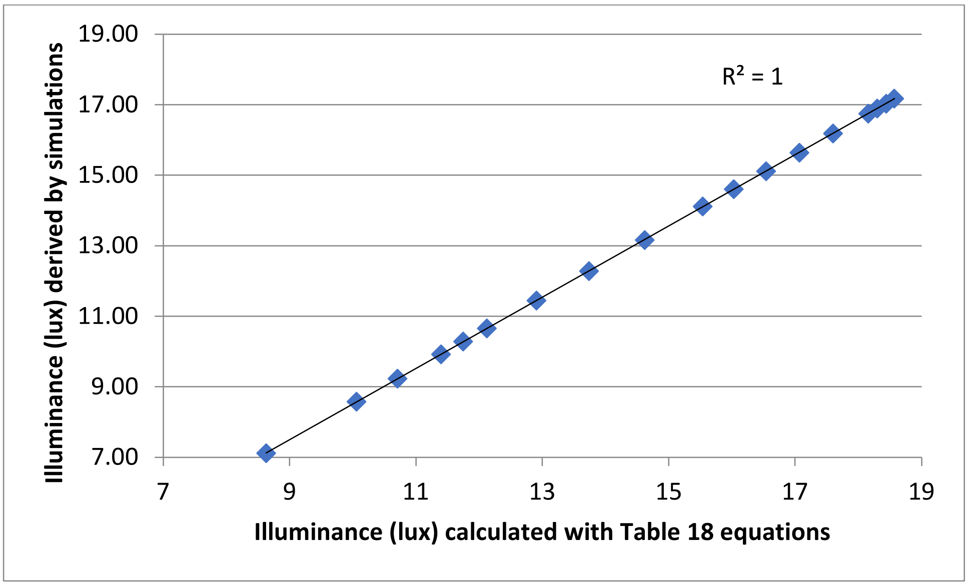
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
7	4	3	0.53	0.25	17.8	15.80
				0.5	17.67	15.66
				0.75	17.54	15.51
				1	17.4	15.37
				2	16.87	14.81
				3	16.36	14.27
				4	15.85	13.74
				5	15.36	13.23
				6	14.9	12.74
				8	14	11.79
				10	13.17	10.90
				12	12.37	10.07
				14	11.62	9.28
				15	11.26	8.91
				16	10.93	8.55
				18	10.27	7.85
				20	9.64	7.20
				25	8.27	5.74



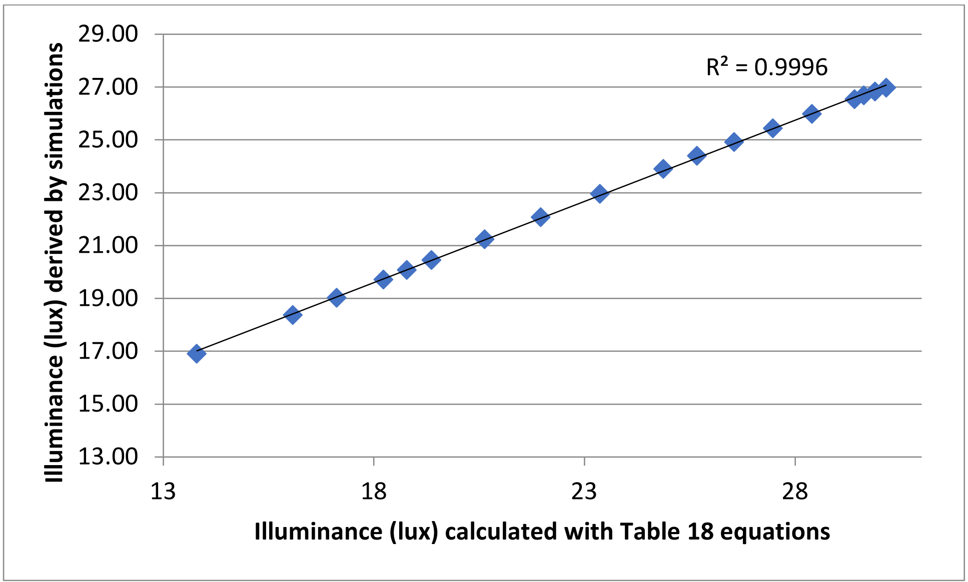
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
5	5	4	0.53	0.25	13.19	13.41
				0.5	13.09	13.26
				0.75	12.99	13.12
				1	12.89	12.98
				2	12.5	12.42
				3	12.12	11.87
				4	11.85	11.35
				5	11.38	10.84
				6	11.04	10.34
				8	10.38	9.40
				10	9.76	8.51
				12	9.16	7.68
				14	8.61	6.89
				15	8.34	6.52
				16	8.1	6.15
				18	7.6	5.46
				20	7.14	4.81
				25	6.13	3.35



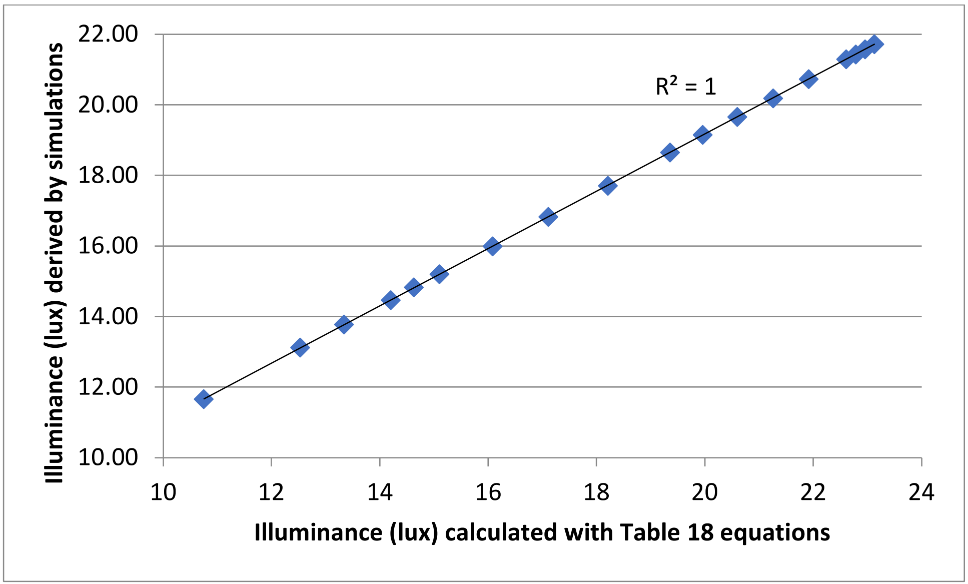
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
6	6	2.5	0.53	0.25	18.57	17.19
				0.5	18.44	17.04
				0.75	18.3	16.90
				1	18.16	16.75
				2	17.6	16.19
				3	17.07	15.65
				4	16.54	15.12
				5	16.03	14.61
				6	15.54	14.12
				8	14.62	13.17
				10	13.74	12.29
				12	12.91	11.45
				14	12.12	10.67
				15	11.75	10.29
				16	11.4	9.93
				18	10.71	9.24
				20	10.06	8.59
				25	8.63	7.12



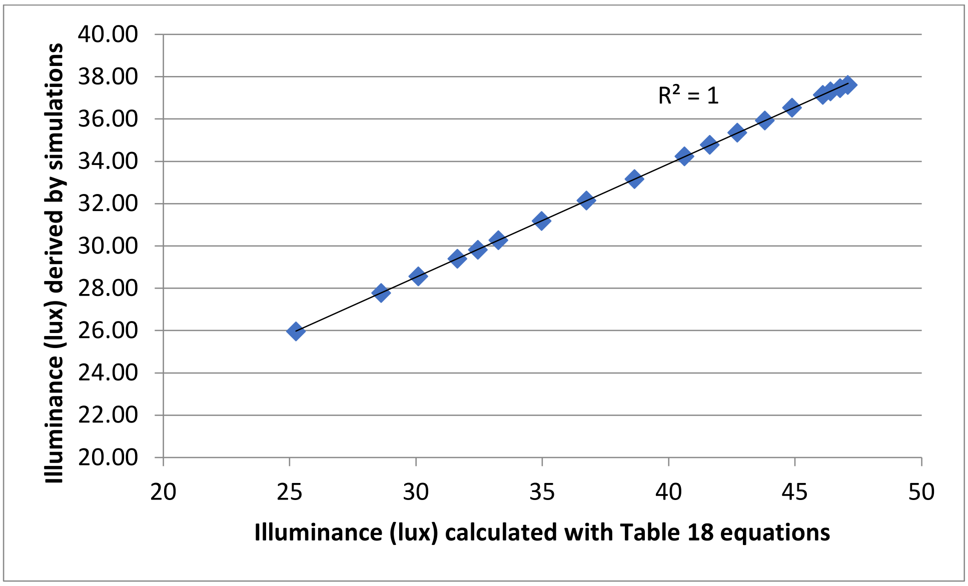
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
4	3	3	0.53	0.25	30.16	26.99
				0.5	29.9	26.84
				0.75	29.63	26.70
				1	29.41	26.56
				2	28.4	26.00
				3	27.47	25.45
				4	26.55	24.93
				5	25.67	24.42
				6	24.87	23.92
				8	23.37	22.98
				10	21.96	22.09
				12	20.63	21.25
				14	19.37	20.47
				15	18.78	20.09
				16	18.23	19.73
				18	17.12	19.04
				20	16.08	18.39
				25	13.8	16.92



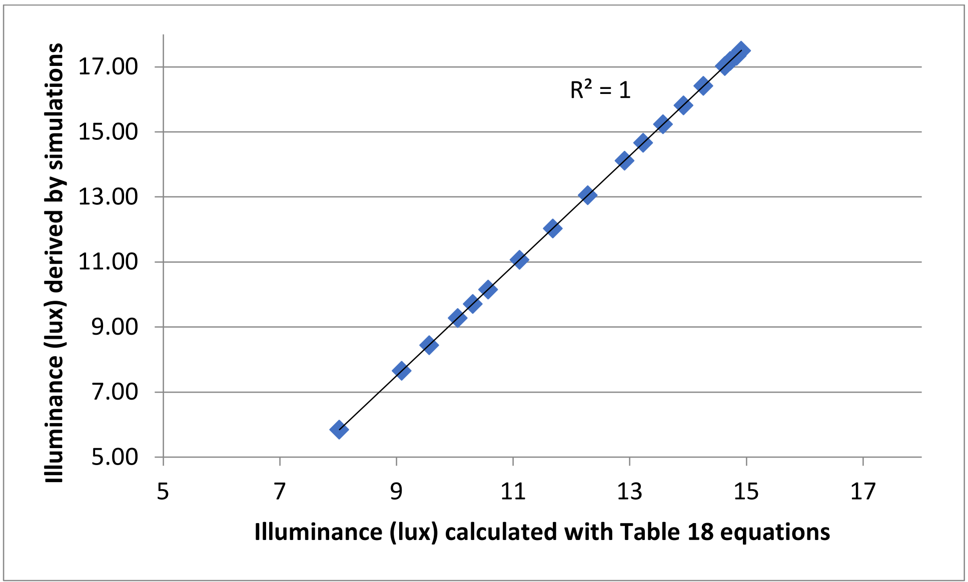
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
5	4	3	0.53	0.25	23.13	21.73
				0.5	22.96	21.58
				0.75	22.79	21.44
				1	22.61	21.30
				2	21.92	20.74
				3	21.26	20.19
				4	20.6	19.67
				5	19.96	19.16
				6	19.36	18.66
				8	18.21	17.72
				10	17.11	16.83
				12	16.08	15.99
				14	15.1	15.21
				15	14.63	14.84
				16	14.2	14.47
				18	13.34	13.78
				20	12.53	13.13
				25	10.75	11.67



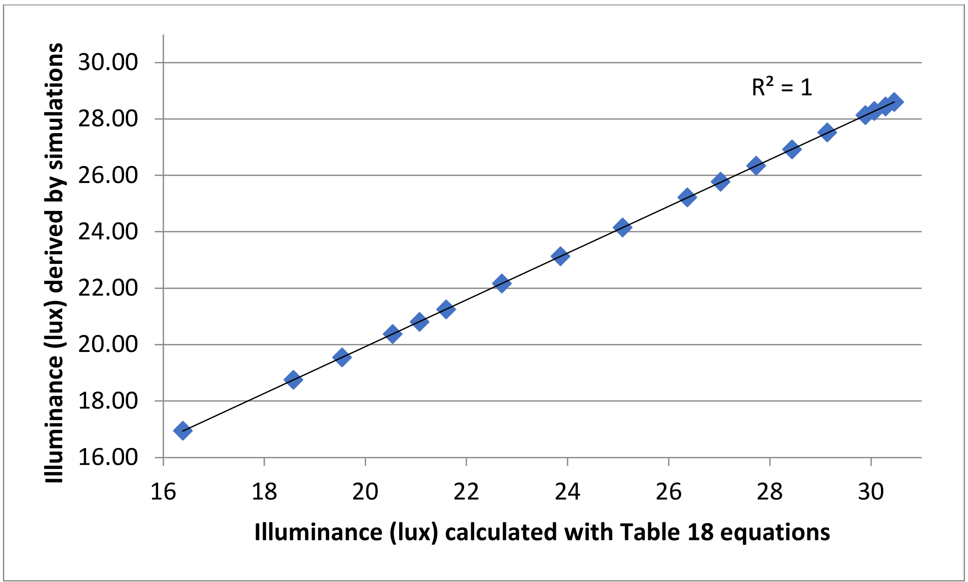
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
4	4	3	0.65	0.25	47.09	37.63
				0.5	46.78	37.47
				0.75	46.4	37.32
				1	46.1	37.16
				2	44.88	36.55
				3	43.8	35.95
				4	42.71	35.37
				5	41.63	34.80
				6	40.62	34.25
				8	38.65	33.18
				10	36.75	32.17
				12	34.97	31.20
				14	33.26	30.28
				15	32.45	29.84
				16	31.64	29.41
				18	30.09	28.58
				20	28.62	27.79
				25	25.25	25.97



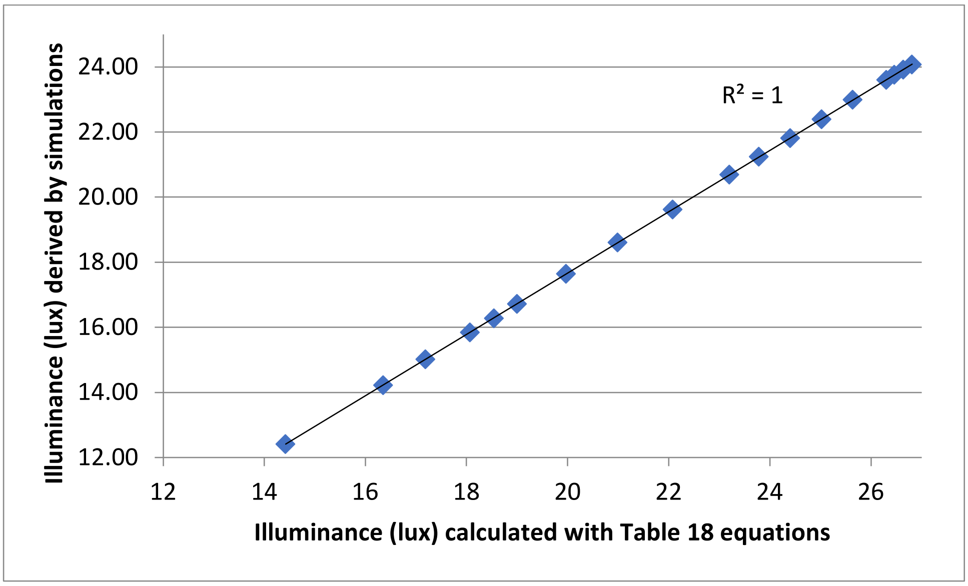
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
4	4	5	0.65	0.25	14.91	17.51
				0.5	14.83	17.35
				0.75	14.72	17.20
				1	14.63	17.04
				2	14.26	16.43
				3	13.92	15.83
				4	13.57	15.25
				5	13.23	14.68
				6	12.91	14.13
				8	12.28	13.06
				10	11.68	12.04
				12	11.11	11.08
				14	10.57	10.16
				15	10.31	9.72
				16	10.05	9.29
				18	9.56	8.45
				20	9.09	7.66
				25	8.02	5.85



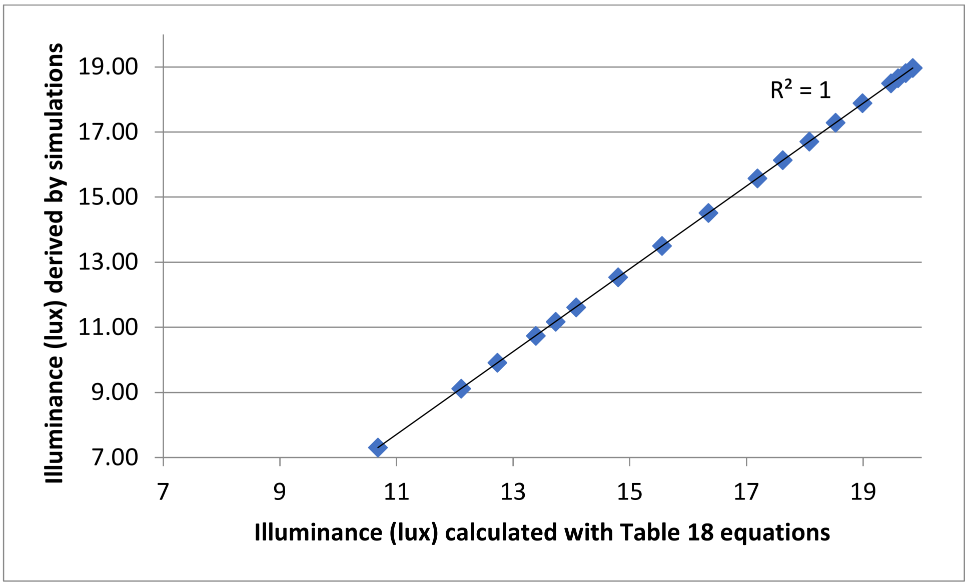
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
6	4	3	0.65	0.25	30.46	28.60
				0.5	30.29	28.44
				0.75	30.07	28.28
				1	29.89	28.13
				2	29.14	27.52
				3	28.44	26.92
				4	27.73	26.34
				5	27.03	25.77
				6	26.37	25.22
				8	25.09	24.15
				10	23.86	23.13
				12	22.7	22.17
				14	21.6	21.25
				15	21.07	20.81
				16	20.54	20.37
				18	19.54	19.54
				20	18.58	18.75
				25	16.39	16.94



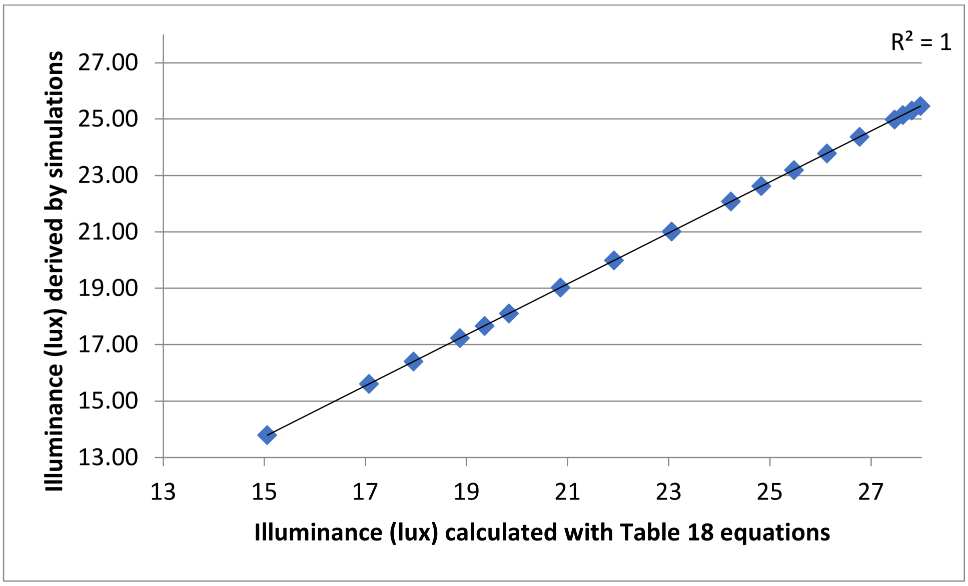
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
7	4	3	0.65	0.25	26.81	24.08
				0.5	26.64	23.92
				0.75	26.46	23.77
				1	26.3	23.61
				2	25.64	23.00
				3	25.02	22.40
				4	24.4	21.82
				5	23.78	21.25
				6	23.2	20.70
				8	22.08	19.63
				10	20.99	18.62
				12	19.97	17.65
				14	19	16.73
				15	18.54	16.29
				16	18.07	15.86
				18	17.19	15.03
				20	16.35	14.24
				25	14.42	12.42



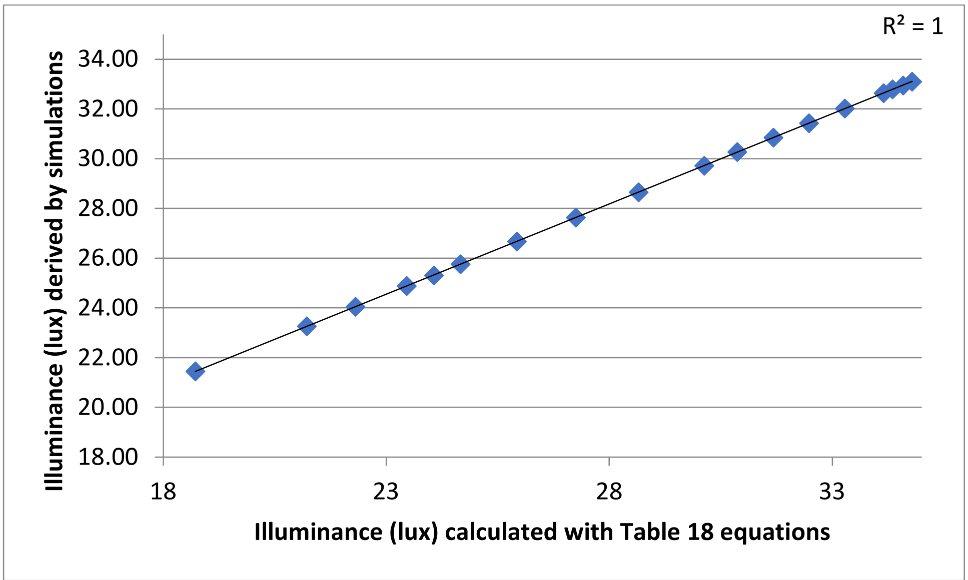
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
5	5	4	0.65	0.25	19.85	18.97
				0.5	19.73	18.82
				0.75	19.6	18.66
				1	19.48	18.50
				2	18.99	17.89
				3	18.53	17.29
				4	18.08	16.71
				5	17.62	16.14
				6	17.19	15.59
				8	16.35	14.52
				10	15.55	13.51
				12	14.8	12.54
				14	14.08	11.62
				15	13.73	11.18
				16	13.39	10.75
				18	12.73	9.92
				20	12.11	9.13
				25	10.68	7.32



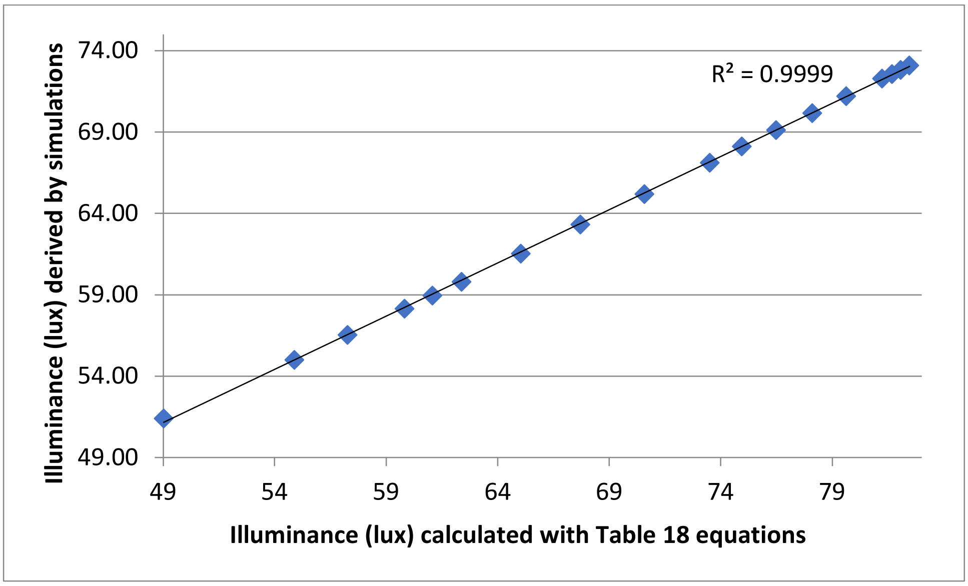
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
6	6	2.5	0.65	0.25	27.98	25.47
				0.5	27.81	25.31
				0.75	27.63	25.15
				1	27.47	25.00
				2	26.78	24.39
				3	26.13	23.79
				4	25.48	23.21
				5	24.83	22.64
				6	24.23	22.08
				8	23.06	21.02
				10	21.92	20.00
				12	20.86	19.04
				14	19.84	18.12
				15	19.36	17.67
				16	18.87	17.24
				18	17.95	16.41
				20	17.07	15.62
				25	15.06	13.81



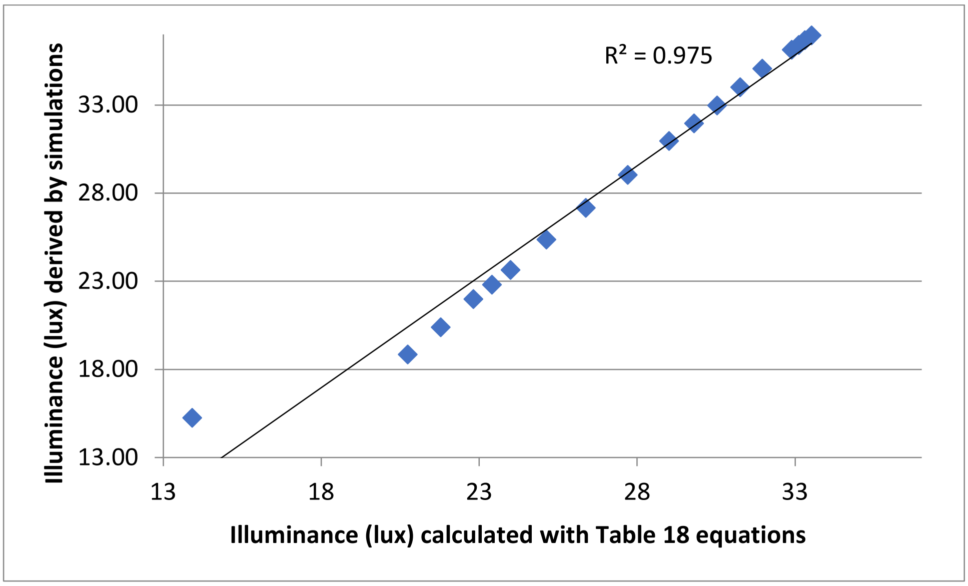
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
5	4	3	0.65	0.25	34.79	33.11
				0.5	34.59	32.96
				0.75	34.35	32.80
				1	34.15	32.65
				2	33.28	32.03
				3	32.48	31.44
				4	31.68	30.85
				5	30.87	30.29
				6	30.13	29.73
				8	28.66	28.66
				10	27.25	27.65
				12	25.93	26.68
				14	24.67	25.77
				15	24.07	25.32
				16	23.46	24.89
				18	22.31	24.06
				20	21.22	23.27
				25	18.72	21.46



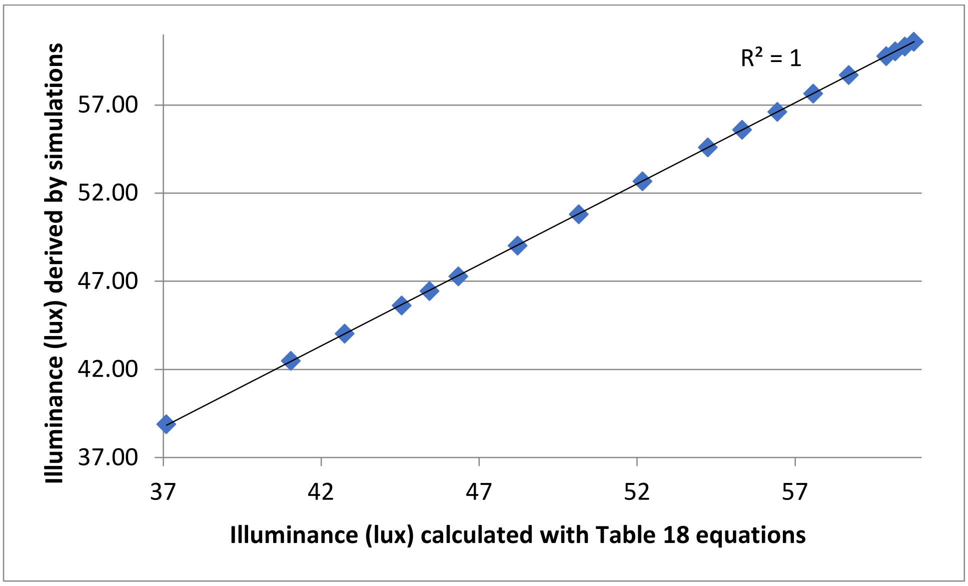
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
4	4	3	0.9	0.25	82.46	73.12
				0.5	82.07	72.85
				0.75	81.68	72.57
				1	81.23	72.30
				2	79.63	71.23
				3	78.1	70.18
				4	76.48	69.14
				5	74.94	68.13
				6	73.51	67.13
				8	70.58	65.20
				10	67.7	63.34
				12	65.03	61.54
				14	62.38	59.82
				15	61.07	58.98
				16	59.83	58.16
				18	57.27	56.56
				20	54.89	55.02
				25	49.02	51.42



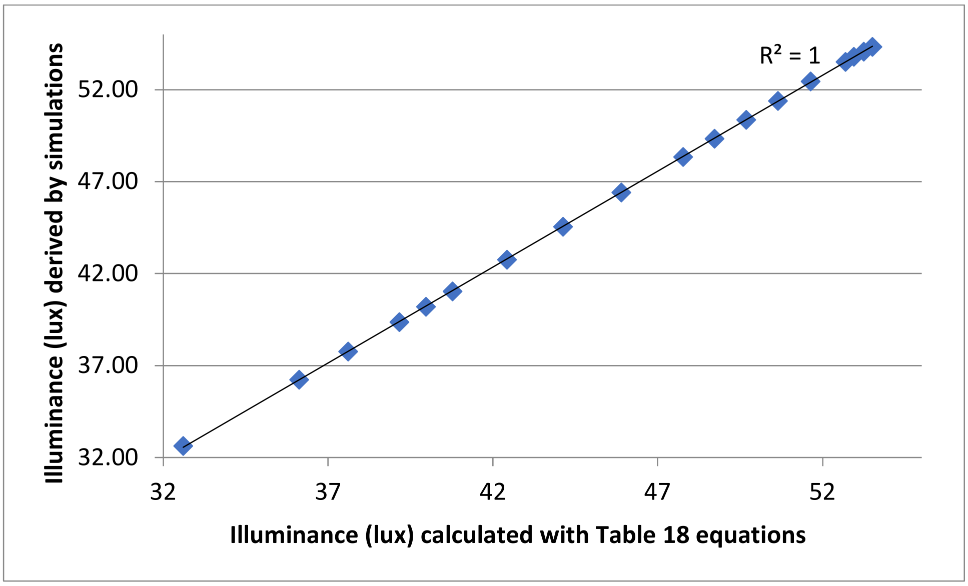
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
4	4	5	0.9	0.25	33.52	36.97
				0.5	33.31	36.69
				0.75	33.12	36.42
				1	32.89	36.15
				2	31.96	35.07
				3	31.26	34.02
				4	30.53	32.99
				5	29.8	31.97
				6	29.01	30.98
				8	27.7	29.04
				10	26.38	27.18
				12	25.13	25.39
				14	24	23.66
				15	23.41	22.83
				16	22.82	22.00
				18	21.79	20.40
				20	20.74	18.86
				25	13.92	15.26



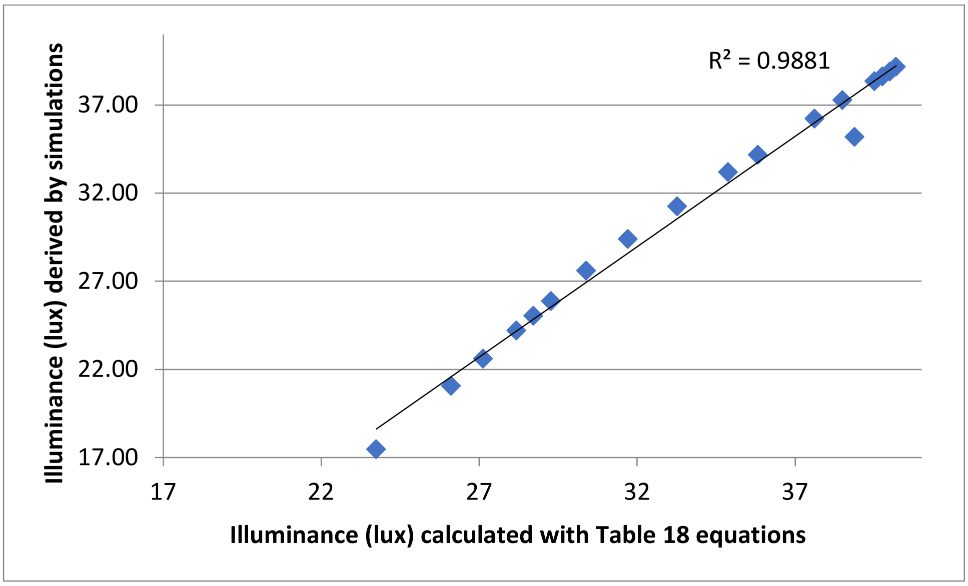
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
6	4	3	0.9	0.25	60.76	60.60
				0.5	60.47	60.33
				0.75	60.17	60.06
				1	59.88	59.79
				2	58.7	58.71
				3	57.57	57.66
				4	56.44	56.63
				5	55.32	55.61
				6	54.24	54.62
				8	52.17	52.68
				10	50.15	50.82
				12	48.22	49.03
				14	46.34	47.30
				15	45.43	46.46
				16	44.55	45.64
				18	42.74	44.04
				20	41.04	42.50
				25	37.1	38.90



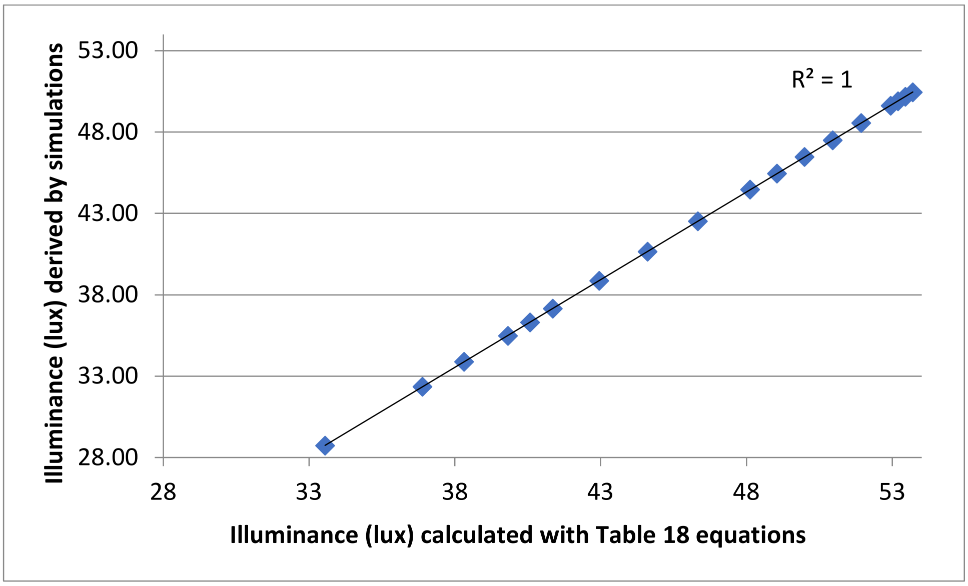
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
7	4	3	0.9	0.25	53.51	54.35
				0.5	53.25	54.07
				0.75	52.95	53.80
				1	52.7	53.53
				2	51.64	52.45
				3	50.65	51.40
				4	49.69	50.37
				5	48.72	49.35
				6	47.77	48.36
				8	45.9	46.42
				10	44.13	44.56
				12	42.43	42.77
				14	40.78	41.04
				15	39.97	40.21
				16	39.17	39.38
				18	37.61	37.78
				20	36.13	36.24
				25	32.61	32.64



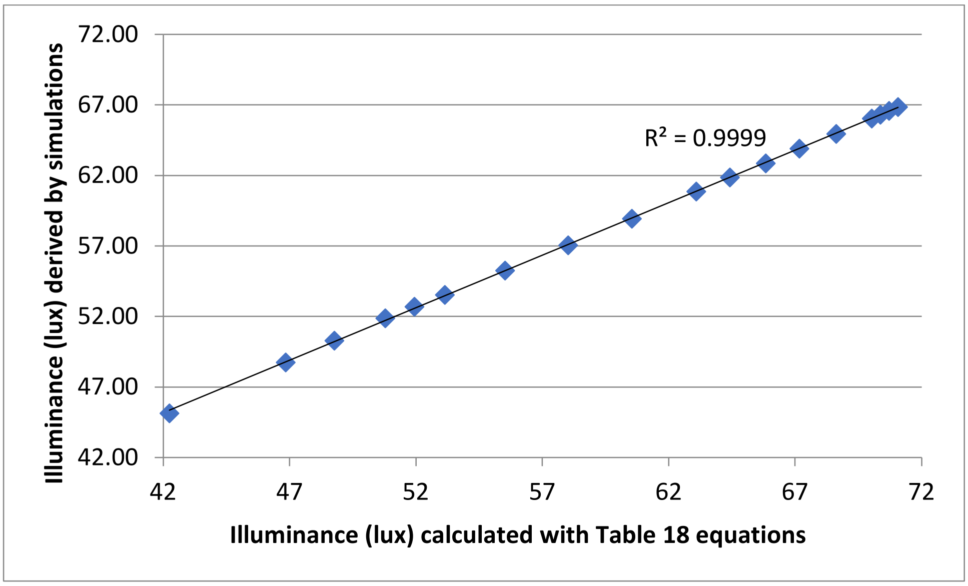
Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
5	5	4	0.9	0.25	40.19	39.19
				0.5	40	38.92
				0.75	39.76	38.65
				1	39.51	38.37
				2	38.5	37.30
				3	37.61	36.25
				4	38.88	35.21
				5	35.82	34.20
				6	34.88	33.21
				8	33.27	31.27
				10	31.7	29.41
				12	30.39	27.62
				14	29.27	25.89
				15	28.71	25.05
				16	28.18	24.23
				18	27.12	22.63
				20	26.11	21.09
				25	23.74	17.49



Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
6	6	2.5	0.9	0.25	53.7	50.46
				0.5	53.45	50.19
				0.75	53.2	49.91
				1	52.94	49.64
				2	51.93	48.57
				3	50.96	47.51
				4	49.99	46.48
				5	49.05	45.47
				6	48.13	44.47
				8	46.33	42.54
				10	44.61	40.68
				12	42.95	38.88
				14	41.36	37.16
				15	40.58	36.32
				16	39.82	35.50
				18	38.32	33.90
				20	36.89	32.36
				25	33.55	28.75



Room Length (m)	Room Width (m)	Room Height (m)	Pipe Diameter (m)	Pipe Length (m)	ILLUMINANCE (lux) simulated	ILLUMINANCE (lux) calculated with the equations in Table 17
5	4	3	0.9	0.25	71.07	66.86
				0.5	70.72	66.59
				0.75	70.38	66.32
				1	70.04	66.04
				2	68.63	64.97
				3	67.17	63.92
				4	65.84	62.88
				5	64.42	61.87
				6	63.09	60.87
				8	60.55	58.94
				10	58.02	57.08
				12	55.53	55.29
				14	53.15	53.56
				15	51.94	52.72
				16	50.79	51.90
				18	48.78	50.30
				20	46.85	48.76
				25	42.25	45.16



Appendix VII

Summarizing tables on the illuminance values calculated with the TTE method, with the Luxplot method and with simulations, where the light pipe is replaced by a luminaire.

Room surface reflectances (%): Walls/Ceiling/Floor-Reference Plane=50/70/30

Reference plane: 0.85m above the floor and 0.50m offset from the walls

$\tau_{dome} \times \tau_{dif}$=0.82, ρ_{pipe}=0.98, MF=0.9

E_{ex}=5,000lux

Room Dimensions (Length/Width/ Height, m)	Light Pipe Diameter (m)	Light Pipe Length (m)	ILLUMINANCE (lux) - TTE Method	ILLUMINANCE (lux) - LUXPLOT Method	ILLUMINANCE (lux) – Light Pipe simulated as a Luminaire
4/4/3	0.25	0.25	18.81	10.24	6.93
		0.5	18.51	10.13	6.89
		1	17.94	9.63	6.53
		3	15.82	8.49	5.75
		6	13.09	7.03	4.77
		12	8.97	4.82	3.25
	0.35	0.25	19.05	20.04	13.56
		0.5	18.83	19.81	13.42
		1	18.4	19.36	13.11
		3	16.79	17.66	11.96
		6	14.62	15.38	10.43
		12	11.1	11.67	7.89
	0.53	0.25	19.21	46.35	31.23
		0.5	19.07	45.99	31
		1	18.77	45.29	30.53
		3	17.64	42.56	28.7
		6	16.08	38.78	26.14
		12	13.35	32.2	21.7
	0.65	0.25	19.26	69.89	47.09
		0.5	19.14	69.45	46.78
		1	18.9	68.59	46.1
		3	17.98	65.24	43.8
		6	16.68	60.53	40.62
		12	14.36	52.1	34.97
	0.9	0.25	19.34	134.55	82.46
		0.5	19.25	133.91	82.07
		1	19.07	132.64	81.23
		3	18.36	127.7	78.1
		6	17.34	120.62	73.51
		12	15.47	107.63	65.03

Room Dimensions (Length/Width/ Height, m)	Light Pipe Diameter (m)	Light Pipe Length (m)	ILLUMINANCE (lux) - TTE Method	ILLUMINANCE (lux) - LUXPLOT Method	ILLUMINANCE (lux) – Light Pipe simulated as a Luminaire
4/4/5	0.25	0.25	12.63	4.08	2.18
		0.5	12.43	4.02	2.12
		1	12.05	3.89	2.06
		3	10.62	3.43	1.81
		6	8.79	2.84	1.5
		12	6.02	1.95	1.02
	0.35	0.25	12.79	8.1	4.27
		0.5	12.64	8	4.22
		1	12.36	7.82	4.14
		3	11.27	7.14	3.77
		6	9.82	6.22	3.29
		12	7.45	4.72	2.49
	0.53	0.25	12.9	18.73	9.86
		0.5	12.8	18.59	9.79
		1	12.6	18.3	9.64
		3	11.85	17.2	9.06
		6	10.79	15.67	8.25
		12	8.96	13.01	6.85
	0.65	0.25	12.93	28.24	14.91
		0.5	12.85	28.07	14.83
		1	12.69	27.72	14.63
		3	12.07	26.37	13.92
		6	11.2	24.46	12.91
		12	9.64	21.05	11.11
	0.9	0.25	12.99	54.38	33.52
		0.5	12.93	54.12	33.31
		1	12.8	53.61	32.89
		3	12.33	51.61	31.26
		6	11.64	48.75	29.01
		12	10.39	43.5	25.13

Room Dimensions (Length/Width/ Height, m)	Light Pipe Diameter (m)	Light Pipe Length (m)	ILLUMINANCE (lux) - TTE Method	ILLUMINANCE (lux) - LUXPLOT Method	ILLUMINANCE (lux) – Light Pipe simulated as a Luminaire
6/4/3	0.25	0.25	20.9	7.72	4.48
		0.5	20.58	7.6	4.35
		1	19.94	7.36	4.23
		3	17.58	6.49	3.72
		6	14.55	5.37	3.09
		12	9.97	3.68	2.1
	0.35	0.25	21.17	15.33	8.77
		0.5	20.93	15.15	8.67
		1	20.46	14.81	8.49
		3	18.66	13.5	7.74
		6	16.25	11.76	6.75
		12	12.33	8.93	5.11
	0.53	0.25	21.36	35.45	20.24
		0.5	21.19	35.17	20.09
		1	20.86	34.63	19.79
		3	19.61	32.55	18.6
		6	17.87	29.66	16.94
		12	14.84	24.63	14.07
	0.65	0.25	21.41	53.45	30.46
		0.5	21.27	53.11	30.29
		1	21.01	52.45	29.89
		3	19.98	49.9	28.44
		6	18.54	46.29	26.37
		12	15.96	39.84	22.7
	0.9	0.25	21.5	102.9	60.76
		0.5	21.4	102.41	60.47
		1	21.19	101.44	59.88
		3	20.4	97.66	57.57
		6	19.27	92.25	54.24
		12	17.2	82.31	48.22

Room Dimensions (Length/Width/ Height, m)	Light Pipe Diameter (m)	Light Pipe Length (m)	ILLUMINANCE (lux) - TTE Method	ILLUMINANCE (lux) - LUXPLOT Method	ILLUMINANCE (lux) – Light Pipe simulated as a Luminaire
7/4/3	0.25	0.25	21.51	6.82	3.94
		0.5	21.17	6.72	3.83
		1	20.52	6.51	3.71
		3	18.09	5.74	3.27
		6	14.97	4.75	2.71
		12	10.26	3.25	1.85
	0.35	0.25	21.79	13.55	7.71
		0.5	21.54	13.39	7.62
		1	21.05	13.09	7.47
		3	19.2	11.94	6.8
		6	16.72	10.4	5.93
		12	12.69	7.89	4.49
	0.53	0.25	21.98	31.33	17.8
		0.5	21.81	31.1	17.67
		1	21.47	30.61	17.4
		3	20.18	28.77	16.36
		6	18.39	26.22	14.9
		12	15.27	21.77	12.37
	0.65	0.25	22.03	47.24	26.81
		0.5	21.89	46.95	26.64
		1	21.62	46.36	26.3
		3	20.56	44.1	25.02
		6	19.08	40.92	23.2
		12	16.42	35.22	19.97
	0.9	0.25	22.12	90.95	53.51
		0.5	22.02	90.52	53.25
		1	21.81	89.66	52.7
		3	20.99	86.32	50.65
		6	19.83	81.54	47.77
		12	17.69	72.75	42.43

Room Dimensions (Length/Width/ Height, m)	Light Pipe Diameter (m)	Light Pipe Length (m)	ILLUMINANCE (lux) - TTE Method	ILLUMINANCE (lux) - LUXPLOT Method	ILLUMINANCE (lux) – Light Pipe simulated as a Luminaire
5/5/4	0.25	0.25	17.92	5.57	2.88
		0.5	17.64	5.49	2.83
		1	17.1	5.32	2.75
		3	15.07	4.73	2.42
		6	12.48	3.88	2.01
		12	8.55	2.66	1.37
	0.35	0.25	18.15	11.06	5.71
		0.5	17.94	10.94	5.65
		1	17.54	10.69	5.53
		3	16	9.75	5.04
		6	13.93	8.49	4.39
		12	10.57	6.44	3.32
	0.53	0.25	18.31	25.6	13.19
		0.5	18.17	25.39	13.09
		1	17.89	25	12.89
		3	16.81	23.5	12.12
		6	15.32	21.41	11.04
		12	12.72	17.78	9.16
	0.65	0.25	18.35	38.58	19.85
		0.5	18.24	38.34	19.73
		1	18.01	37.87	19.48
		3	17.13	36.02	18.53
		6	15.9	33.42	17.19
		12	13.68	28.76	14.8
	0.9	0.25	18.43	74.28	40.19
		0.5	18.34	73.93	40
		1	18.17	73.23	39.51
		3	17.49	70.5	37.61
		6	16.52	66.59	34.88
		12	14.74	59.42	30.39

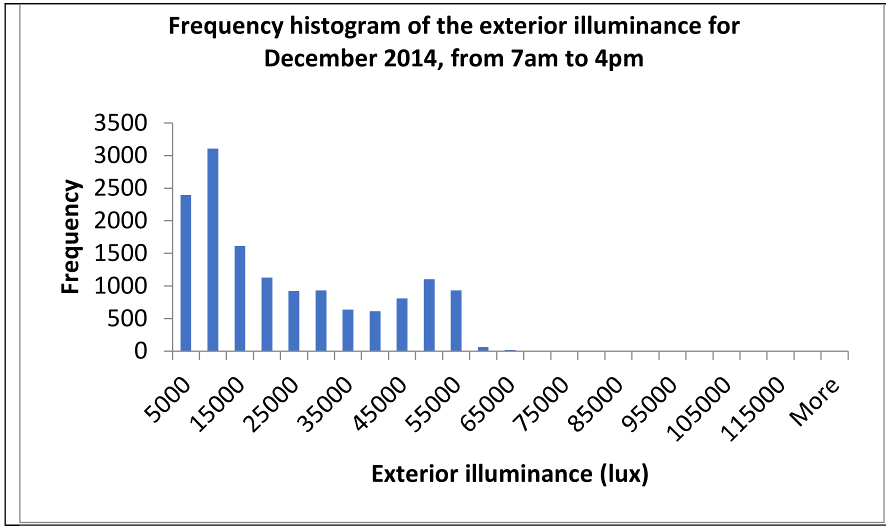
Room Dimensions (Length/Width/ Height, m)	Light Pipe Diameter (m)	Light Pipe Length (m)	ILLUMINANCE (lux) - TTE Method	ILLUMINANCE (lux) - LUXPLOT Method	ILLUMINANCE (lux) – Light Pipe simulated as a Luminaire
6/6/2.5	0.25	0.25	26.09	3.06	4.1
		0.5	25.69	3	3.99
		1	24.89	2.91	3.87
		3	21.94	2.57	3.41
		6	18.16	2.13	2.83
		12	12.45	1.46	1.92
	0.35	0.25	26.43	6.07	8.04
		0.5	26.13	6	7.94
		1	25.53	5.86	7.78
		3	23.29	5.35	7.09
		6	20.29	4.66	6.18
		12	15.39	3.53	4.68
	0.53	0.25	26.66	14.03	18.57
		0.5	26.45	13.92	18.44
		1	26.05	13.71	18.16
		3	24.48	12.89	17.07
		6	22.31	11.74	15.54
		12	18.52	9.75	12.91
	0.65	0.25	26.72	21.16	27.98
		0.5	26.56	21.02	27.81
		1	26.23	20.76	27.47
		3	24.95	19.75	26.13
		6	23.14	18.32	24.23
		12	19.92	15.77	20.86
	0.9	0.25	26.83	40.73	53.7
		0.5	26.71	40.54	53.45
		1	26.46	40.15	52.94
		3	25.47	38.66	50.96
		6	24.06	36.52	48.13
		12	21.47	32.58	42.95

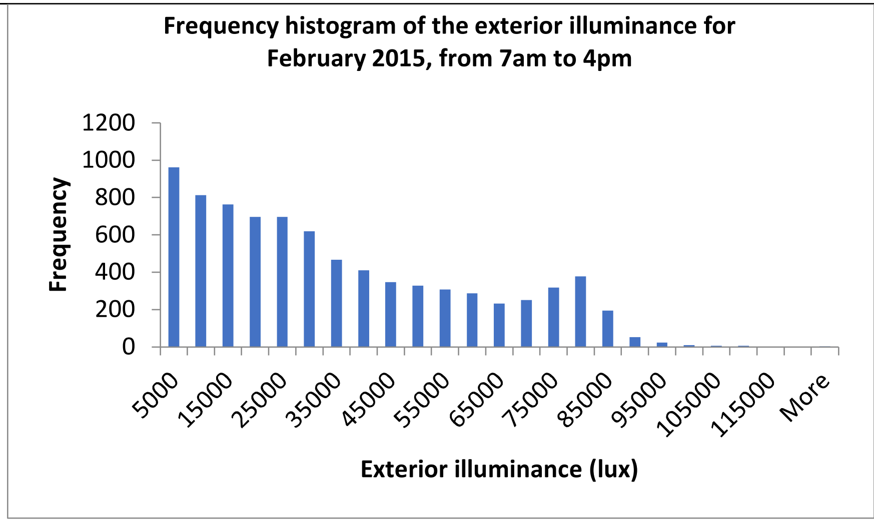
Room Dimensions (Length/Width/ Height, m)	Light Pipe Diameter (m)	Light Pipe Length (m)	ILLUMINANCE (lux) - TTE Method	ILLUMINANCE (lux) - LUXPLOT Method	ILLUMINANCE (lux) – Light Pipe simulated as a Luminaire
4/3/3	0.25	0.25	16.71	10.98	6.59
		0.5	16.45	10.81	6.41
		1	15.94	10.48	6.22
		3	14.05	9.24	5.14
		6	11.63	7.65	4.55
		12	7.97	5.24	3.09
	0.35	0.25	16.93	21.81	5.12
		0.5	16.73	21.56	4.98
		1	16.35	21.07	4.83
		3	14.91	19.22	4.25
		6	12.99	16.74	3.53
		12	9.86	12.7	2.4
	0.53	0.25	17.07	50.44	30.16
		0.5	16.94	50.05	29.9
		1	16.68	49.28	29.41
		3	15.68	46.32	27.47
		6	14.28	42.2	24.87
		12	11.86	35.04	20.63
	0.65	0.25	17.11	76.05	41.71
		0.5	17.01	75.57	41.55
		1	16.8	74.63	41.24
		3	16.38	70.99	40.03
		6	14.82	65.86	38.33
		12	12.76	56.69	35.28
	0.9	0.25	17.19	146.41	82.71
		0.5	17.1	145.71	82.44
		1	16.94	144.33	81.89
		3	16.31	138.95	79.77
		6	15.41	131.25	76.72
		12	13.75	117.11	71.14

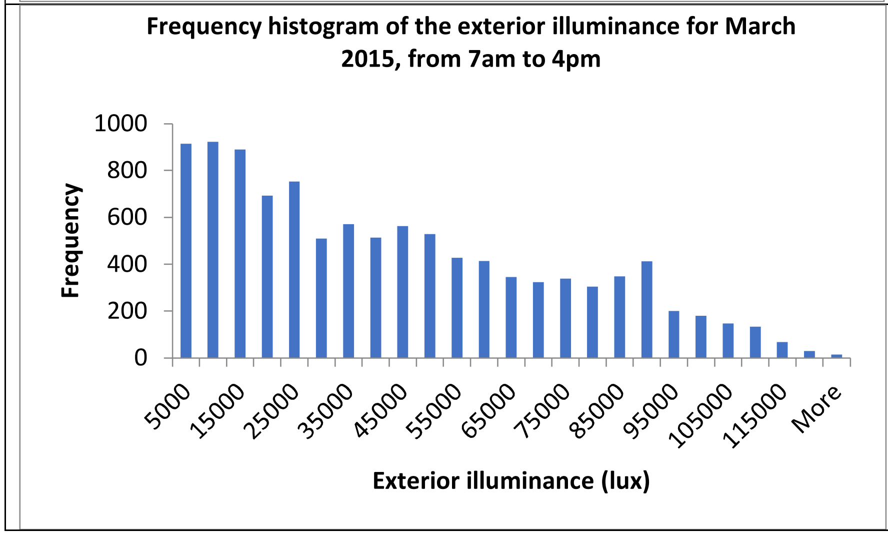
Room Dimensions (Length/Width/ Height, m)	Light Pipe Diameter (m)	Light Pipe Length (m)	ILLUMINANCE (lux) - TTE Method	ILLUMINANCE (lux) - LUXPLOT Method	ILLUMINANCE (lux) – Light Pipe simulated as a Luminaire
4/4/3	0.25	0.25	20.06	8.77	5.12
		0.5	19.75	8.63	4.98
		1	19.14	8.36	4.83
		3	16.87	7.37	4.25
		6	13.97	6.1	3.53
		12	10.85	4.18	2.4
	0.35	0.25	20.32	17.4	10.03
		0.5	20.09	17.2	9.92
		1	19.63	16.81	9.71
		3	17.91	15.33	8.85
		6	15.6	13.36	7.72
		12	11.84	10.14	5.84
	0.53	0.25	20.5	40.25	23.13
		0.5	20.34	39.94	22.96
		1	20.02	39.32	22.61
		3	18.82	36.96	21.26
		6	17.15	33.68	19.36
		12	14.24	27.96	16.08
	0.65	0.25	20.54	60.68	34.79
		0.5	20.42	60.3	34.59
		1	20.16	59.55	34.15
		3	19.18	56.65	32.48
		6	17.79	52.56	30.87
		12	15.32	45.24	25.93
	0.9	0.25	20.63	116.83	71.07
		0.5	20.53	116.27	70.72
		1	20.34	115.17	70.04
		3	19.58	110.88	67.17
		6	18.5	104.74	63.09
		12	16.5	93.45	55.53

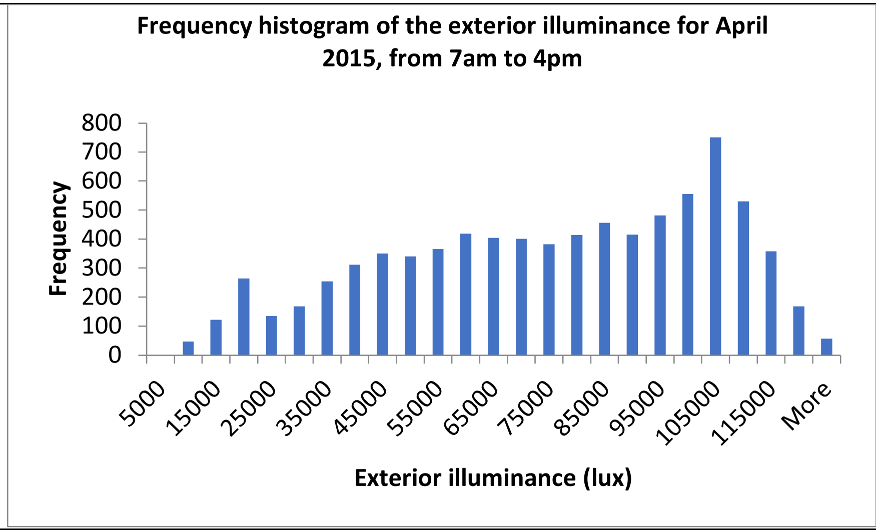
Appendix VIII

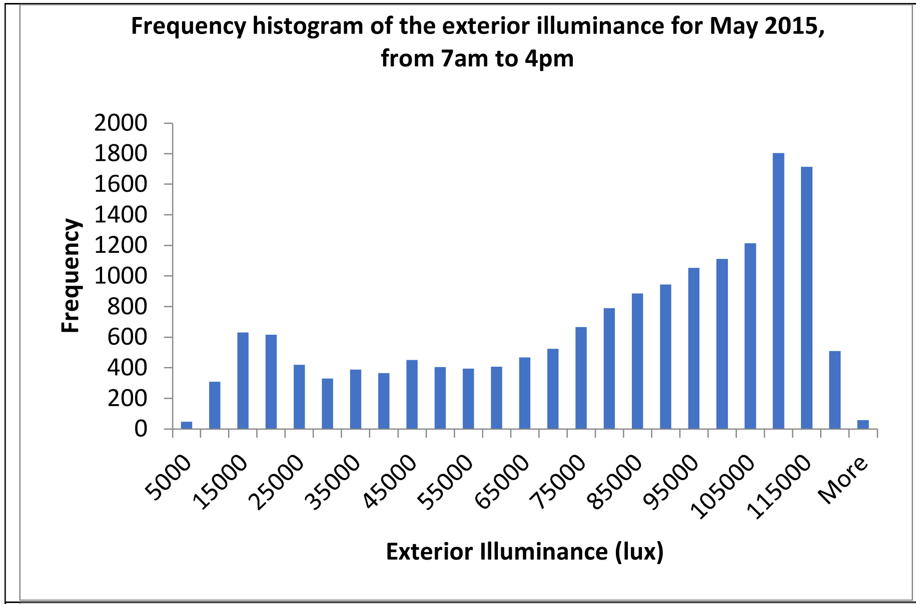
Frequency histograms of exterior illuminance for the months December 2014 and February-July 2015, from 7am to 4pm

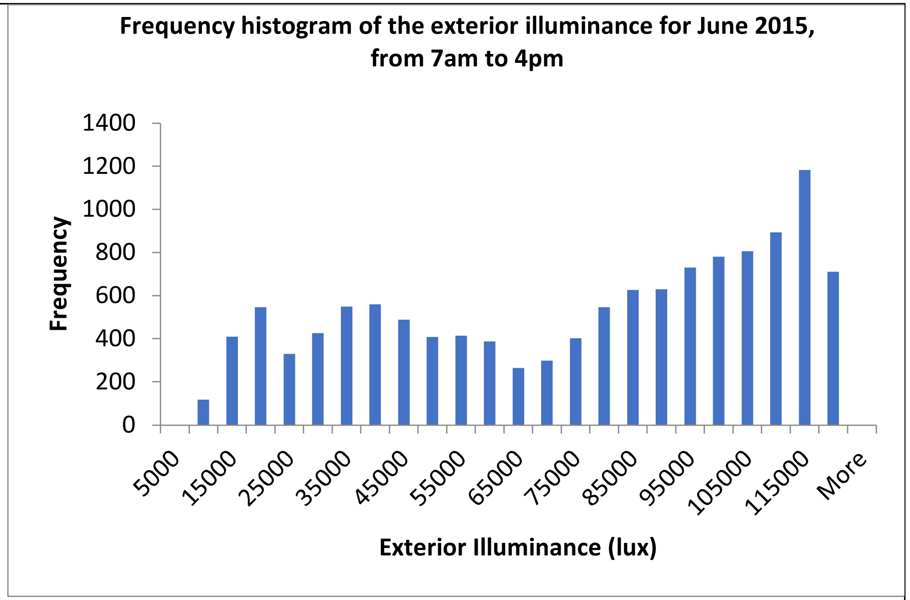


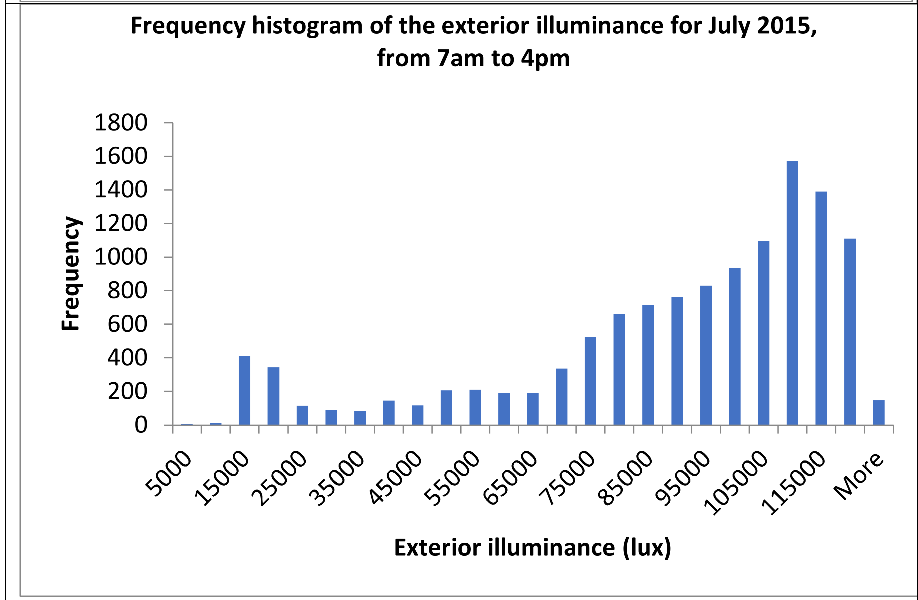


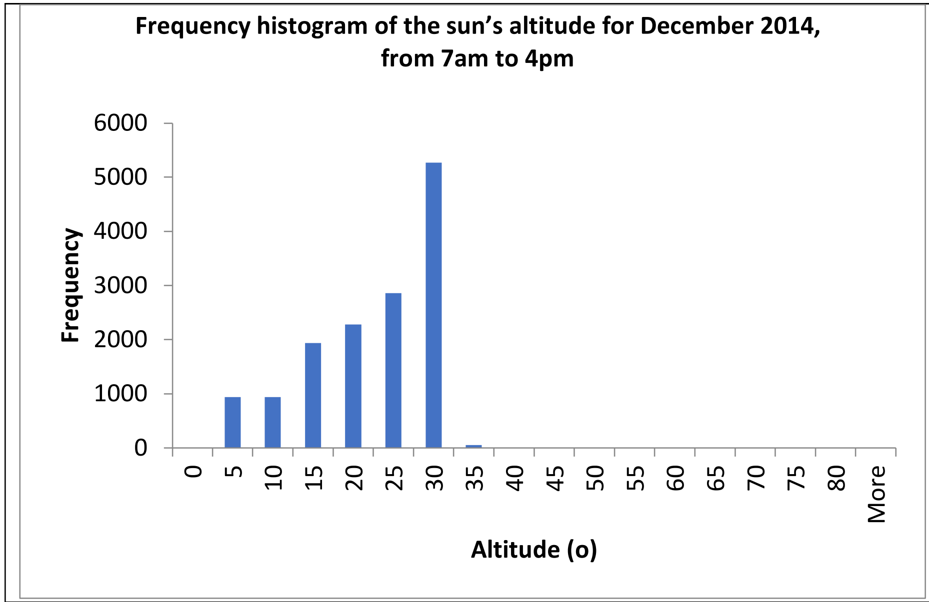


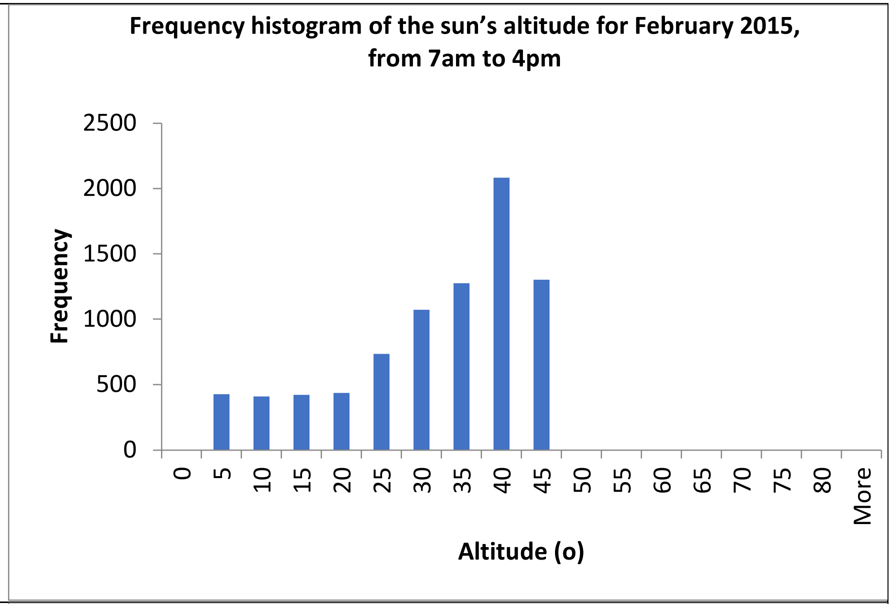


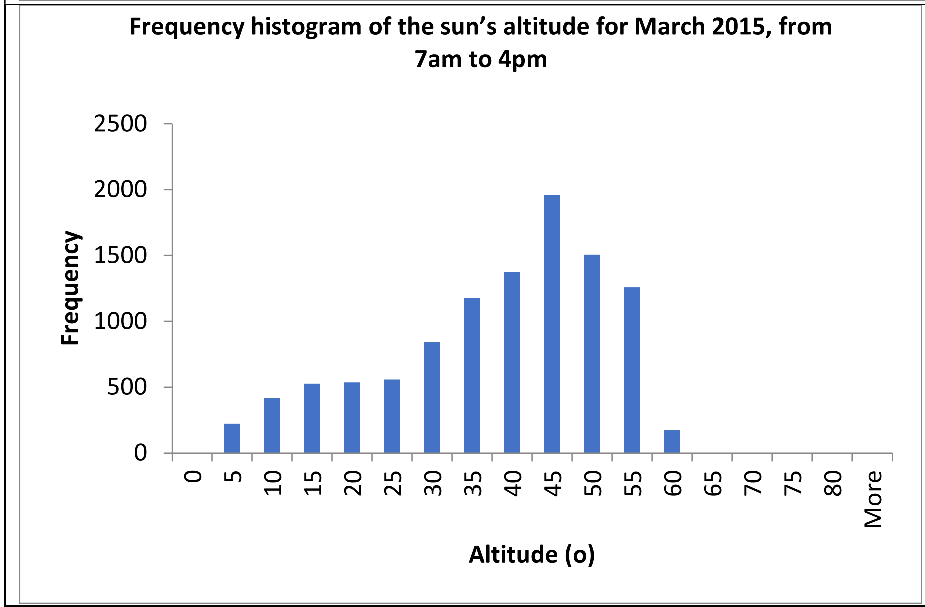

Frequency histogram of the exterior illuminance for May 2015, from 7am to 4pm
Frequency
2000
1800
1600
1400
1200
1000
800
600
400
200
0
5000
15000
25000
35000
45000
55000
65000
75000
85000
95000
105000
115000
More
Exterior Illuminance (lux)

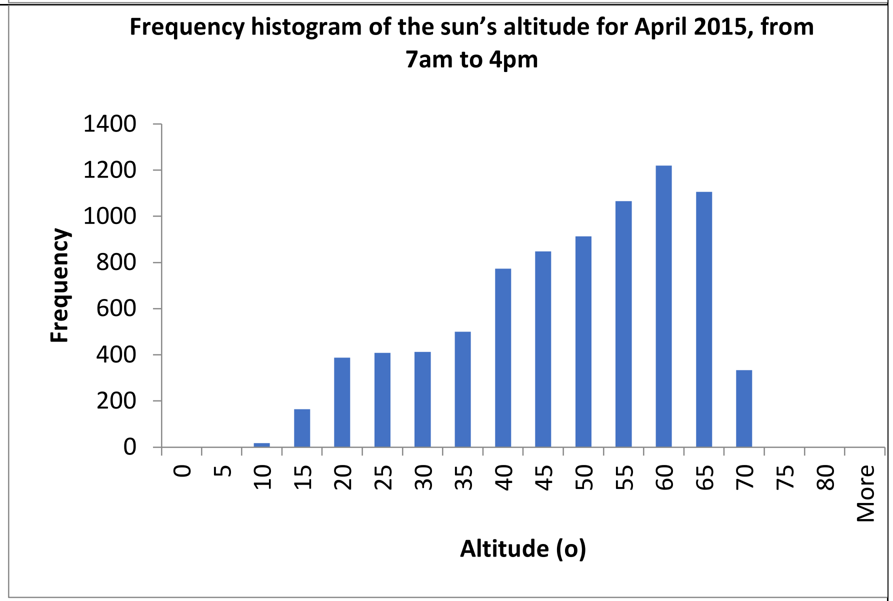

Frequency histogram of the exterior illuminance for June 2015, from 7am to 4pm
Frequency
1400
1200
1000
800
600
400
200
0
5000
15000
25000
35000
45000
55000
65000
75000
85000
95000
105000
115000
More
Exterior Illuminance (lux)


Frequency histogram of the exterior illuminance for July 2015, from 7am to 4pm
Frequency
1800
1600
1400
1200
1000
800
600
400
200
0
5000
15000
25000
35000
45000
55000
65000
75000
85000
95000
105000
115000
More
Exterior illuminance (lux)

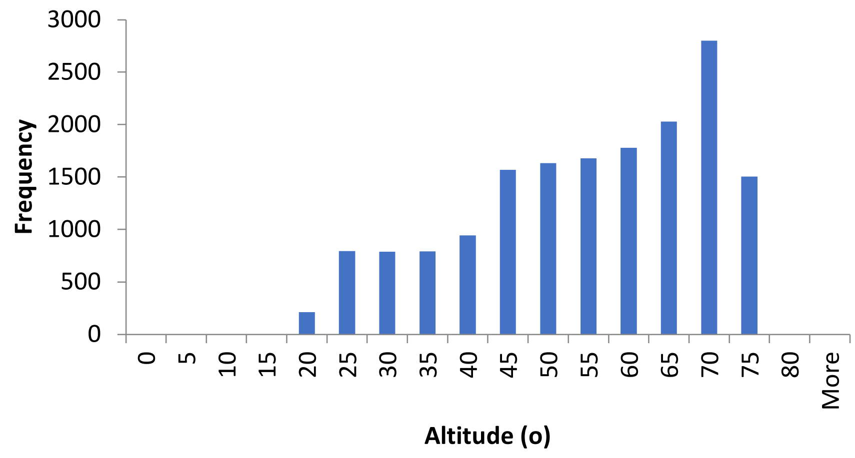

Frequency histogram of the sun's altitude for December 2014, from 7am to 4pm
Frequency
Altitude (o)
0 1000 2000 3000 4000 5000 6000
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 More


Frequency histogram of the sun's altitude for February 2015, from 7am to 4pm
Frequency
Altitude (o)
0 500 1000 1500 2000 2500
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 More

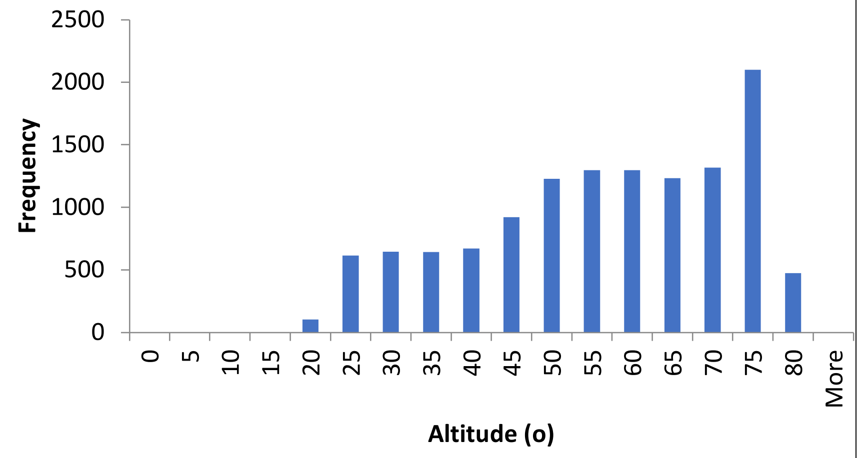

Frequency histogram of the sun's altitude for March 2015, from 7am to 4pm
Frequency
Altitude (o)
0 500 1000 1500 2000 2500
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 More


Frequency histogram of the sun's altitude for April 2015, from 7am to 4pm
Frequency
Altitude (o)
0 200 400 600 800 1000 1200 1400
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 More

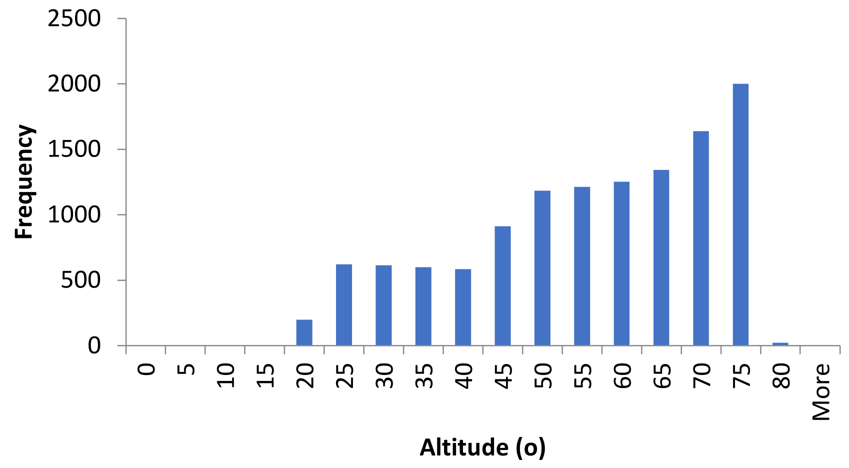
Frequency histogram of the sun's altitude for May 2015, from 7am to 4pm

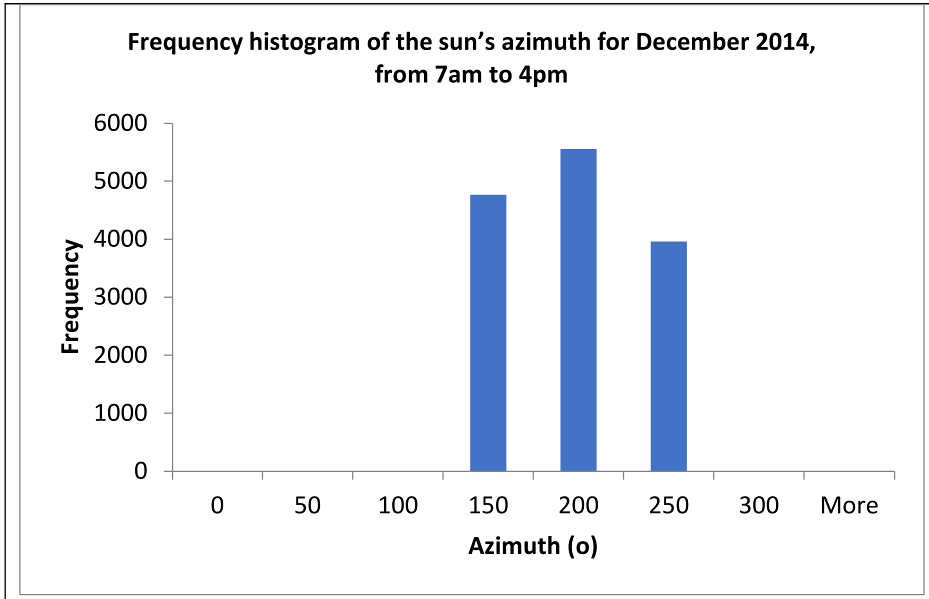


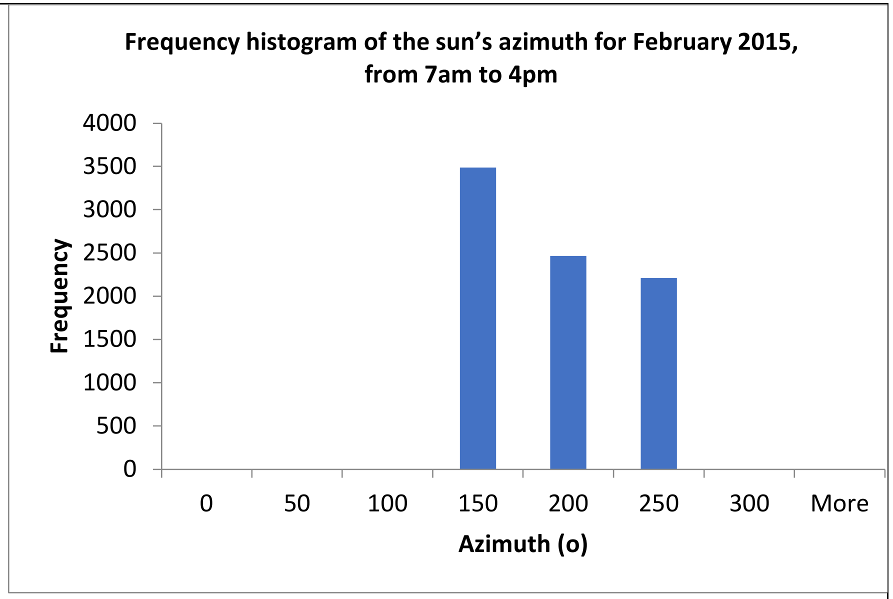
Frequency histogram of the sun's altitude for June 2015, from 7am to 4pm

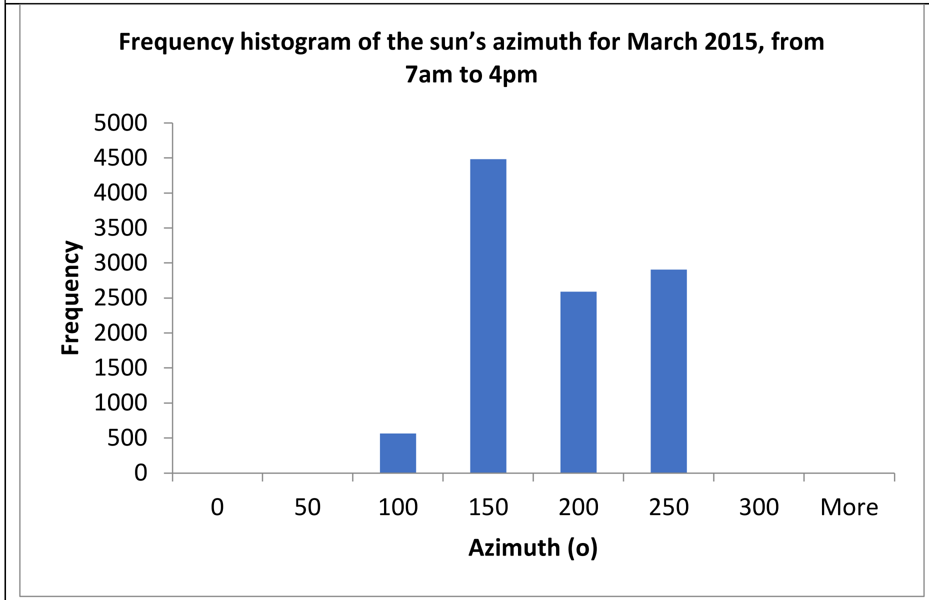


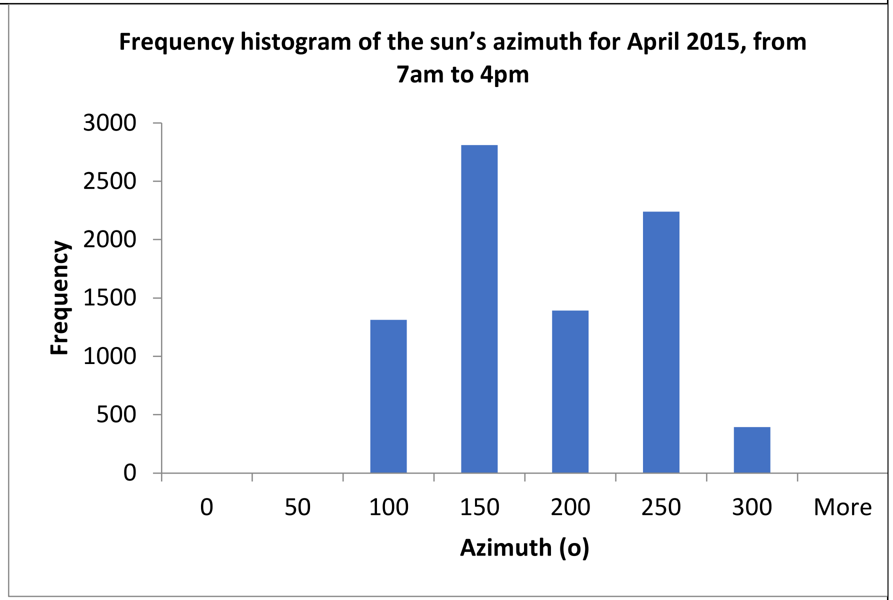
Frequency histogram of the sun's altitude for July 2015, from 7am to 4pm

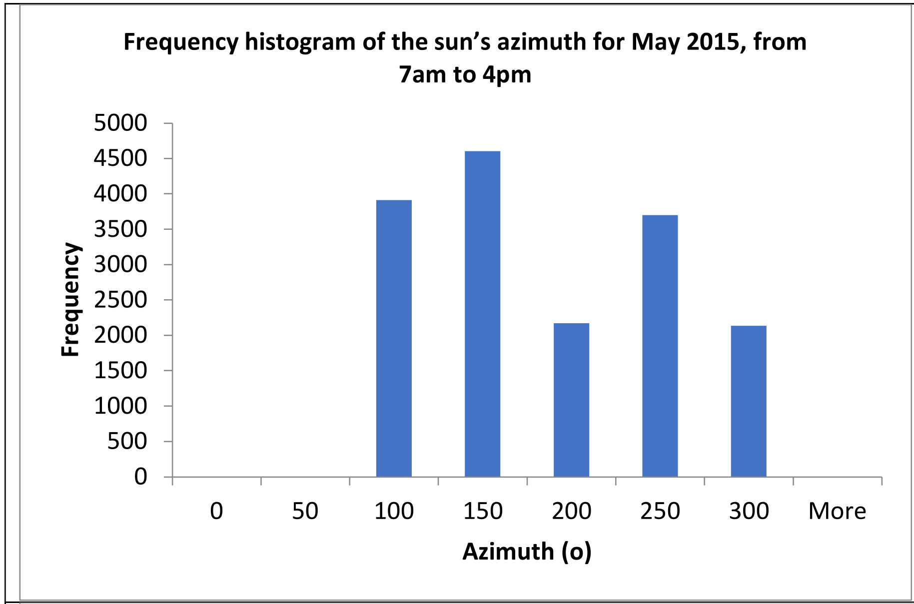


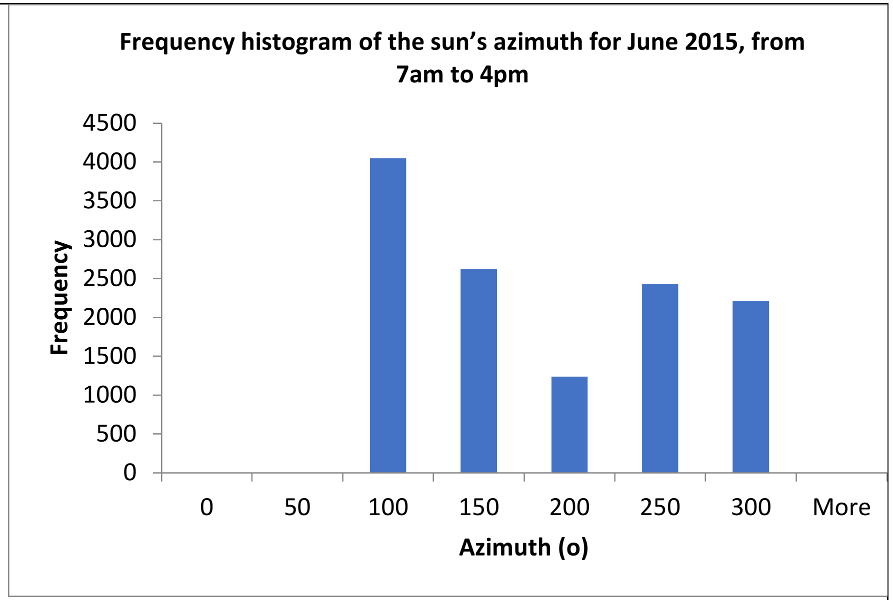

Frequency histogram of the sun's azimuth for December 2014, from 7am to 4pm
Frequency
6000
5000
4000
3000
2000
1000
0
0
50
100
150
200
250
300
More
Azimuth (o)

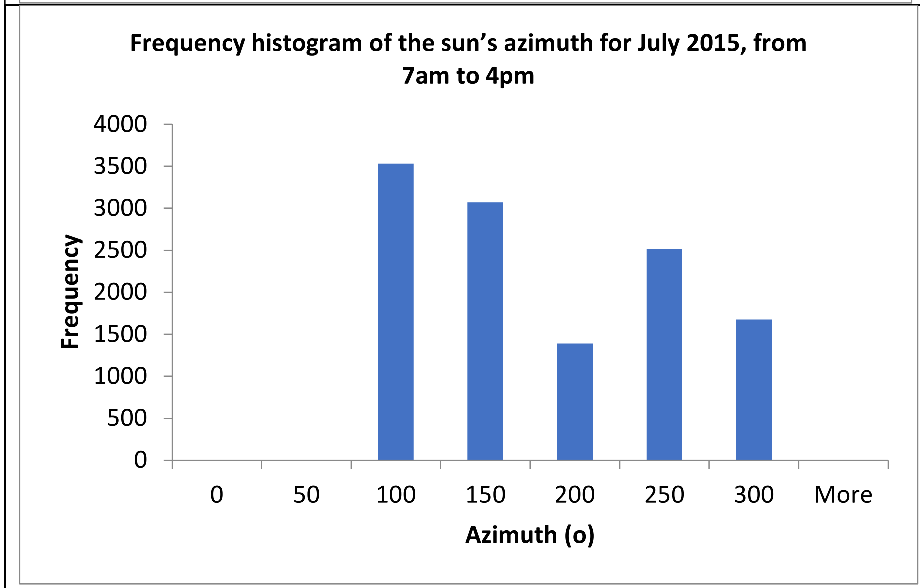

Frequency histogram of the sun's azimuth for February 2015, from 7am to 4pm
Frequency
4000
3500
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
More
Azimuth (o)

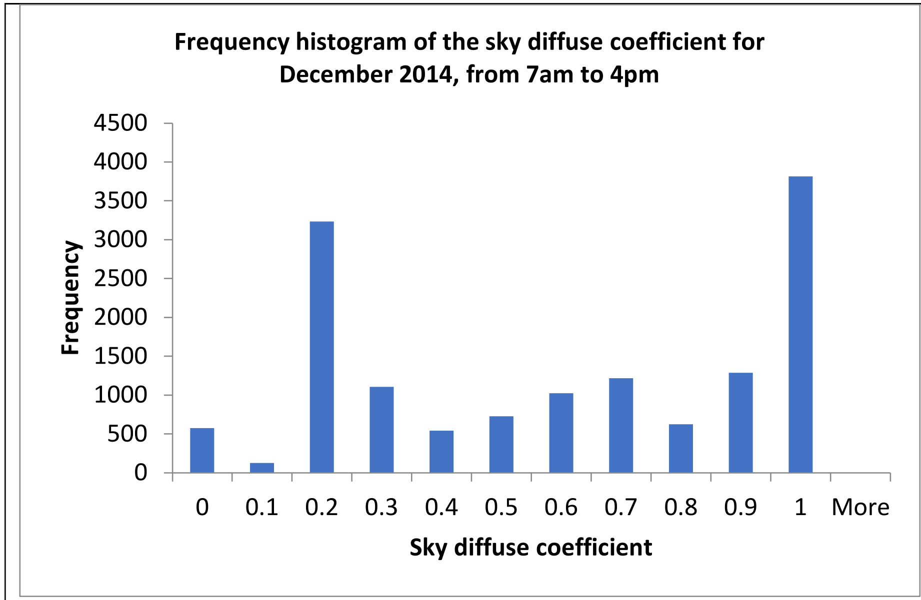

Frequency histogram of the sun's azimuth for March 2015, from 7am to 4pm
Frequency
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
More
Azimuth (o)

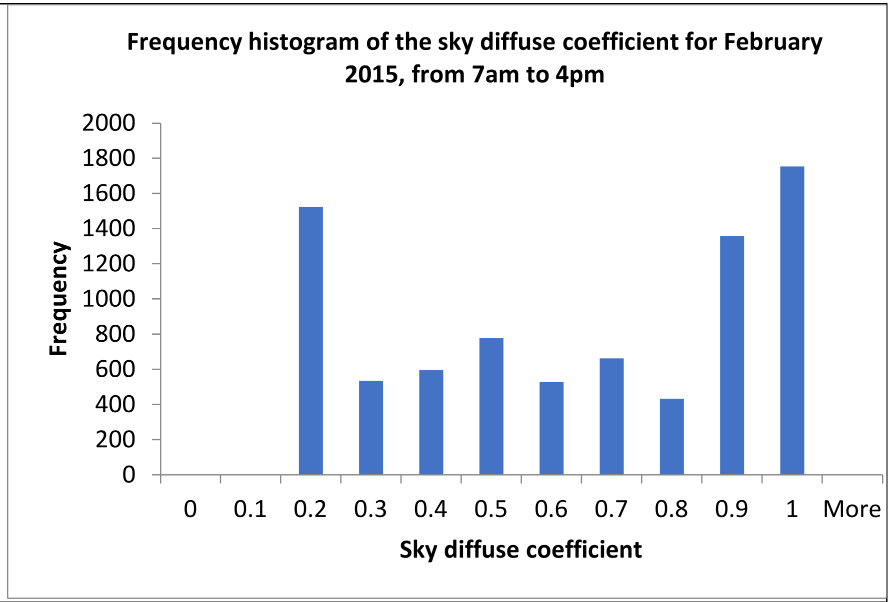

Frequency histogram of the sun's azimuth for April 2015, from 7am to 4pm
Frequency
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
More
Azimuth (o)

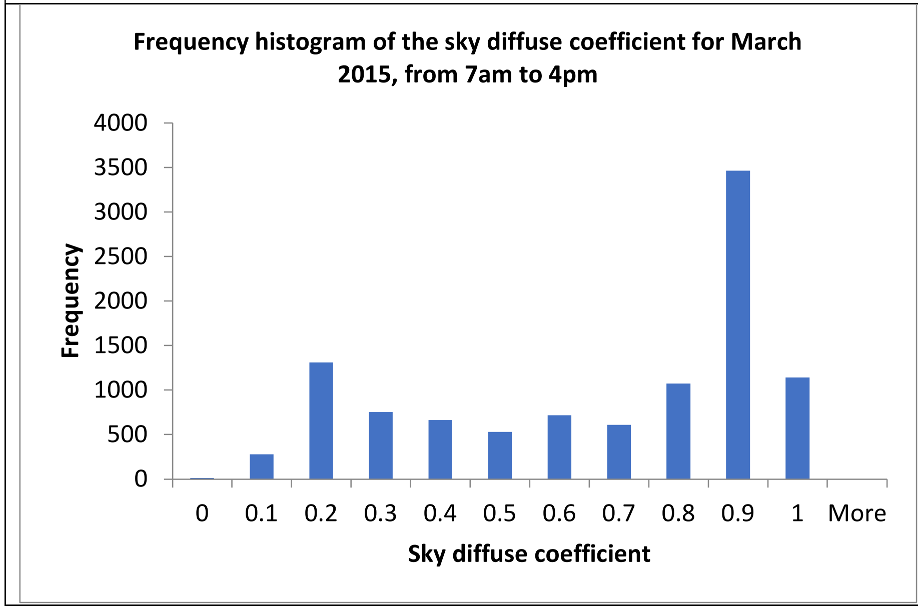

Frequency histogram of the sun's azimuth for May 2015, from 7am to 4pm
Frequency
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
More
Azimuth (o)

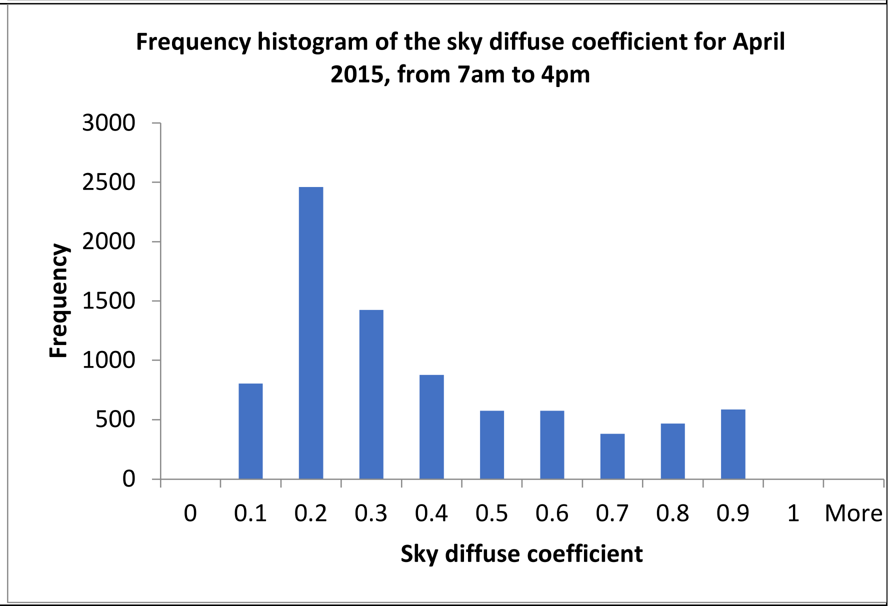

Frequency histogram of the sun's azimuth for June 2015, from 7am to 4pm
Frequency
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
More
Azimuth (o)

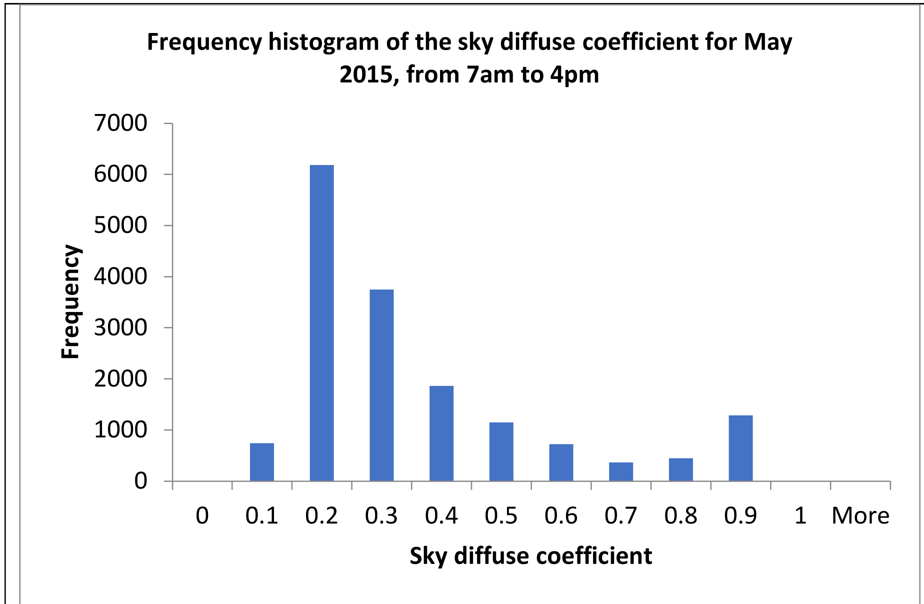

Frequency histogram of the sun's azimuth for July 2015, from 7am to 4pm
Frequency
4000
3500
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
More
Azimuth (o)

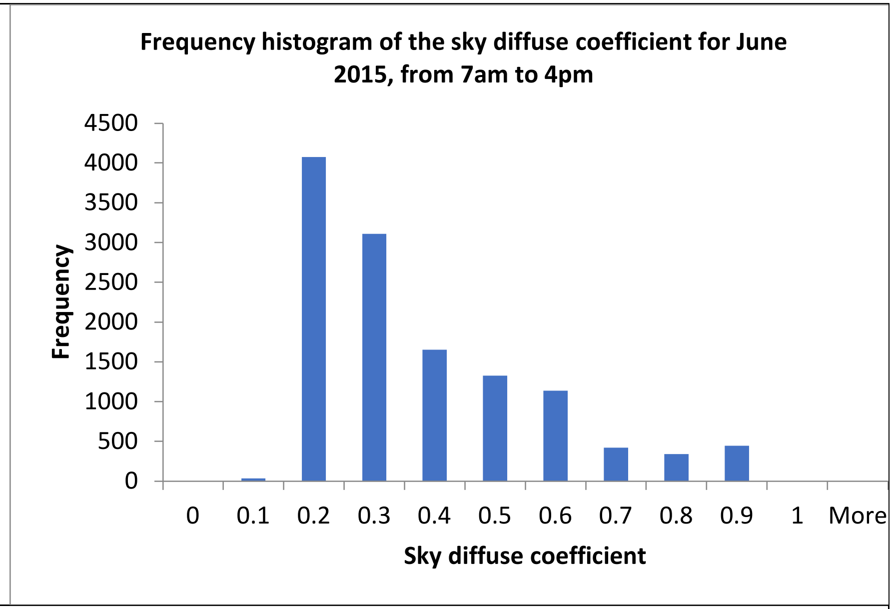

Frequency histogram of the sky diffuse coefficient for December 2014, from 7am to 4pm
Frequency
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 More
Sky diffuse coefficient

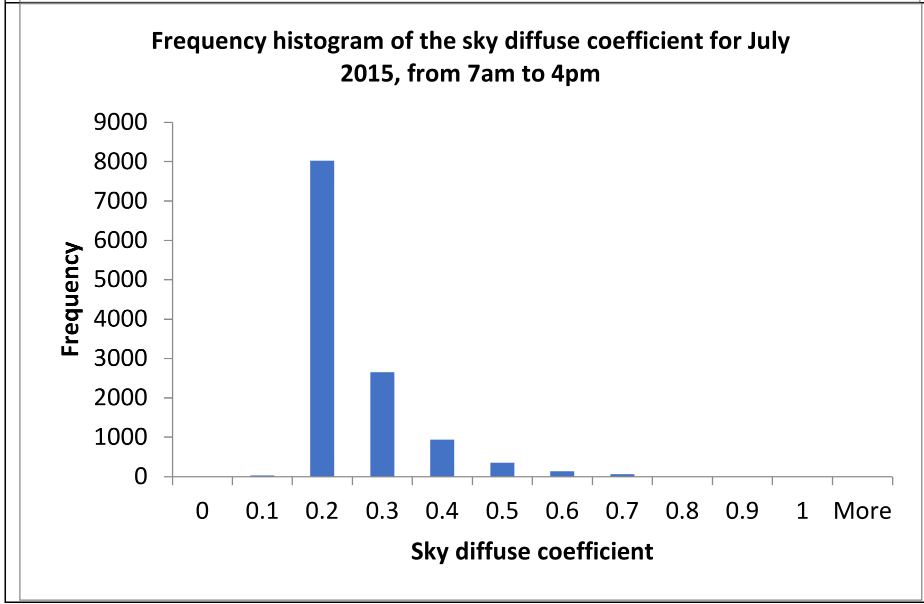

Frequency histogram of the sky diffuse coefficient for February 2015, from 7am to 4pm
Frequency
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 More
Sky diffuse coefficient


Frequency histogram of the sky diffuse coefficient for March 2015, from 7am to 4pm
Frequency
4000
3500
3000
2500
2000
1500
1000
500
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 More
Sky diffuse coefficient


Frequency histogram of the sky diffuse coefficient for April 2015, from 7am to 4pm
Frequency
3000
2500
2000
1500
1000
500
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 More
Sky diffuse coefficient


Frequency histogram of the sky diffuse coefficient for May 2015, from 7am to 4pm
Frequency
7000
6000
5000
4000
3000
2000
1000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
More
Sky diffuse coefficient


Frequency histogram of the sky diffuse coefficient for June 2015, from 7am to 4pm
Frequency
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
More
Sky diffuse coefficient


Frequency histogram of the sky diffuse coefficient for July 2015, from 7am to 4pm
Frequency
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
More
Sky diffuse coefficient