

Methodology for a tool to assess daylight reflector tilt

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Master thesis in Energy-efficient and Environmental Buildings
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Lund University

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The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

Artificial lighting energy consumption in buildings can be reduced by efficiently daylighting the occupied spaces. Artificial lighting comprehends 21 % of the total energy consumption in tertiary buildings (Swedish energy agency, 2015). In many buildings daylight access is neglected, thus redirecting daylight is an efficient strategy to optimize daylighting while keeping the same area of openings for daylight. Furthermore, daylighting has proven to improve health and productivity of users (G. i Pallardo, 2011).

This thesis, which final goal is to improve daylight in buildings, describes the methodology to design and develop a tool to assess optimal tilt for planar daylight reflectors in courtyards. This methodology builds a tool which extracts efficiency values related to input data and reach a result. The tool development has four phases:

First, the factors influencing daylight with reflectors in courtyards were described. Through computer simulation with Honeybee for Grasshopper in Rhinoceros 5.0, case condition were simulated by varying one factor per simulation while keeping others constant. Afterwards, efficiency results were obtained by comparing the simulation with reflector results with the results of the simulation without reflector. And finally, using a study case conditions input in the tool and comparing those conditions to the previously simulated with similar conditions, a tilt is assessed.

With the developed methodology, a tool was achieved with which a tilt for fixed reflectors was assessed for a case conditions. Moreover, the tool results included efficiency table with an estimated efficiency for each result.

This document also includes parametric study to assess the optimal tilt for a reflector in a case and compare its results with the result obtained by the tool. The comparison showed an accurate tilt assessment and comparable daylight improvement assessment.

By developing the tool, the time taken to assess possible efficiency and tilt for a reflector is reduced. Furthermore, the tool is transferable and easy to use by non-qualified users.

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Glossary

Analysis surface: imaginary surface where simulations are measured.

Annual simulation: simulation for 8760 hours of a year dependant of weather data.

Artificial lighting: use of artificial sources of light for lighting.

Bisecting: vector that separates an angle in two angles of equal dimension.

Database: structure of data contained in software and accessible by it.

Data mining: computing method to gather data from large sets of information.

Daylight: light with the sun as source.

Daylighting: the use of daylight for lighting.

Daylight Autonomy: DA (%) Percentage of the occupied times of the year when the minimum illuminance requirement (e.g. 300 lx) at the sensor is met by daylight alone.

Daysim: a validated RADIANCE-based daylighting analysis software, calculates annual illuminance profiles, features an user behavior model that predict manual lighting and blind

control. It uses RADIANCE scripts.

Diffuse irradiance: source irradiance reflected by the atmosphere or geometry.

Direct irradiance: irradiance unobstructed from the source.

Grasshopper: plug- in for Rhinoceros used for parametric design.

Honeybee: plug-in for Grasshopper that adapts Daysim and allows parametric study of daylighting.

Illuminance: luminous flux per unit area. Its unit is lm/m^2 or lux.

Irradiance: radiant flux per unit of area (W/m^2)

Lighting: use of light to illuminate a space.

Luminous flux: energy radiated per unit of time in visible wavelength from a source. It is measured in lumens (lm).

Parametric study: parameter- based study where is evaluated the results for different conditions.

Photometry: science of the measurement of light, in terms of its perceived brightness to the human eye.

RADIANCE: set of scripts used for rendering, daylighting and raytracing simulation. The script tools take standardized input and processed it into standardized output.

Radiant flux: energy emitted by a source measured in Watts (W).

Reflectance: efficiency to reflect radiant energy.

Reflector: static surface installed to reflect light.

Rhinoceros 5.0: commercial 3D computer graphics and computer-aided design (CAD) application software.

Solar azimuth: angle along the horizon, with zero degrees corresponding to South.

Solar vector: vector connecting the sun position with the local location on Earth in it local axes.

Solar zenith: Vertical angle with zero degrees corresponding to the solar azimuth.

Specularity: capacity to reflect the incident energy in a single direction with the same angle with the normal to the incidence.

Spreadsheet tool: interactive computer application for organization, analysis and storage of data in tabular form.

Surface roughness: deviation from the normal vector of the surface. It defines the texture of the material.

Tilt: slope or inclination. Here referred to reflectors inclination.

Vector reflector-surface: Vector formed between the reflector and the analysis surface.

Weather file: Weather data measured for a location and compiled in a readable file.

Nomenclature

δ	Declination	[-]
n	day number	[-]
ω	hour angle	[°]
hh	hour	[-]
mm	minutes	[-]
Lst	state latitude	[°]
Ll	local latitude	[°]
E	equation of time	[-]
R_{loc}	solar vector for local axes	[-]
λ	latitude	[°]
X	Local axe	[-]
Y	Local axe	[-]
Z	Local axe	[-]
α	Angle	[°]
v	Vector	[-]
α_{tilt}	Tilt angle	[°]
v_{solar}	Solar vector	[-]
$v_{surface}$	Reflector-Surface vector	[-]
v_z	Z axis vector	[-]
ϕ_v	luminous flux	[lm]
ϕ_e	radiant flux	[W]
DA	Daylight autonomy	[%]
EPW	EnergyPlus Weather Data	[-]
ab	Ambient bounces	[-]
ad	Ambient divisions	[-]
aa	Ambient accuracy	[-]
ar	Ambient resolution	[-]
ILL	Illuminance file	[-]
RAD	Radiation file	[-]
WEA	Weather file	[-]

1 Introduction

1.1 Introduction

Worldwide, countries are setting new goals towards energy efficiency to reduce global warming. Buildings use 40 % of the total energy consumed in developed countries (Swedish energy agency, 2015). Artificial lighting comprehends 21 % from the energy use in tertiary buildings, such as office and commercial buildings (i Pallardo, G 2011). Daylighting is a passive efficient strategy to reduce the use of artificial lighting. To improve daylight, reflectors is an available option which can control daylight levels depending on the reflector characteristics.

Reflectors are used in buildings to improve the daylight levels in needed spaces. The most common situation are large scale buildings, which require courtyards, skylights or atria to improve daylighting, considering fenestration on façade cannot supply core spaces. Other situations, where reflectors are used, are high rise buildings in dense cities where shading from neighbors' buildings occurs. The last common case to use reflector are existent buildings requiring refurbishment which were designed with different approach to energy consumption and daylighting than current requirements. For these cases, the use of reflectors improves daylight levels under same geometrical conditions. Therefore, to achieve required daylight levels, bigger fenestration or atria might not necessary if reflectors are installed.

The decision to use reflector comes from the desire to improve daylight performance in the core of buildings. By improving daylight levels on a courtyard with reflectors there is a directly proportional improvement on the daylight levels in the interior spaces adjacent to the courtyard (Du, J., Sharples, S. 2011). By improving daylighting, it can make use of advantages such as daylight credit accomplishment in building certification due to credit based on requirements of daylighting (BREEAM, 2013). Moreover, daylighting has positive effects on buildings occupants' health and working performance (Kim, J.T., Kim, G. 2009).

Currently, a tool applying a simple method to assess the characteristics of a daylight reflector is not available. To obtain the optimal tilt for a reflector requires of parametric design method in a tool such as Galapagos or similar script and plug-in in Grasshopper. The goal of this thesis is to develop a method that allows the creation of a tool in order to fast and easily assess the optimal tilt for fixed-planar-reflector. This kind of tool saves time to lighting consultants and designers to set an initial reflector tilt by reducing the study required otherwise to achieve similar results.

1.2 Background

The legend tells that Archimedes delayed the siege of Syracuse by burning the sails of the Roman fleet with a gigantic mirror (Meijer, F, 1986). This legend was developed during the 17th and 18th century with the popularity and study of optical technologies.

Historically, the use of fixed reflectors has earlier origin with the use of light-shelves on windows during the 17th century (Rashed, R. 1990). The invention of the heliostat, an advance reflector system, which is defined as a movable device that turns to reflect sunlight, has a mirror surface which is kept aligned with the solar vector at any hour. It dates from the 18th century (Dictionary, 1763). With the popularization of artificial lighting, daylight lost importance and therefore reflectors use declined in architecture. Yet during the 20th century, the study of modern architecture and the quality of light brought back the use of reflectors. (Baker, N., Steemers, K. 2002). To achieve uniform daylighting in interiors, as artificial lighting can provide, is generally used a double reflector, one parabolic to bring daylight and a second to diffuse the light. This design is used in cultural interior spaces where direct light is not always desired. An example of this is the Kahn building in Kimbell art museum, Texas which is shown in figure 1.1.



Figure 1.1 Kahn building, Kimbell art museum in Fort Worth, Texas

Currently, daylighting is more developed thanks to it being one of the energy-efficient passive strategies necessary to achieve building certification (BREEAM, 2013). The use of reflectors increased due to requirements and a desire to achieve better daylight in the buildings' core. There are many examples as main architectural feature such as Fulton centre Sky reflector-net in New York or the cupola of the German parliament in Berlin.



Figure 1.2 Sky net-reflector, Fulton center

The latest daylight technologies use reflecting surfaces also for new demands of daylighting in the building core. To satisfy these demands core systems, such as solar pipes, are used when designing larger spaces dedicated to daylighting when there is not another available solution. Core systems gather sunlight with exterior heliostats and transport the light through light pipes of fibre optics (Tsangrathusulis, A. 2008).

The use of reflectors to increase sunlight levels on a desired surface is mainly found for solar energy optimization as an element in a solar panel system. In case of photovoltaic panels the power output increase reached 75 % more by setting a reflector (J. Nilsson, 2007). For solar collectors, the use of a reflector can improve the solar radiation by 62 % more than the same system without reflector (Grigonienė, J. Karnauskas, M. 2009). Reflectors are also commonly used to improve artificial lighting quality, performance and distribution. (Livingston, J. 2014)

Most reflectors in architecture are either heliostat or parabolic-shaped fixed reflectors to obtain direct daylight at most solar positions of the year towards the occupied space. For parabolic reflectors, designers can use Fermat's principle to shape the curvature (Nilsson, J. 2007). But parametric studies in computer simulation are used to assess

an efficient shape of fixed reflectors with more complex shapes (Lam Partners, 2017). These parametric studies require large amount of preparation and development time, therefore there is need for a fast method to assess similar conclusions.

Integrated-design and the consultation of specialist for architectural decision depend on fast, yet accurate, communication. This communication must lead to final designs, which could be limited by deadlines. (Balasubramanian N., Lee, J., and Sivadasan J. 2015). The consultation is also generally budgeted by time spent on it, therefore the development of a tool to shorten the decision-making process is beneficial for both clients and consultants.

1.3 Aim and objectives

The thesis aims to create a methodology to assess the optimal tilt of a fixed reflector through analysing the factors that influence illuminance levels on a desired surface. Thus the time required to assess the optimal tilt can be reduced by having the results calculated with the tool developed by the thesis methodology. It allows to the users to efficiently reach a decision and to evaluate different options.

1.4 Overall approach

The methodology commences with an investigation which purpose was to recognize the factors that influence the daylight performance due to reflectors in courtyards. The following step in the research consisted in a database building. Therefore, a quantitative methodology was the approach chosen to fill out the database and a posterior analysis to test the efficacy of the resultant tool.

Once the database was filled out with results of models with characteristics associated to the factor influencing daylight performance, it was tested and compared its results with a test model performed with traditional method of reflector tilt assessment. Through the comparison of results shown with graphic figures in results, the conclusions were drawn about the efficiency of the methodology.

1.5 Limitations

The methodology developed considers the analysis criteria on daylight illuminance performance exclusively, thus the objective tool for the methodology does not assess other factors related with sunlight such as thermal and visual comfort.

The surrounding geometry conditions and database precision of the study case are simplified, the geometry was studied as a two-dimensional geometry. Hence the results are not dependent on a three-dimensional geometry. Furthermore, the simulated cases did not include all the possible conditions but sets categories that comprehends similar conditions. Moreover, different reflector shapes, materials other than metallic, courtyard proportions and geographic locations are not taken into account.

2 Theoretical background

2.1 Tool development: Database

Since the sixties, prototype software has usually used database as a simple but reliable method to obtain accurate results from previously stored and arranged data. A database is an accumulation of associated information, organized and generally accessible by computing means (WordReference, 2017). For more detail, the used in this thesis methodology is an active database. It is active since the data stored in it is directly used by the tool to provide results in function of the inputted data. (Paton, N. W., Díaz. O. 1999).

2.2 Photometry

The photometry is necessary to explain how daylight is measured and which are the factors affecting daylight simulations. It is the presentation of the factors used to assess the efficiency of reflectors and therefore the construction of the tool database.

2.2.1 Solar radiation

Solar radiation or radiant flux is the energy emitted by the sun measured in Watts (W). The data used was measured irradiance which is the radiant flux per unit of area (W/m^2). The measured data available divides the irradiance in three parameters: Direct normal irradiance, diffuse horizontal irradiance and the combination of both measured horizontally, global horizontal irradiance.

The direct normal irradiance is the irradiance originating from the sun and measured orthogonally to the solar vector.

The diffuse irradiance is measured horizontally and it is the irradiance reflected by the atmosphere. It is measured by shading the direct irradiance. Thus it has direction from any angle of visible sky.

2.2.2 Luminous flux and Illuminance

Luminous flux is the energy radiated per unit of time in visible wavelength from a source. It is measured in lumens (lm). Lumens is a direct equivalent to W, the unit of radiation. The conversion depends on the visible wavelength of the radiation. White light irradiance converted to luminance with an efficacy factor of 179 lm/W. The simulation tool used had the conversion for the light spectrum as in equation 1 (Radiance, 2017).

$$\phi_v = (\phi_{e_{red}} \cdot 0.263 + \phi_{e_{green}} \cdot 0.655 + \phi_{e_{blue}} \cdot 0.082) \cdot 179 \left[\frac{lm}{W} \right] \quad \text{Eq.1}$$

Where:

ϕ_v is luminous flux in lm
 ϕ_e is the radiant flux in W

Illuminance, which is the measured quantity used to assess daylight levels in the simulations performed, is the luminous flux per unit area, and therefore its unit is lm/m^2 or lux.

2.2.3 Daylight autonomy

Daylight autonomy (DA) measures the illuminance for each year hour and is the percentage of hours where the illuminance is above a required illuminance value (Daysim, 2017). To perform a simulation for DA, the simulation tool calculates the illuminance for each hour of the year.

2.3 Simulation tool

For daylight simulation, the plug-in Honeybee for Grasshopper in Rhinoceros 5.0 was used. Grasshopper allowed to set parametric changes to the simulation and automatize the changes to perform several simulations. Honeybee used Daysim as simulation engine, of which RADIANCE was the script to follow for daylight simulation. Honeybee was an adaptation of Daysim to Grasshopper and it improves the visualization of the possible analysis.

2.3.1 Simulation type

Honeybee allowed many daylight simulation types. The simulation required for daylight autonomy is an annual type. The DA simulation records the illuminance value for each hour of the year. While using a point-in-time simulation type, as an illuminance simulation is, would have extended the time of simulation as it would require 8760 simulations.

In Honeybee, a daylight simulation requires the definition of the sky. To define the sky characteristics is used ambient values, which define this precision of the simulation. These values are ambient bounces, ambient divisions, ambient accuracy and ambient resolution. Ambient bounces are the maximum number of times a light ray is reflected on the surrounding, in figure 2.1 a single light ray bounces 4 times on the geometry. Ambient divisions are the number of divisions the generated sky has. Ambient accuracy is the error produced by interpolating two values of illuminance. Ambient resolution defines the maximum number of pixels per division of sky in the simulated environment (Daysim, 2017).

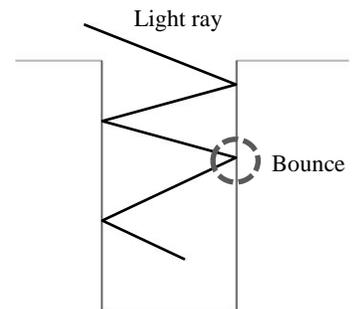


Figure 2.1 light ray bounces on 2D geometry

In the case of DA simulations, the diffuse irradiance was not uniformly distributed on the sky (Bourgeois, D., Reinhart C. F. and Ward, G. 2008). The simulation tool used Perez sky modeling which considers non uniform illuminance (Mardaljevic, 2016). The sky area adjacent to the sun position had higher diffuse illuminance at same irradiance.

Consequently, this could affect a reflector efficiency position at constant diffuse irradiance due to the solar.

2.3.1.1 Simulation in honeybee

The simulations, as explained in section 2.3, was performed in Honeybee in Grasshopper. A grasshopper script was necessary to perform the simulation. To create such script, an annual simulation script can be found in Honeybee description and introduction (Honeybee, 2017). Figure 2.2 shows the main groups of components used in the script. The figure is described in the following text.

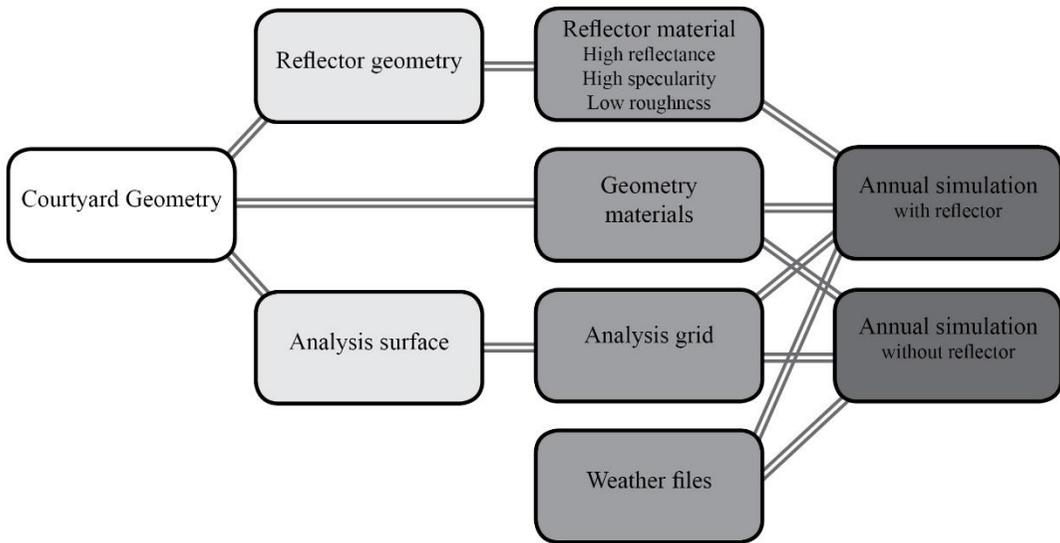


Figure 2.2 Tool components diagram

“Courtyard Geometry” contained the surfaces of architectural elements with influence on daylight distribution over the analysis surface.

Depending on the courtyard geometry the next column of components was formed. “Reflector geometry”, where the reflective surface was defined, as in section 3.1.3 is explained. “Analysis surface” had the script components that defined the position and dimensions of the surface where the analysis results were simulated.

The third column of components was translating the information as an input for the simulation. “Reflector material” and “Geometry material” connected the geometries to the script components and assigned reflective and texture characteristics. “Analysis grid” divided the surface into a grid of points and a mesh to allow detailed analysis. The size of the grid had a 1 m separation between nodes and consequently a single node obtained the illuminance measured in the center of an area of 1 m². The grid normal vector must be vertical to obtain valid results, since the simulation tool does not take in consideration light from the back of the surface. “Weather files” contained the the weather files as a list, both modified and original data. A script component

called slider allowed the selection of one weather file at a time. This slider can be animated to perform several simulations, one after another, automatically.

The last columns are the annual simulation components one connected to the reflector components and another unconnected to those components. Thus the comparison of the results between these two simulations allowed to assess the effects of the reflector on the daylight performance in the courtyard.

2.3.2 Weather files

Daylighting requires complex simulations to achieve accurate and realistic results. DA uses weather data collected from weather stations. The source of the weather files used was Energy plus. Energy plus compiles the measured weather data from other agencies such as International Weather for Energy Calculations (Energy plus, 2017).

An EPW file contains the weather data of one or several years by a weather station. Depending on the source it can be measured or synthetic data. The general information, including geographical location, source and conditions of the data, is at the beginning of the file. This information is important for the tool to locate the solar vector and for the user to understand the content of the weather data without further analysis.

Bellow the general information, the weather data for each hour of the year, including year, month, day, hour and minute, is listed. The weather data used in DA simulations were direct normal irradiance and diffuse horizontal irradiance correspondent to columns O and P in a spreadsheet. During the methodology this information is modified, thus it is important to locate it.

The illuminance data were neglected by the simulation tool. However, this data was available for verifying the validity of the simulation tool by comparing simulation result with the data measured at the given irradiance. With simple illuminance simulation on a plane normal to the solar vector the direct normal illuminance result should be the same than the specified on the weather file. Furthermore with the analysis plane horizontal the illuminance result should coincide with the global horizontal illuminance. Similarly with horizontal plane and overcast sky the result should be the diffuse horizontal illuminance specified on the weather file.

The files generated by the simulations were located in the folder of the simulation created by Honeybee, such as: ILL file, with the illuminance results is the main file to consider. The weather file or WEA file where the date and irradiance used were detailed. The files RAD showed the material for geometries and sky. Finally, PTS file detailed the coordinates of the simulation nodes. All these files allowed to identify the simulation since Honeybee storage of backup files did not allow to identify the simulation by name, in case that the simulations were automated to perform.

2.4 Reflector characteristics

A reflector is a surface designed to reflect light in a desired direction. The reflector, used in this thesis for the analysis performed, was fixed and planar. Aside from geometrical dimensions, other factors that influence the performance of daylighting are the reflectors' material reflectance, surface roughness and specularity.

Reflectance is the efficiency to reflect radiant energy. Surface roughness is the deviation between the surface irregularities normal vector with the surface normal vector. Surface roughness defines the texture of the material, thus a polish metal the surface roughness is low while corten steel has high surface roughness. Specularity is the capacity to reflect incident energy in a single direction. At high specularity, the angle between incident energy and the surface normal is the same as the reflected energy and the surface normal (Nayar, S., Ramamoorthi, R., Hanrahan, P. 2013).

High reflectance, high specularity and low roughness are required for the correct function of a reflector. This principle could vary in function of the distribution of light required. Lower specularity would diffuse the incident energy. A Lambertian surface has a material with no specularity and therefore all incident energy is reflected uniformly in every direction.

These three material characteristics are measured from 0 to 1. Metal and glass are the usual materials used on reflectors due to their high reflectance of 0.9, low roughness with values below 0.1, and high specularity with values above 0.9 (Honeybee, 2017).

3 Methodology

The methodology consisted in developing a database tool for optimal tilt calculations and included the following phases. Initially the variables influencing daylight values were defined such as those involved in the geometry and the photometry. With that knowledge, a database was created with the simulated results for each daylight values previously defined. The tool access to the database with the geometry and photometry values inputted by the tool user. Then, the optimal tilt was assessed for the inputted conditions with a spreadsheet tool. And finally, the results of the tool for a study case was compared with the results obtained through parametric study. Figure 3.1 shows the elements involved and explained in this methodology.

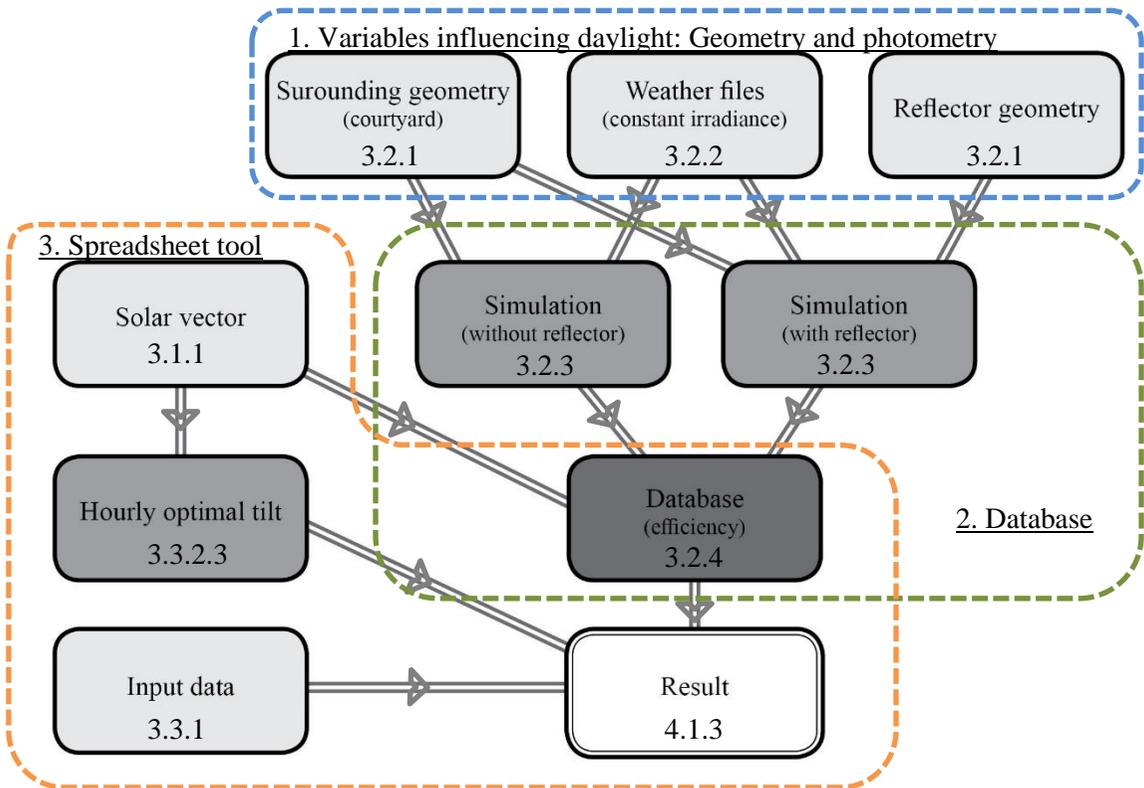


Figure 3.1 Methodology diagram

3.1 Daylight

This section describes the variables and factors affecting the values involved in daylighting calculations. The trigonometry involved in solar vector and the photometry to measure daylighting were calculated to assess the tilt and its efficiency.

3.1.1 Solar vector calculation

The solar vectors are the vectors formed by the sun and the earth. The solar vector (Figure 3.2), vector connecting the sun position point to the local location point on Earth, was calculated using the local axes. The local axes are Z as vertical vector, X as tangent to the parallel and Y as tangent to the meridian. The calculation of the solar vector for the local axes, used in the methodology to assess the optimal tilt on a given hour, used the steps explained in Appendix A.

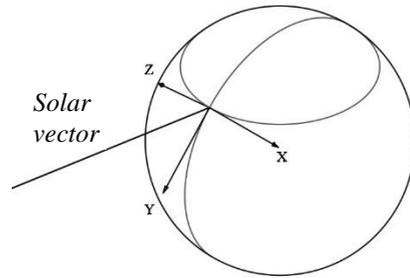


Figure 3.2 Planet with local axes

3.1.2 Solar vector use

From the solar vector, the azimuth angle (horizontal component) and the zenith angle (vertical angle) were calculated using basic trigonometry. The use of the solar azimuth and solar zenith is to create an access to the database for the solar vectors, as shown in figure 3.1, with similar values of these two angles. The axes used in this process are the same as the local axes in 3.1.1.

The vector was projected on the plane formed by axes YZ, thus the angle formed between this projection and the axis Y was the zenith angle.

Similarly the projection of the vector on the plane XY and the axis X formed the azimuth angle. Both processes are shown in figure 3.3.

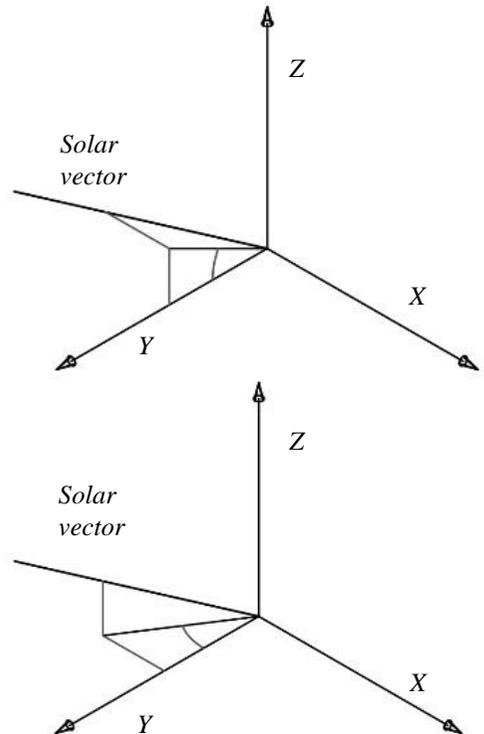


Figure 3.3 Vertical and horizontal angle

3.1.3 Tilt calculation

The reflector material was considered metal, with a high specularity thus the reflected solar vector formed the same angle to the reflector's normal as the incident solar vector. Furthermore, the optimal tilt was considered the one which allowed the reflected solar vector to coincide with a vector formed between the reflector and the analysis surface. Therefore, the bisecting of the angle between incident solar vector and reflector-surface vector was considered the normal to the reflector. Consequently, the reflector tilt is perpendicular the bisecting as it is shown in figure 3.4.

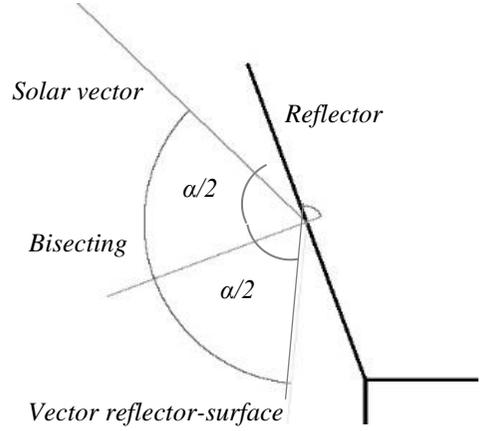


Figure 3.4 Reflection, bisecting and reflector

Equation 7 is the angle (α) formed by two vectors using inner product space method (Axler, Sheldon, 1997).

$$\alpha = \text{acos} \left(\frac{v_{\text{solar}} \cdot v_{\text{surface}}}{\|v_{\text{solar}}\| \cdot \|v_{\text{surface}}\|} \right) \quad \text{Eq.7}$$

Where:

v_{solar} is the solar vector

v_{surface} is the vector reflector-

surface

The vector reflector-surface was not vertical, therefore to calculate the tilt, in local axes, was necessary to assess the angle between the solar vector and axis Z, this is shown in figure 3.5. Equation 2 was used to calculate the reflector tilt angle (α_{tilt}) with the solar vector. This equation allowed to calculate the optimal tilt for any solar position in a year which was necessary to create a list of tilts for each hour of the year, which were necessary to obtain results as shown in figure 3.1.

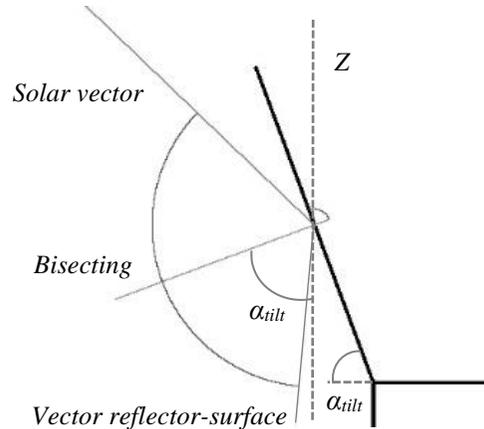


Figure 3.5 Reflection, bisecting and reflector

$$\alpha_{\text{tilt}} = \frac{\text{acos} \left(\frac{v_{\text{solar}} \cdot v_{\text{surface}}}{\|v_{\text{solar}}\| \cdot \|v_{\text{surface}}\|} \right)}{2} + \text{acos} \left(\frac{v_{\text{solar}} \cdot v_z}{\|v_{\text{solar}}\| \cdot \|v_z\|} \right) + 90^\circ \quad \text{Eq. 2}$$

Where:

v_{solar} is the solar vector

$v_{surface}$ is the vector reflector-surface

v_z is the axis Z

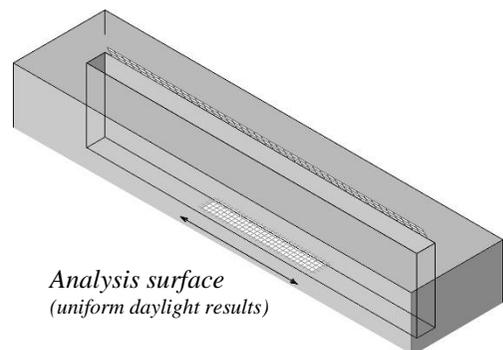
3.2 Database construction

The database, as shown in figure 3.1, is the accumulation of the results obtained in simulations with and without reflector. To include a complete variety of results in the database, the simulations performed had constant values on the factors explained in this section except one factor that varies from one simulation to another. For example, it was kept the same values of irradiance while the tilt of the reflector varies as explained in this section.

The database accumulates the results from simulations to cover most of the possible simulation conditions and these results are organized in function of the solar position, the tilt of the reflector and the irradiance values that the simulations had. These values make it accessible to a tool. The steps required to assemble the database are shown in figure 3.1.

3.2.1 Geometry

The geometry considered to gather the database was a three-dimensional courtyard geometry where the length, X axis in local axes, was 1000 m (figure 3.6). By having such length, the results obtained on the analysis surface were uniform and independent of any geometry on X axis, thus the simulation in the courtyard center was considered two-dimensional. This geometry decision is to simplify the variations of geometry required for the database to a width/depth proportion.



For the reflector, the width was set to 1.5 m.

The variation of tilt for the database was simplified to steps of 5° , considering from 45° to 85°

3.2.2 Weather file modification

The weather file needed to be modified to have constant irradiance values for the simulations to assemble the database. To modify the weather file was necessary to achieve constant irradiance and obtain results for the database. As explained in section 2.3.2, the weather file has the hourly weather data ordered in columns, where only the irradiance columns were changed to constant values for every hour of the year. The direct normal irradiance were modified to values of 0, 100, 200, 300, 400, 500, 600,

700 and 800 W/m² and were combined with the diffuse horizontal irradiance values of 50, 100, 150, 200, 250, 300, 350 and 400 W/m². Those values were selected due to simplification and limited by minimum and maximum irradiance recorded in the original weather file. That generated 72 differently combined weather files combined in table 3.1.

Table 3.1 Weather file irradiance combination

		Direct normal irradiance /W/m ²								
		0	100	200	300	400	500	600	700	800
Diffuse horizontal irradiance /W/m ²	50	0 & 50	100 & 50	200 & 50	300 & 50	400 & 50	500 & 50	600 & 50	700 & 50	800 & 50
	100	0 & 100	100 & 100	200 & 100	300 & 100	400 & 100	500 & 100	600 & 100	700 & 100	800 & 100
	150	0 & 150	100 & 150	200 & 150	300 & 150	400 & 150	500 & 150	600 & 150	700 & 150	800 & 150
	200	0 & 200	100 & 200	200 & 200	300 & 200	400 & 200	500 & 200	600 & 200	700 & 200	800 & 200
	250	0 & 250	100 & 250	200 & 250	300 & 250	400 & 250	500 & 250	600 & 250	700 & 250	800 & 250
	300	0 & 300	100 & 300	200 & 300	300 & 300	400 & 300	500 & 300	600 & 300	700 & 300	800 & 300
	350	0 & 350	100 & 350	200 & 350	300 & 350	400 & 350	500 & 350	600 & 350	700 & 350	800 & 350
	400	0 & 400	100 & 400	200 & 400	300 & 400	400 & 400	500 & 400	600 & 400	700 & 400	800 & 400

The modification to simulate with constant irradiance levels allowed to obtain illuminance results for the whole spectrum of irradiance conditions. Thus, it prepared the database to have data for any irradiance value. Therefore the database will be useful for different weather files and provide with valid illuminance results.

3.2.3 Simulation definition

The values defining the simulations for the database construction are shown in table 3.2. The ambient values were defined in the section 2.3.1.

Table 3.2 Simulation component definition

Component	Ambient bounces (ab)	Ambient divisions (ad)	Ambient accuracy (aa)	Ambient resolution (ar)
Value	5	2048	0.1	256

The materials assigned to the geometries involved in the simulations were as described in the table 3.3.

Table 3.3 Material characteristics

Element	Wall	Floor	Reflector
Reflectivity	0.6	0.3	0.9
Roughness	0.05	0.05	0
Specularity	0.1	0.1	0.9

The Honeybee script, specific for the required simulation, explained in 2.3.1.1, was developed to perform simulations automatically towards accumulate the data for the database. For this purpose, the daylight analysis was set to store the previous simulation in an exterior file by creating backup files where the data was extract from.

3.2.4 Data mining

The file where the illuminance results from the simulations was “simulation_name”.ILL. It had the results for every node of the analysis surface. The illuminance results to use on the database had to be from the same node from the analysis surface, as shown in figure 3.6, to obtain accurate and valid data. Table 3.4 shows an example.

Table 3.4 Example of spreadsheet visualization of ILL file

Illuminance for the database	Month	Day	Hour	Illuminance / lux Node 1	Illuminance / lux Node 2	Illuminance / lux Node 3
3900	1	1	12.5	3500	3900	3800
3300	1	1	13.5	3200	3300	3400

3.2.4.1 Efficiency database

The database contains the results of the difference between the results with and without reflector to the tilt of a reflector calculated for each hour, which is called efficiency. Thus the database contains the efficiency values for the simulation conditions previously described.

To reduce the size of the database for the spreadsheet a simplification in the tilts simulated was needed. The database contains the efficiency value for every 5° tilt variation with it 72 weather combination. Table 3.5 shows an example of database.

Table 3.5 Example of efficiency database for specific simulation conditions

Time /hour	Efficiency at 0 & 50 (W/m ²)					Efficiency at 100 & 50 (W/m ²)					...	Efficiency at 800 & 400 (W/m ²)				
	45°	50°	...	80°	85°	45°	50°	...	80°	85°		...	45°	50°	...	80°
1	-	-	...	-	-	-	-	...	-	-	...	-	-	...	-	-
2	-	-	...	-	-	-	-	...	-	-	...	-	-	...	-	-
...
10	0.95	0.99	...	1	1	0.98	1.39	...	1.08	1.06	...	1	1.42	...	1.1	1.02
11	0.98	1.02	...	1	1	0.98	1.42	...	1.08	1.05	...	1	1.43	...	1.12	1.02
...
3114	0.9	0.95	...	1	1	0.9	0.95	...	1.34	1.29	...	0.86	0.96	...	1.33	1.3
3115	0.89	0.95	...	1	1	0.89	0.95	...	1.35	1.28	...	0.88	0.95	...	1.35	1.27

...
8750	0.98	1.02	...	1	0.99	0.97	1.42	...	1.08	1.05	...	1	1.43	...	1.12	1.02
8751	0.96	0.99	...	1	1	<u>0.98</u>	1.39	...	1.08	1.06	...	0.99	1.42	...	1.1	1.02
...
8760	-	-	...	-	-	-	-	...	-	-	...	-	-	...	-	-

The access to the database and recalls the efficiency value for the specific conditions set by the user, these conditions are the solar azimuth, the solar zenith, the reflector tilt and the irradiance values. Continuing with the example, if the tool calculates the optimal tilt of 50° for the solar azimuth of 25° , solar zenith of 76° , correspondent to hour 8751, at direct irradiance 100 W/m^2 and diffuse irradiance 50 W/m^2 , the database provides with the efficiency of 0.98. Which is underlined in the table 3.5.

3.3 Tool description

The tool was divided in two parts. One part where the user inputs data and can visualize the outputs. The other part is the tool operations with the calculations and the database.

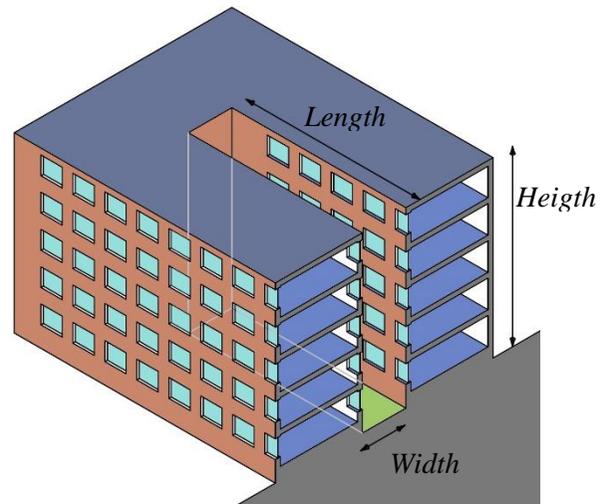
3.3.1 Input data

The data described in this section was the required to define a reflector optimal tilt with a tool. This data had to be compared with the one in the database for assessing the tool results.

3.3.1.1 Geometry

3.3.1.1.1 Courtyard definition

One of the simulations conditions with highest variability was the courtyard geometry. Of the courtyard geometry depended the access of light to the occupied areas. The definition of the courtyard geometry was complex due to a wide range of architectural design options. The tool offered a simple definition by considering only width, length and height. Figure 3.5 shows the shape of a courtyard and the geometric limitations. Thus, any geometry different to a rectangular cube had to be simplified to it.



3.3.1.1.2 Analysis surface

The analysis surface was constrained by the courtyard dimensions. Yet several possible conditions of the surface were considered, such as being horizontal or vertical surface or the distance to the parallel surface of the courtyard. Such variables described the occupancy spaces and information related with designers' purpose.

A vertical analysis surface shows interest on the daylight performance improvement on adjacent spaces to the courtyard. While a horizontal analysis surface is related to the occupancy of the courtyard itself. In figure 3.6 the surface occupies the habitual occupancy space in a courtyard, which is the area occupied at the height a sitting person would read, 0.8 m from the floor.

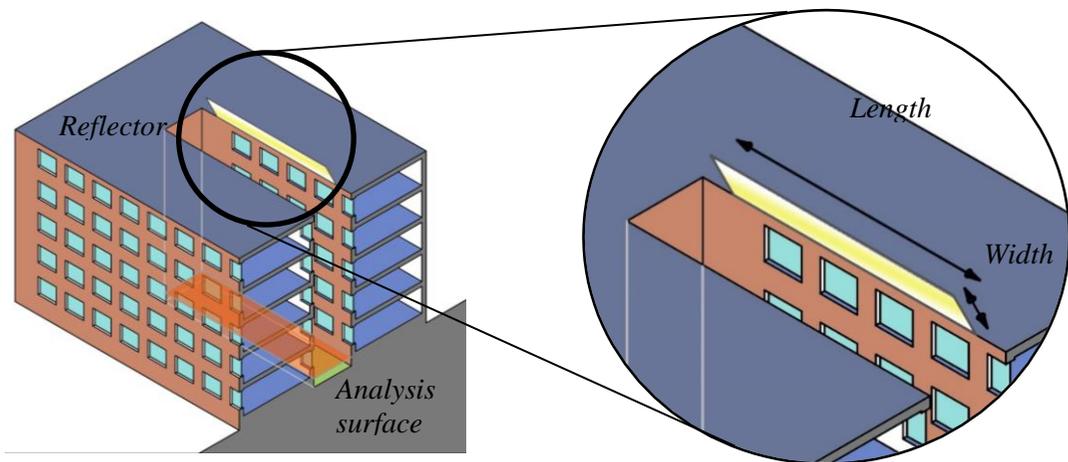


Figure 3.6 Analysis surface and reflector on courtyard shape

3.3.1.1.3 Reflector definition

The reflector geometry was defined as length, width and position related to the courtyard geometries. Length and width affected the efficiency of the reflector by redirecting more light and shading larger portions of sky, and therefore of diffuse luminance. The position is also determining in the calculation of the vector reflector-surface explained in section 3.1. In figure 3.7, the reflector geometry is shown as well as the reflector position was set on the north courtyard façade to reflect lights from the South.

3.3.1.2 Weather file

A weather file with which the irradiance values could be compared was crucial to be provided in the tool to obtain more relevant results. Moreover, the weather file contained information necessary for the solar vector and subsequent calculations, as

explained in section 2.3.2. A sheet was set as space for pasting the weather file to import the weather data into the tool.

3.3.1.3 Radiation threshold

The tool includes a radiation threshold to neglect a range of irradiance values. This threshold allows to consider determined weather conditions and sky types. Thus, the user can decide to obtain the results for improved or worsened conditions than the described in the weather file.

Setting the threshold above low levels of irradiance neglected winter hours and sunrise and sunset irradiance levels. Furthermore, low levels of irradiance are related to overcast skies and therefore, by setting the threshold above low levels of irradiance this types of sky are not considered in the calculation. Figure 3.8 shows the irradiance levels measured in an example weather file. While limiting high levels of irradiance neglected summer hours and clear skies.

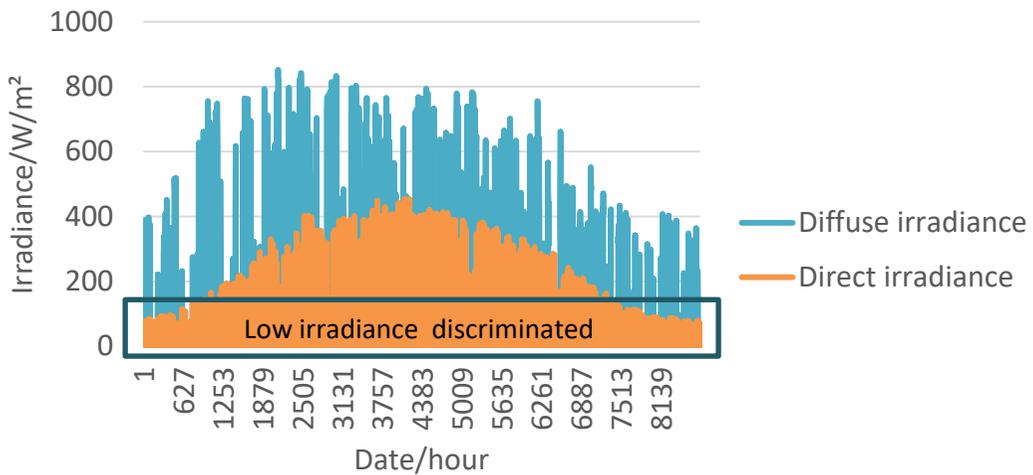


Figure 3.8 Example of weather file direct and diffuse irradiance

3.3.2 Tool operations

In this section is explained how the tool analyzes the input data and assesses the output results. The process consist in calculating the hourly tilt, assign to it the efficiency and create a list with the tilts to choose the optimal for the inputted data.

3.3.2.1 Tilt assignation

The tilt calculated from the angle between solar vector and reflector-surface vector was assigned to each hour. The solar vector was dependent on the latitude, which the tool obtained from the weather file previously inputted.

3.3.2.2 Efficiency assignation

From the weather file, the direct normal irradiance and the diffuse horizontal irradiance were assigned to each tilt. With those three values, tilt, direct and diffuse irradiance, the efficiency from the database was sorted for each case as shown in 3.2.4.1. The efficiency was related to the range of solar irradiance in the database as explained in section 3.2.2. Thus, the tool access to the database by checking the following steps:

- (1) Check the tilt: 45° to 85° in steps of 5°
- (2) Check the direct normal irradiance: 0 W/m² to 800 W/m² n steps of 100 W/m²
- (3) Check the diffuse irradiance: 50 W/m² to 400 W/m² in steps of 50 W/m²

In a case where the optimal tilt were 81° for the solar position correspondent of the hour 3114 where the direct irradiance was 800 W and the diffuse irradiance was 400 W/m² the efficiency selected would be 1.33 as shown in table 3.6.

Table 3.6 Example of database check.

Time /hour	Efficiency at 0 & 50 (W/m ²)					Efficiency at 100 & 50 (W/m ²)					...	Efficiency at 800 & 400 (W/m ²)				
	45°	50°	...	80°	85°	45°	50°	...	80°	85°		...	45°	50°	...	80°
1	-	-	...	-	-	-	-	...	-	-	...	-	-	...	-	-
2	-	-	...	-	-	-	-	...	-	-	...	-	-	...	-	-
...
10	0.95	0.99	...	1	1	0.98	1.39	...	1.08	1.06	...	1	1.42	...	1.1	1.02
11	0.98	1.02	...	1	1	0.98	1.42	...	1.08	1.05	...	1	1.43	...	1.12	1.02
...
3114	0.9	0.95	...	1	1	0.9	0.95	...	1.34	1.29	...	0.86	0.96	...	1.33	1.3
3115	0.89	0.95	...	1	1	0.89	0.95	...	1.35	1.28	...	0.88	0.95	...	1.35	1.27
...
8750	0.98	1.02	...	1	0.99	0.97	1.42	...	1.08	1.05	...	1	1.43	...	1.12	1.02
8751	0.96	0.99	...	1	1	0.98	1.39	...	1.08	1.06	...	0.99	1.42	...	1.1	1.02
...
8760	-	-	...	-	-	-	-	...	-	-	...	-	-	...	-	-

3.3.2.3 Tilt selection

The efficiency value multiplied by 10 established the number of times the tilt, which the efficiency value corresponded to, was repeated in the list. The reason to repeat it 10 times is to reduce de error due to rounding the efficiency to build the list. By repeating the tilt, the list increased in values. Thus the most efficient tilt were most repeated. From this list, average, median, highest efficiency and most repeated

rounded value were considered. The most accurate method was compared to real weather parametric study and the median value was the most accurate as it is shown in the results. Table 3.7 shows an example of this process.

Table 3.7 Efficiency and tilt list example

Time /hour	Tilt	Efficiency	Tilt list													
1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
...
10	49°	1.01	49°	49°	49°	49°	49°	49°	49°	49°	49°	49°				
11	50°	1.23	52°	52°	52°	52°	52°	52°	52°	52°	52°	52°	52°	52°		
...
3114	72°	1.42	72°	72°	72°	72°	72°	72°	72°	72°	72°	72°	72°	72°	72°	72°
3115	63°	1.24	63°	63°	63°	63°	63°	63°	63°	63°	63°	63°	63°	63°		
...
8750	69°	1.37	69°	69°	69°	69°	69°	69°	69°	69°	69°	69°	69°	69°	69°	69°
8751	67°	1.09	67°	67°	67°	67°	67°	67°	67°	67°	67°	67°	67°			
...
8760	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Following the example, for the tilt 63°, the efficiency was 1.24 consequently the tilt is repeated 12 times in the list. To select the optimal tilt, the list of tilts has a total of 60 values and the median values is 63°.

Furthermore the optimal tilt for each month was calculated by considering the median value for the hours of such month. Thus the tool offered the optimal tilt for a determined month.

3.3.2.4 Efficiency

The average efficiency was calculated for the tilt assessed by dividing the efficiency, values assigned in the tool at the irradiance values provided by the weather data, by the number of hours of daylight. Furthermore, the efficiency was calculated for each month using the same method than annually but using the list to the month hours.

3.4 Case study

A case was studied by performing simulation with Honeybee to compare the tilt parametrically obtained with the tilt calculated by the tool and choose the most accurate method.

3.4.1 Geometry

The geometry of the case study, to correctly compare with the tool results, needed to have the same proportions both in the simulation and in the tool. In this case, the infinite-long courtyard with same proportions and a limited long courtyard were compared. The proportions were 5 m wide, 20 m deep and 1000 m long or 5 m long respectively.

Equally, the analysis surface was placed 1 m above the floor and divided in 1·1 m² mesh. The 1.5 m wide reflector was placed on top of the north courtyard wall facing south and with the same length as the courtyard.

3.4.2 Location

The location was Copenhagen, with latitude 55.63° and the weather file was obtained from energy plus database. This location was the same as the one used to build the database thus the solar vectors were the same.

3.4.3 Parametric study

The parametric study was performed by varying 1° the tilt of the reflector to assess the optimal tilt. The study was performed through Honeybee simulations.

4 Results

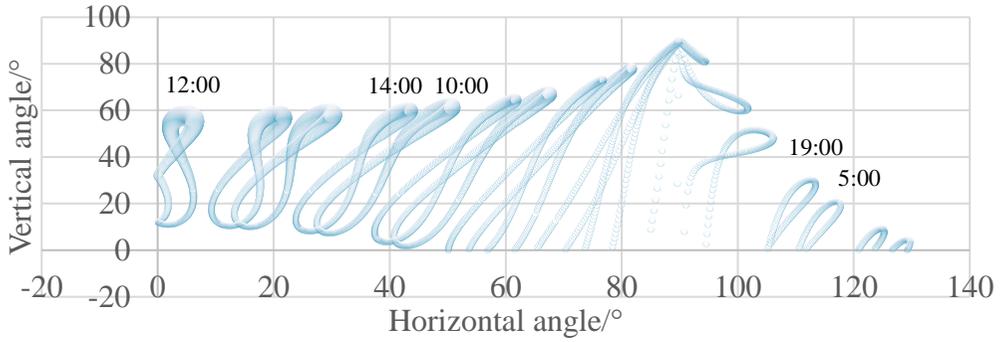
4.1 Daylighting

4.1.1 Constant results

In this section it is shown how a single factor varied, while the others are kept constant, affected the efficiency of reflectors for the study case.

4.1.1.1 Solar vector variation

The solar vector variation has effect on constant direct irradiance. The results are shown in figure 4.1. The circumference radius varies at vertical and horizontal solar angle. The measured illuminance increases with the increase of vertical solar angle. In the figure the solar path creates 8 shaped figures for each hour. These 8-shaped figures are composed by circles which radio are the illuminance obtained for such solar position and at constant irradiance. For any chosen hour there is a visible difference in radius, illuminance result, between winter, low vertical angle, and summer position, with high vertical angle. In summer, the vertical angle is higher and thus the illuminance measured in the courtyard is higher.



○ Illuminance at constant direct irradiance 400 W

Figure 4.1 Illuminance at constant direct irradiance in a constrained courtyard

4.1.1.2 Tilt variation

The reflector tilt variation is shown as the efficiency obtained by comparing with the illuminance without a reflector. The results shown on figure 4.2 and 4.3 are for constant irradiance for each at 12:00, solar azimuth at 0°. The first figure shows direct irradiance with no diffuse irradiance and the second shows diffuse without direct irradiance. Both cases show how tilts from 55 and 65° are more efficient for lower azimuth angles. Each angle has their own optimal efficiency for different dates of the year.

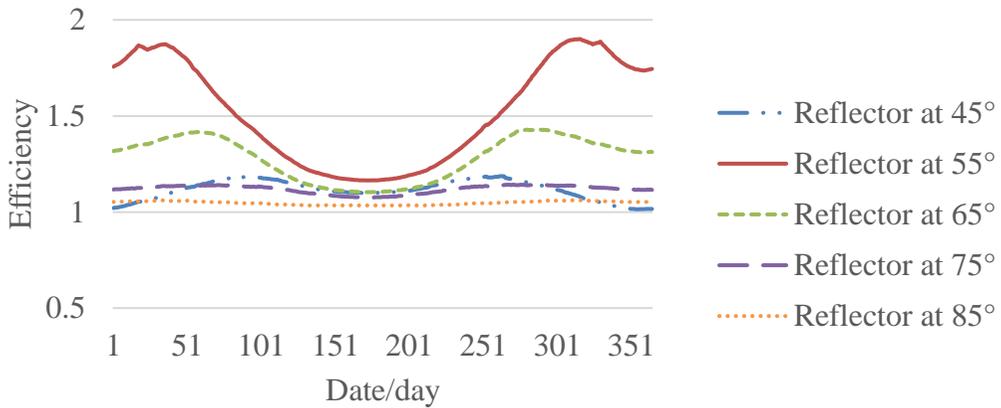


Figure 4.2 Tilts efficiency at constant direct irradiance 400 W at 12:00

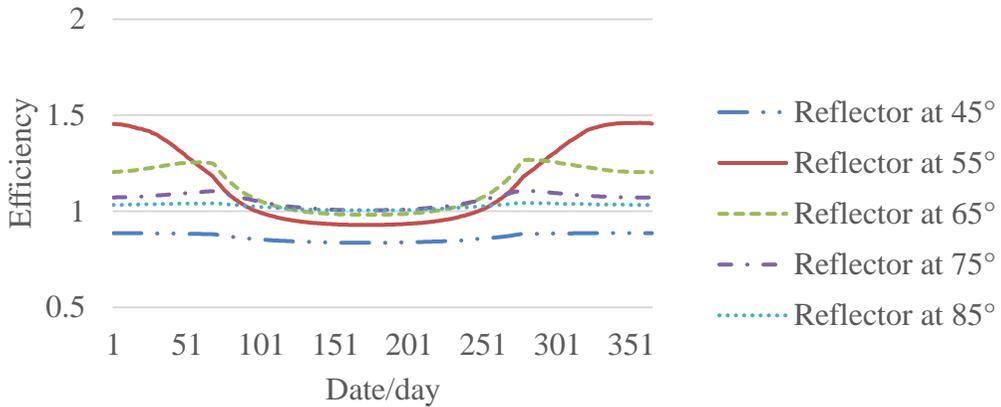


Figure 4.3 Tilts efficiency at constant diffuse irradiance 400 W at 12:00

Furthermore the influence of reflector tilt during the hours of daylight in different dates of the year are shown in figure 4.4. These results are for direct irradiance since constant diffuse irradiance has less variation efficiency during the day. The efficiency increases with lower solar zenith, correspondent low solar azimuth thus normal to the reflector.

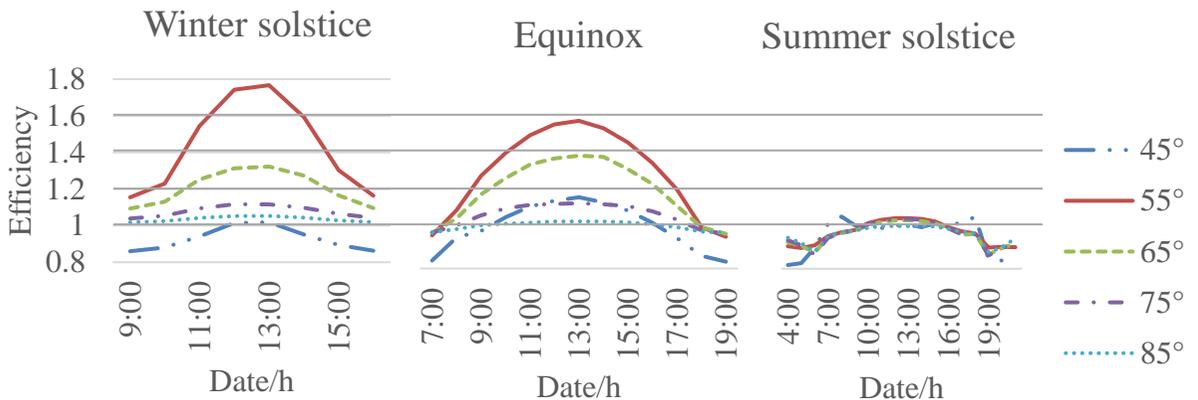


Figure 4.4 Efficiency at different hours of the day on solstices and equinox at constant irradiance 400 W

4.1.1.3 Irradiance variation

The irradiance variation affects the illuminance results, while the results between the simulations with and without reflector showed no variation in efficiency value, thus this section figures shows the illuminance results. Figure 4.5 shows the illuminance measured for constant direct irradiance without the reflector. Figure 4.6 compares with and without reflector for constant direct irradiance at 600 W/m². It shows the difference of measured illuminance under same simulation conditions.

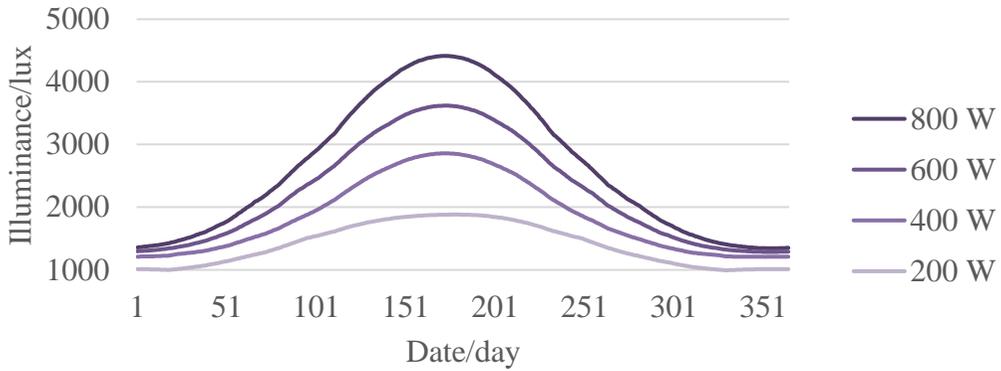


Figure 4.5 Illuminance at constant direct irradiance variation without reflector at 12:00

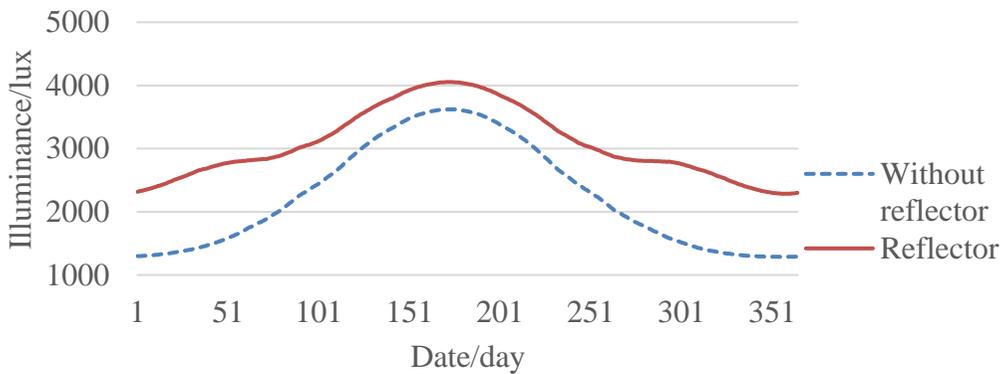


Figure 4.6 Comparison of illuminance at constant direct irradiance 600 W/m² at 12:00

Figure 4.7 instead shows the illuminance results to diffuse irradiance, equivalent to overcast sky. The results shown are without reflector. It shows that the simulation tool does not consider uniform sky, thus the higher irradiance are not parallel to the lower.

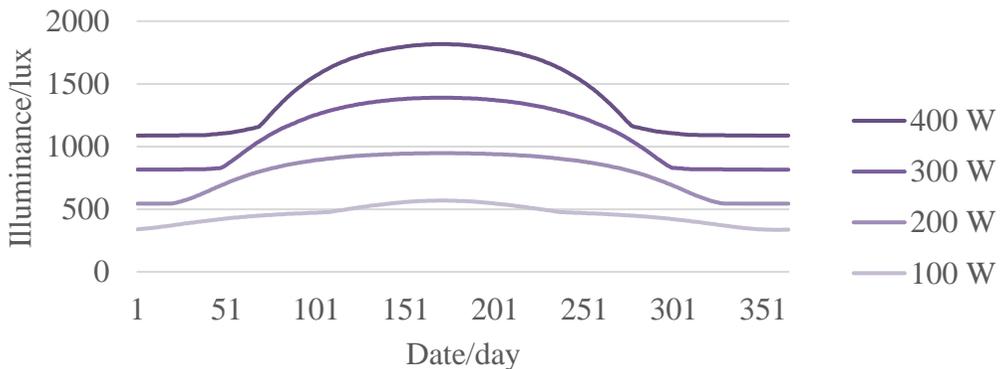


Figure 4.7 Illuminance at constant diffuse irradiance variation without reflector at 12:00

The comparison between the situation with and without reflector, figure 4.8, show how the reflector can reduce the efficiency by shading more diffuse than it reflect due

to solar position in summer season. Yet, in winter season, the illuminance measured has higher values while the irradiance was only diffuse.

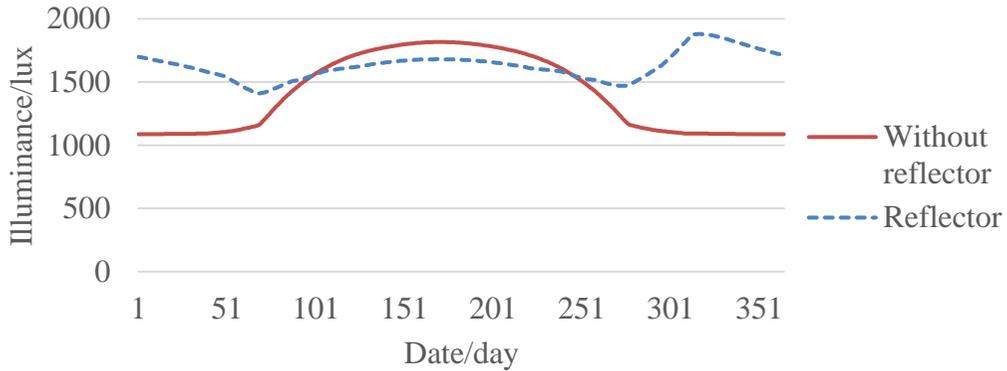
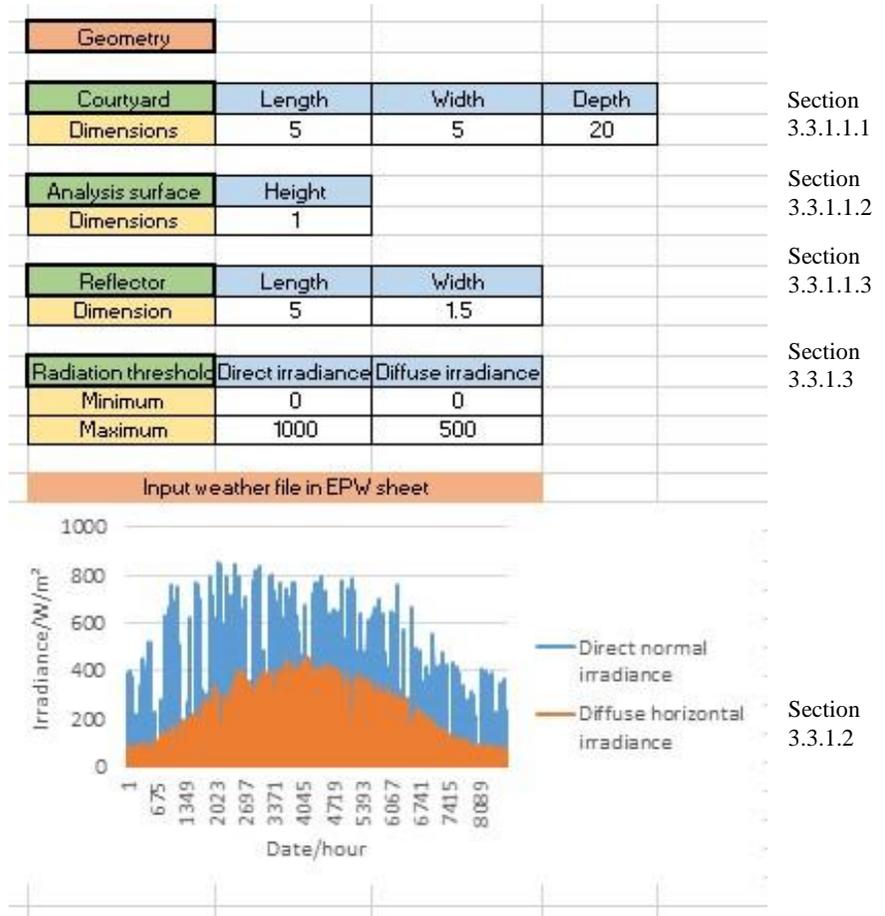


Figure 4.8 Comparison of illuminance at constant diffuse irradiance 400 W/m² at 12:00

4.1.2 Tool

The tool produces several results. It included a calculated optimal tilt for the reflector and the efficiency for the year and for each of the months. Furthermore it provide with the information for the optimal tilt for each month of the year and the efficiency for the year performance at such tilt and the performance for each months.

The tool spreadsheet main sheet contains the input geometry shown in figure 4.9 for the case in which the results were compared with and a figure to show the irradiance measured from the inputted weather file.



The first row is the courtyard dimensions. The analysis surface position and the reflector dimensions are the following rows. The last rows are

the radiation threshold to control which are the irradiances analyzed as explained in 3.3.1.3.

The result screen is shown in table 4.1 with the tilt results calculated by the tool on the first row and their efficiency on the second table. On right side are the output data, framed in red it is the main annual result. To the right from the annual result are the optimal tilts calculated for each month.

Table 4.1 Tilts calculated with the tool

Results	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tilt/°	63	50	54	60	69	73	74	74	70	63	55	51	49

Following the previous figure, the annual efficiency calculated for each of the tilts. In table 4.2, the annual efficiency is the first row. The rows below are the efficiency calculated by the tool for each month and corresponding to the tilts showed in table 4.1.

Table 4.2 Efficiency calculated with the tool

Efficiency for:	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Annual	1.08	1.03	1.08	1.08	1.06	1.06	1.06	1.06	1.06	1.08	1.08	1.03	1.03
Jan	1.20	1.18	1.20	1.20	1.10	1.10	1.10	1.10	1.10	1.20	1.20	1.18	1.18
Feb	1.16	1.11	1.16	1.16	1.09	1.09	1.09	1.09	1.09	1.16	1.16	1.11	1.11
Mar	1.09	1.02	1.09	1.09	1.08	1.08	1.08	1.08	1.08	1.09	1.09	1.02	1.02
Apr	1.03	0.96	1.03	1.03	1.05	1.05	1.05	1.05	1.05	1.03	1.03	0.96	0.96
May	1.00	0.94	1.00	1.00	1.02	1.02	1.02	1.02	1.02	1.00	1.00	0.94	0.94
Jun	0.98	0.93	0.98	0.98	1.01	1.01	1.01	1.01	1.01	0.98	0.98	0.93	0.93
Jul	0.99	0.93	0.99	0.99	1.01	1.01	1.01	1.01	1.01	0.99	0.99	0.93	0.93
Aug	1.01	0.95	1.01	1.01	1.04	1.04	1.04	1.04	1.04	1.01	1.01	0.95	0.95
Sep	1.05	0.98	1.05	1.05	1.07	1.07	1.07	1.07	1.07	1.05	1.05	0.98	0.98
Oct	1.15	1.07	1.15	1.15	1.10	1.10	1.10	1.10	1.10	1.15	1.15	1.07	1.07
Nov	1.17	1.13	1.17	1.17	1.09	1.09	1.09	1.09	1.09	1.17	1.17	1.13	1.13
Dec	1.20	1.20	1.20	1.20	1.10	1.10	1.10	1.10	1.10	1.20	1.20	1.20	1.20

Following the results showed in the two tables, the annual optimal tilt is 63° with an annual average efficiency of 1.08. Yet the average efficiency of 63° tilt in January is 1.20. If the user rather optimize the tilt for summer, the tool calculates optimal tilt for June and July 74°, reducing the annual average efficiency to 1.06. Yet in summer, the monthly average efficiency increases in 0.03 to 1.01.

4.1.2.1 Tilt

The annual results depended on a list of optimal tilt explained in 3.3.2.2. The median value from the list are shown in table 4.1. The annual result for the study case coincides with the tilt for early spring and late summer.

Table 4.3 Tilt annual result

	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tilt/°	63	50	54	60	69	73	74	74	70	63	55	51	49
Annual efficiency	1.08	1.03	1.03	1.08	1.06	1.06	1.06	1.06	1.06	1.08	1.08	1.03	1.03

The value for the average of the tilt list was 60°. The most efficient tilt was 54° with 1.19 efficiency. And the most repeated tilt in the list was 74°. Following are the calculated tilts optimal for the month and the annual efficiency for such tilt.

Furthermore, additional results were provided, assessing the efficiency of the selected tilt for each month, thus the user can compare the month behavior for the given fixed reflector tilt. Figure 4.10 shows the efficiency during the year for the three tilts calculated.

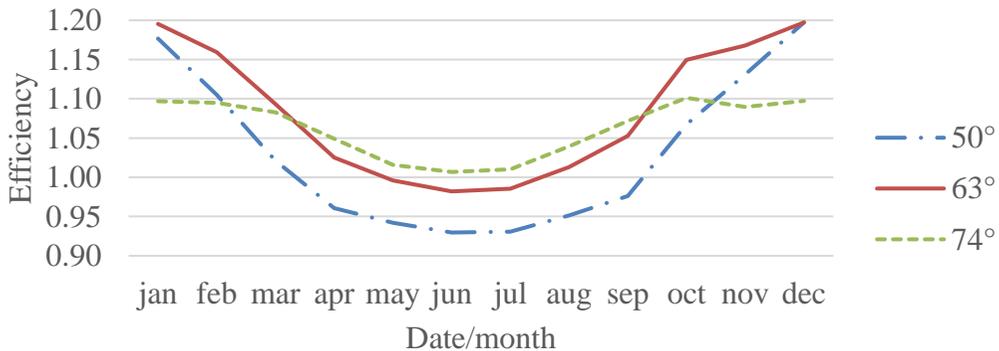


Figure 4.10 Tool calculated efficiency

This results show how optimizing for summer reduce the efficiency in winter while the opposite does make inefficient the reflector in several of the warmer months.

4.1.3 Parametric study

4.1.3.1 Tilt

For annual improvement, the efficiency obtained from the simulations with Honeybee are shown in figure 4.11 as function of the reflector tilt angle. The optimal tilt is 63° as marked with the vertical line.

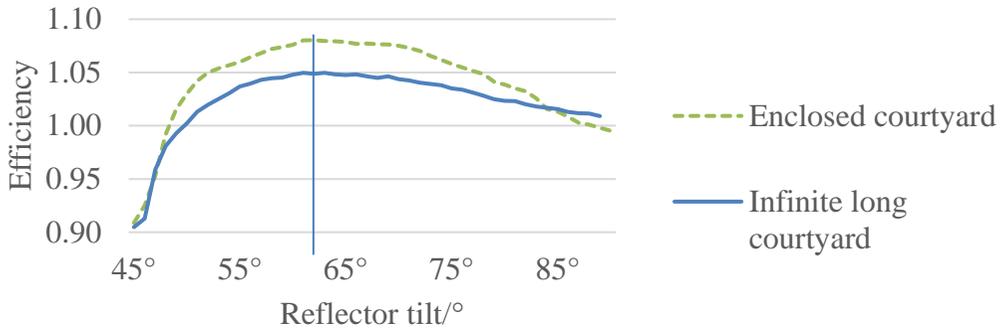


Figure 4.11 Annual efficiency for different tilts.

The reflector, for the simulated cases, can improve the annual daylight illuminance performance by 8 % in the case with enclosed courtyard, while a 5 % is the maximum annual efficiency for the infinite long courtyard.

Considering different periods of optimization the results vary from 52° for winter solstice, to 75° of summer solstice for the noon hours. Figure 4.12 shows the efficiency in function of the tilt angle for different dates. For the lowest solar azimuth seasons of the year, the optimal tilt can vary from 50° to 60°, while an optimal tilt for the highest comprehend between 70° and 80°.

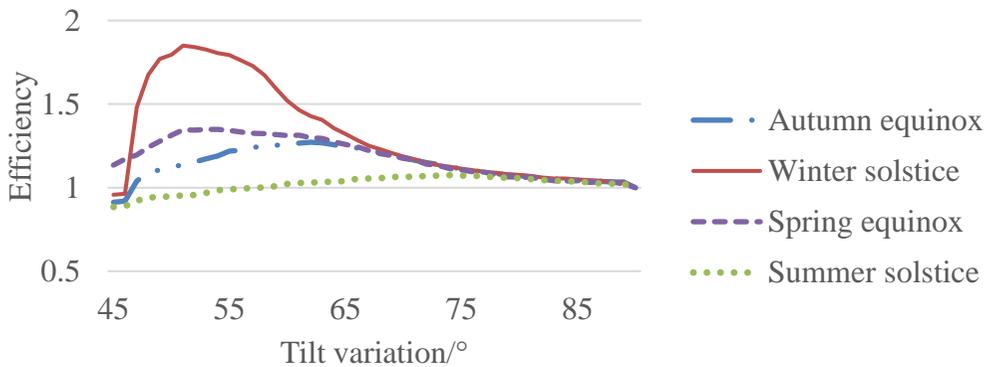


Figure 4.12 Efficiency for different dates

These results can be compared with the results from figure 4.13. Which shows the efficiency for determined tilts for everyday of the year. With the weather data it shows that reflector tilt under 75° shade diffuse irradiance during days of completely overcast sky. The overcast sky dates can be assumed since the efficiency drops. And below 55° the highest solar azimuth of the year also reduce efficiency.

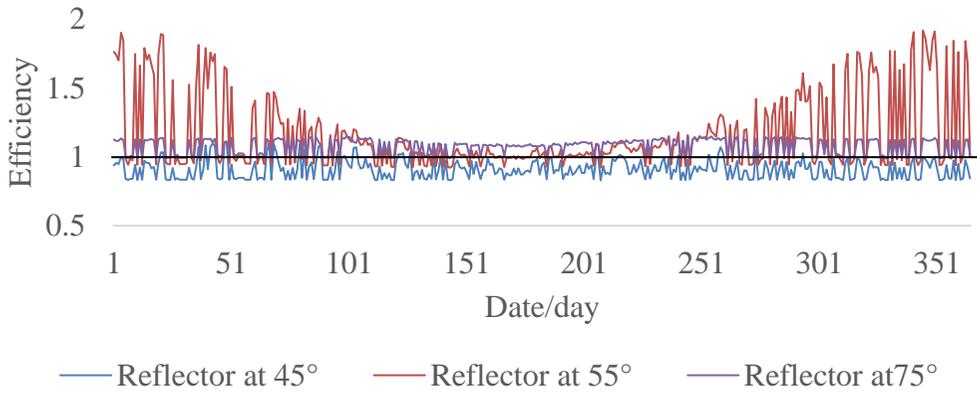


Figure 4.13 Efficiency for different tilts during the year

To show compare with the tool efficiency figure 4.14 shows the efficiency during the year for the three tilts compared in the tool results. Figure 4.15 the direct comparison for both tool calculated and parametric study efficiency results.

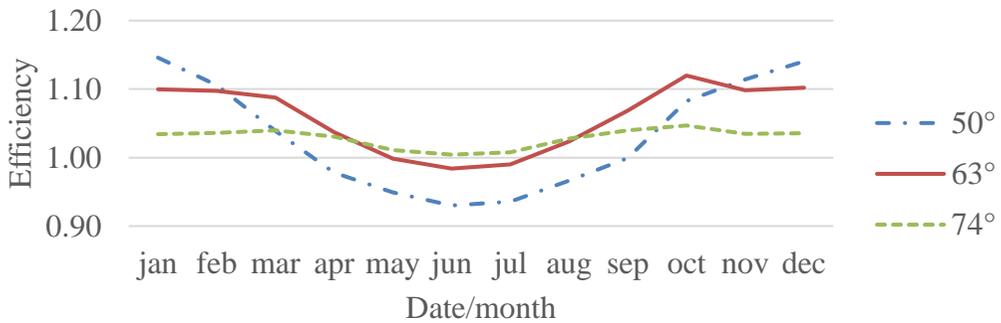


Figure 4.14 Efficiency for given tilts

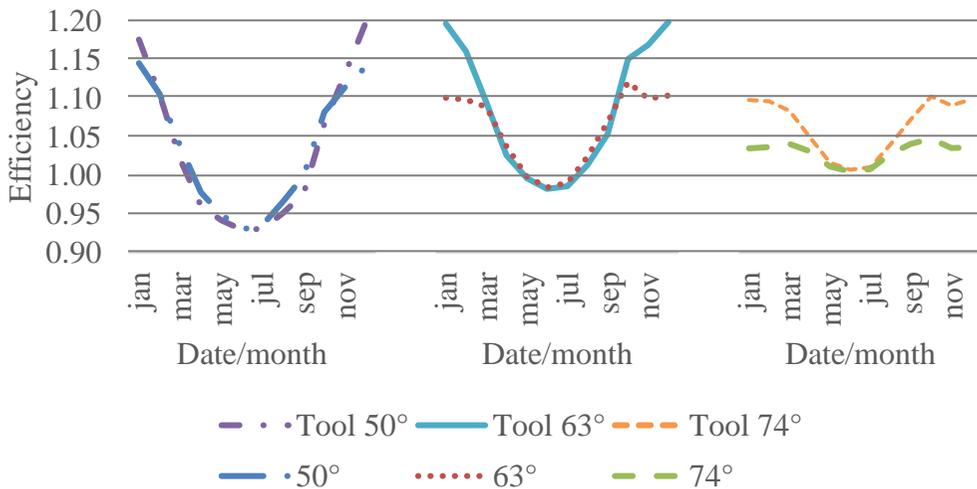


Figure 4.15 Efficiency calculated by tool and parametric study

5 Discussion

The access to an optimal tilt calculator tool reduces the time for assessing the parameters of study by already having a generic database that can cover multiple cases. The generation of such a database requires more time than the simulation of the specific study case. Yet the database is part of a tool prepared in advance and thus, accessible when it is required. The tool provides easy access to results that would require knowledge to, otherwise, reasonable assess. Thus, it is a transferable introductory tool to the behavior of fixed reflectors.

5.1 Methodology

The database methodology has the potential to cover a wide range of situations. However, during the process explained in 3.2, it is difficult to add enough variables to obtain a realistic result and still have a manipulable database and fast operations required to obtain the result. Therefore a database simplification is required to create the tool in a spreadsheet software.

Furthermore, the database methodology requires of simplifications, such as it is described in section 3.2, since it cannot contain all possible cases. This simplifications require of operations that overcome the imprecisions on the results. However, it is expected that the tool user will do their own simulation study once results outside of the scope of the tool are required.

Since the methodology requires simplifications, thus prediction is needed to exclude unnecessary data for the assessment. Therefore, the user have to foresee the most usual cases to assess in his professional life and thus having a more precise database. For example, creating a database related to the location where the user usually works instead of a location where the user will rarely has to work in.

By building the database with constant simulation conditions, the tool has access to results for alternative simulation conditions. The section 4.1.1, the constant simulation conditions results show the range of conditions. The influence of the solar position, figure 4.1, shown that higher solar zenith, summer season, increase the illuminance in the courtyard, reducing the need and influence of a reflector. The reduced efficiency of a reflector for summer season is reinforced by the results shown in figures 4.2 and 4.3, which show season to improve are autumn and winter.

The tilts down to 55° are more efficient than higher tilts in winter seasons because the illuminance obtained in winter is lower due to the low solar zenith. Therefore a low tilted reflector can obtain higher efficiencies by improving the least daylight illuminance season. Yet, the efficiency shown in figures 4.2 and 4.3 for 45° tilt shows that such tilt reduces the efficiency at any season of the year due to shading, with the reflector surface, more diffuse daylight than it reflects diffuse and direct. Therefore

45° shades daylight on the courtyard. This is reasonable since there are not many hours of the year where the solar position has a solar zenith below 10° which would have been reflected optimally with 45° tilted reflector.

Furthermore, figure 4.3 shows that overcast skies are simulated as non-uniform diffuse irradiance distribution, and therefore the solar position did influence the illuminance on the courtyard.

The hours of higher reflector efficiency during the day, as figure 4.4 shows, are between 10 and 14 hours. This is due to the reflector face towards south, yet if the goal to improve is on different hours of the day, as could be in a school improving mornings, the orientation of the reflector can affect to the efficiency.

The relation between irradiance and illuminance is shown in figures 4.5 and 4.7, where the higher the irradiance is, the higher is the illuminance measures, as it was expected. Yet figure 4.7 shows the illuminance for only diffuse irradiance proves that the solar position influences on the illuminance obtained from the simulations with Honeybee. The curve corners are where the influence of the solar position starts to overcome the illuminance obtained by the diffuse irradiance independently of the solar position. Thus the solar position is less influent on the illuminance during the year with higher diffuse irradiance with no direct irradiance available.

Figure 4.6 shows that a reflector is more efficient than having no reflector, increasing the illuminance during the whole year for clear and intermediate skies with direct irradiance. In winter, the reflector can duplicate the illuminance in the courtyard and the installation of a reflector is more efficient for winter season. With overcast skies, as figure 4.8 shows, in summer the reflector can shade part of the sky and therefore reduce the illuminance. However the reflector is more efficient in winter even with overcast sky.

5.2 Tool

The database was built with the same location and geometric dimensions as the case study thus the tool provided more accurate result than if the location and geometry were different.

5.2.1 Input

The geometry variation explained in 3.4.1 from the original case had small influence on the final results. Only slight variations in the vector reflector-surface and therefore the optimal tilt for each hour. As explained in section 3.1.1, the variation of the vector reflector-surface varies the optimal tilt for an hour in half a degree for every degree variation. Furthermore, the database was compiled, as explained in 3.2.1, with data for tilts in steps of 5°. Thus the results were similar for any geometry variation that varied the hourly tilt in less than 5°.

The main influential characteristic on the results was the weather data imported; it provided the irradiance levels. The irradiance levels variation, as figures 4.5 and 4.7 show, has impact on the efficiency of the reflector. Likewise, it defined the location data for the solar vector calculation and consequently, the weather data affects on the optimal tilt.

5.2.2 Output

As a tool it provided a result for the optimal tilt and furthermore, provided efficiency performance to be able to understand the behavior of the reflector during the year. From this output it can be assess when a reflector would shade more solar irradiance than it redirects it, as it shows figure 4.13. Thus the tool provide the chance to consider the reflector tilt, through interpretation of the reflectors performance in different months of the year, further than a simple annual daylighting improvement. Thus, it gives the chance to consider optimization for a period of time shorter than a year.

There was a difference between the tool calculated efficiency and the parametric study efficiency, which was due to the simplifications on the tool database as figure 4.15 and the comparison of figures 4.10 and 4.14 proves. The tool gathered the efficiency from simulation conditions varied on steps, as explained in section 3.2, consequently the efficiency was not precise and it showed considerably similar values for the results obtained under similar simulation conditions such as difference of optimal tilt for an hour under 5°, difference direct irradiance under 100 W or difference diffuse irradiance under 50 W.

Based on the results of the tool compared to the parametric study result, the methodology could be consider satisfactory. The tool tilt results did coincide with the parametric study result. Yet, it requires further analysis and testing to consider the accuracy of the tool outputs. The results of the database and the parametric study are for very similar simulation conditions and same location of weather data. Therefore the tool is successful to calculate the optimal tilt for the case study and a reasonable location and geometry variations.

The tool results are weather dependent, thus the result for a same location with different measured irradiance provides different results and allows to assess the efficiency of a reflector installation under different predictions for future weather conditions.

5.3 Reflector efficiency

The results presented in figures 4.14 to 4.15 showed that a reflector can improve or reduce the daylight efficiency during a day or a year. The reflector can be designed to shade during undesired bright season and improve the daylight in others. Those are decisions that can modify the optimal tilt required, where the objective is no longer the annual improvement.

In the study case, installing a reflector could improve the daylight annual performance less than a 10 %. But the simulated efficiency in specific dates could increase above 50 % in winter season, due to the fact that redirected light from low solar zenith towards the required space has higher potential of improvement than from high solar zenith. Thus, a reflector can be beneficial for the location studied, considering clear or intermediate sky.

In case of overcast skies, the reflector can be beneficial depending of the diffuse irradiance and solar position level as figure 4.8 due to the use of non-uniform sky models by the simulating tool. The tool and the study case did not consider factors such as surrounding geometries, thus any case study requires of further study and consideration.

6 Conclusions

The methodology can achieve an accurate tool, as it is shown in section 4.1.4 by obtaining the same results with the tool and parametric study on a case study to calculate the optimal tilt of a daylight reflector and an approximated efficiency during the year.

Furthermore, the optimal tilt depends on the desired season to improve the daylight performance. The reflector can reduce daylight performance if the optimal tilt is decided to optimize one season over the others.

Reflectors are efficient for daylighting improvement in Copenhagen location in the case study performed as shown in figure 4.13. It is especially efficient for winter season when the solar zenith is low and the incidence angle does not allow direct irradiance to reach the bottom of the courtyard.

The installation of a reflector on courtyards is less efficient for higher solar zenith. Conclusively, reflectors can be more efficient as illuminance improvement method in courtyards on locations with high latitude, and therefore low zenith angles.

Future development

This methodology and tool require of more development to be able to assess more variable situations such as covered courtyards, different reflector materials or reflector dimensions. Thus, a database with access to data for different global locations and geometry variations will be improved.

Another daylight factor to consider is visual comfort due to glare. This factor is related to the material of the reflective surface. Consequently, reflectors can be a source of glare that can reduce the visual comfort for the user.

Furthermore, the inclusion of thermal influence of the reflector in the building performance could provide with another fundamental factor and complete the usefulness of a reflector.

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Figure 1.1: *Kahn building, Kimbell art museum in Fort Worth, Texas.*

Author: Andreas Praefcke

Source:

https://en.wikipedia.org/wiki/Kimbell_Art_Museum#/media/File:Kimbell_Art_Museum_Fort_Worth_galleries_1.jpg Visited: June 2017

Figure 1.2: *Sky net-reflector, Fulton center,*

Author: MusikAnimal

Source: https://en.wikipedia.org/wiki/Fulton_Center#/media/File:Sky_Reflector-Net_in_Fulton_Building.JPG Visited: June 2017

Appendix A: Solar vector calculation

To calculate the solar vector, the following steps must be followed:

Calculate the declination δ , which is the angle between the solar vector and the Earth plane, with equation 1.

$$\delta = 23.45 \sin\left(\frac{360(284+n)}{365}\right) \quad \text{Eq.1}$$

Where:

n is the day number

Calculate the hour angle ω , which is the angle formed with the solar noon at an hour, with equation 2 and subsequent. The hour angle for noon is 0° .

$$\omega = \left((hh - 12) + \frac{mm+E}{60} \right) 15 + L_{st} + L_l \quad \text{Eq.2}$$

Where:

hh is the hour

mm is the minutes

L_{st} is the state latitude

L_l is the local latitude

$$E = 229.2(0.000075 + 0.001868 \cos(B) - 0.0032 \sin(B) - 0.014615 \cos(2B) - 0.04089 \sin(2B)) \quad \text{Eq.3}$$

$$B = 360 \frac{n-1}{365} \quad \text{Eq.4}$$

Where:

n is the day number

And finally the solar vector for local axes with equation 5.

$$R_{loc} = (\cos(\delta) \sin(\omega), \cos(\delta) \cos(\omega) \sin(\lambda) - \sin(\delta) \cos(\lambda), \cos(\delta) \cos(\omega) \cos(\lambda) + \sin(\delta) \sin(\lambda)) \quad \text{Eq.5}$$

Where:

λ is the latitude

The calculated solar vector using the spreadsheet was compared with the solar vector calculated in grasshopper by Honeybee EPW importer for verification.

The solar vector was calculated in the spreadsheet and by honeybee are shown in figure A.1 to verify the validity of the calculations. The results shown are daily vector tilt at 12:00. Each data has parallel scale to show the result for both calculation system. The difference between winter solstice and summer solstice is of 46° which coincides with the annual zenith. Consequently it is considered solar vector calculation valid to assess the hourly tilt of the reflector.

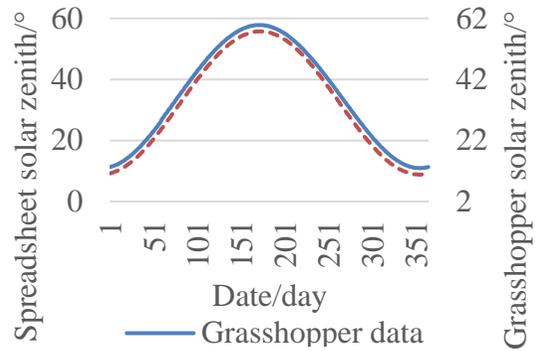


Figure A.1 Solar zenith calculation results with honeybee and spreadsheet



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