POLITECNICO DI MILANO

Building and Architectural Engineering

Track: Building Engineering

CHAMELEON: SHAPING VISUAL COMFORT.

A PARAMETRIC TOOL FOR FAÇADE FORM- FINDING IN THE EARLY DESIGN PHASE.

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ABSTRACT

This thesis work explains the process and the steps of the definition of Chameleon, a parametric tool for Grasshopper. Chameleon is intended as a plug-in for designers, allowing them to consider visual comfort and energy savings in the earlier stages of the design, during the form-finding, leading them to a more conscious choice of the final shape of the façade. The main aim of this tool is to bring some parameters into the clue of the design, using them not anymore as criteria to validate or reject the proposed solutions, but as integrated parts of the design, guiding it towards the optimization for the daylight comfort and the energy reduction from the very first stages of the process.

KEYWORDS: Climate Based Daylight Modeling, Visual Comfort, Parametric Design, Chameleon, Plug-In, Annual Sunlight Exposure, Spatial Daylight Autonomy, Building Integrated Photovoltaic, Form-Finding

ABSTRACT

Questo lavoro di tesi si pone l’intento di spiegare il processo e i passaggi logici che hanno portato alla definizione di Chameleon, uno strumento parametrico utilizzabile mediante il software Grasshopper. Chameleon vuole essere un plug-in per progettisti, permettendo loro di considerare possibili valori di comfort visivo e di risparmio energetico nelle prime fasi di design, durante il processo di form-finding, portandoli a una scelta più consapevole di quella che risulterà essere la forma finale della facciata. L'obiettivo principale di questo strumento è di permettere ad alcuni parametri, altrimenti utilizzati come criteri di convalida di una soluzione proposta, di assumere un ruolo principale ed entrare nel vivo del progetto come parti integranti, guidandolo verso l’ottimizzazione del comfort diurno e del risparmio energetico sin dalle primissime fasi del processo.

NOMENCLATURE

ACRONYMS

ASE	Annual Sunlight Exposure
sDA	Spatial Daylight Autonomy
BIPV	Building Integrated Photovoltaic
SVF	Sky View Factor
NZEB	Nearly Zero Energy Building
DF	Daylight Factor
UDI	Useful Daylight Illuminance
DA	Daylight Autonomy
HB (HB+)	Honeybee Legacy (Honeybee+)
GH	Grasshopper
CBDM	Climate-based Daylight Modelling
VT	Visual Transmittance
SHGC	Solar Heat Gain Coefficient

UNITS OF MEASUREMENT

ASE	[%]
sDA	[%]
SVF	[-]
DF	[%]
UDI	[lux]
DA	[lux]
VT	[%]
SHGC	[-]
Thermal transmittance (U-Value)	[W/m^{2}K]
Linear thermal transmittance (Ψ)	[W/mK]

“Architecture is an art of pure invention. Unlike the other arts, [it] does not find its patterns in nature, they are unencumbered creations of the human imagination and reason. […] For, regardless of which artistic creation of architecture we look upon, it was primarily and originally always conceived to satisfy particular material needs, primarily that of shelter and protection from the onslaught of climate and the elements or their hostile forces. And since we can gain such protection only through combining the materials nature offers to us into solid structures, we are always forced to adhere closely to the structural and mechanical laws.”

Gottfried Semper, 1854

1. INTRODUCTION

This thesis work arises as the completion of our two years Master of Science Degree, putting together the topics dealt with in these two years which represent a common field of interest. In fact, this work treated many aspects of façade design, meeting the interests of all the components of the group. The aim is the definition of a parametric tool, which at the end of the process came out as a climate-based plug-in for Grasshopper called Chameleon, to design façades to guarantee visual comfort and reduce energy consumption. Along with the most engineered part of the work, which includes mathematic, geometric and energy calculations, another relevant component of the study has been its combination with the architectural issue, in order to obtain results and "bend" the work for a more effective designer's approach to the topic.

This work fits well in a context of studies that are moving towards the design of responsive envelopes, which see the "building skin as a responsive skin, as one component of the sustainable low energy concept."[1] Lang states that there are some questions that the designer needs to address related to a façade, which are related mainly to three areas: Function, Construction and Form. Moreover, after the increasing attention that it is paid to the ecological awareness, to the research of means of CO_2 emissions reduction, to the requirement of the lowest possible energy needs and their satisfaction through a production of energy done by the building itself, according to the principle of NZEB, a new factor should be added, which is Ecology.

- Function: what is the practical purpose of the building/the building skin?
- Construction: what are the elements/components of the building skin and how are these elements assembled into a whole?
- Form: what does the building/building skin look like?
- Ecology: what is the energy consumption of the building/building skin during construction, use and demolition?

The aim of this study is to create a tool which can combine all the aspects seen before; as a matter of fact nowadays, the trend in the construction field is to move towards the realization of complex models where the interoperability is the keyword and all the information and the different aspects

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[1] C. Schittich, "In DETAIL Building skins", Birkhauser, Berlin,2001

of the building are recorded together: different characters work together applying changes, adding information in real time, which change downstream the overall project. However, the BIM process is introduced in a step subsequent the form-finding one; form-finding is a step where the “old manner” approach is still used: the designer’s idea needs to be checked and validated by engineers about thermal, energy, structural and other aspects; every time a change is applied, the project comes back to the designer, in a looped process until the final project is validated by everyone.

Therefore, there is a lack of tools especially studied for the designer which comprehend all the engineered aspects and allows him to perform a design of the façade without the need of the iterative process explained before. Hence the aim of creating a tool especially designed for the architect, which can perform the form-finding process, taking into account the energy, daylight and visual comfort and the construction issues. The geometries proposed to the designer have been previously studied in order to guarantee the satisfaction of the technical and production requirements; they will be tested in different fields: visual comfort, energy production and consumption, allowing the designer to make a conscious choice of the final façade.

This process is complex, since it implies the study and the deepening of many different aspects which will converge to reach the final goal. Along with the researches on the parameters to consider and evaluations on the ways of assigning a hierarchy to the factors considered, the main challenge has been the definition of the characteristics of the tool. Both following a path tracked by one of our colleagues, Pietro Pavesi, with his work titled “A parametric design workflow applied to a responsive curtain wall system for daylight optimization of an existing building” and considering the direction taken by similar studies, the final decision has been the development of a Plug-in for Grasshopper, able to obtain at the end of the optimization process a performing configuration of the façade.

Pietro Pavesi’s thesis was a study on a form-finding process which was based and driven by the energy efficiency of the system and the indoor visual comfort. It lays the foundations for a design process aiming to guarantee to the inhabitants a comfort in terms of daylight and energy savings with the definition of a performing combination of shapes and materials. Though, this process was especially studied for a climate with all the relative restraints; as a consequence, a further optimization of the study would be the definition of a more complex flow, which can allow the calculation of the final performing configuration starting from whichever climate and context, making this process as general as possible.

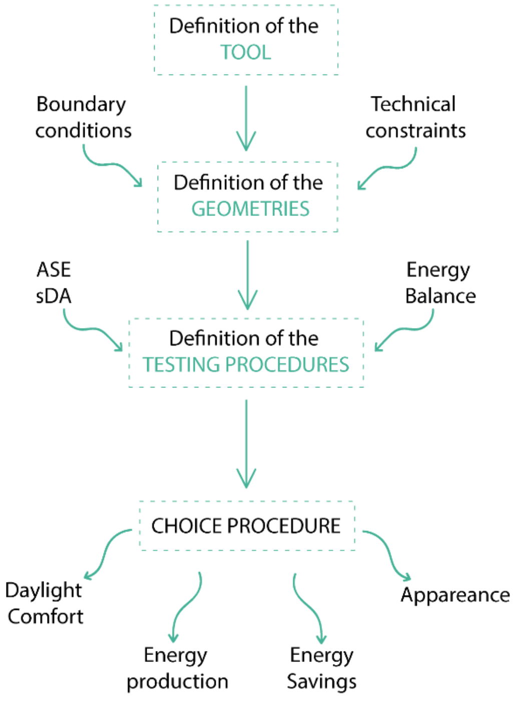

Figure 1-1: Main steps of the process

It is possible to simplify this thesis study in four main stages, which start from the definition of the tool: this phase comprehends all the preliminary studies done on the parameters to be considered, on the existing prescriptions for the daylight and thermal comfort, on the different rating systems and the already existing tools performing similar analyses. The subsequent step has been the evaluation of the technological aspects which may possibly influence the geometry and giving it some constraints and limitations. Ideally, the definition of geometries, intended also as a combination of different materials can be evaluated according to the boundary conditions, which have been studied too, in order to establish which are the inputs that the user has to provide. Subsequently, the flow for the testing procedure has been developed, defining simplified methods of calculations for the daylight values and the energy balance. The output of the testing procedure will be object of further optimizations according to the will of the user, who will choose at the end the best configurations between the possible ones, guided mainly by four main factors: daylight comfort, energy production, energy savings and architectural appearance. Hence the name chosen for the tool: Chameleon; in fact, the tool combinates materials and shapes, in order to obtain the best configuration according to the boundary constraints and to the environment the building it is placed in.

In the next chapters all of these steps will be explained, enhancing the merits, the pros of the choices done and the improvements made on the analysis procedure; difficulties and struggles met during the development of this study will be addressed too, in order to suggest further implementations of a tool which can, according to our opinion, comprehend and have implications also on different aspects of the building engineering field, than the ones studied and which can represent a really innovative tool.

2. DAYLIGHT COMFORT

Lighting is getting always more importance in the design of buildings due to its fundamental role in the experience of the interior spaces, in the comfort of inhabitants, due to its influence on the energy consumptions and many other aspects which are increasingly considered.

The aim of this chapter is to make an overview on the daylight topic, focusing on the different parameters that may be considered in the design process, the current most renown certifications and standards related to the daylight issue and the parameters and assumptions that will be used in this thesis work in order to make the reader aware of the reasons why the light has been chosen as the driving parameter of the entire design process.

2.1 EFFECTS OF DAYLIGHT ON HUMAN WELL-BEING

Light influences the human health not only considering the sight aspect and the fatigue related to visual activities carried out in a not well daylit place. Actually, the human dependency on light has been evaluated mainly on studies in which the man has been deprived of the light or on the contrary exposed to an excessive amount of light. Moreover, psychological studies underlined the importance of the light on the sanity of people and its influence on their mood.

Another important aspect of the light is its effect on the human biorhythm, the so-called circadian rhythm. The circadian rhythm is based on the alternation of day and night along the day, due to the earth rotation, which consequently activates the production of hormones: cortisol and melatonin. Along the circadian period, which is a day, a person sleeps around 8 hours and stays awake around 16. During the waken period, the body has a fruitful activity, with also a higher production and regeneration of cells and tissues; on the other hand, while a person sleeps, there is a decrease in all the activities, exception for the two hours before the awakening, when the body reactivates itself to be prepared for the activity.

2.2 DAYLIGHT IN BUILDINGS

Due to the importance of the light underlined in the previous paragraph, it may be understood that inside buildings, where people spend the most of their time, the illuminance is a crucial aspect. In buildings along with the natural light, the highest amount of light is provided by electrical sources: they are "adequate for performance visual tasks, but they can lack the appropriate spectral composition and intensity required to stimulate the circadian system. All zones within a building that do not regularly achieve the lighting conditions necessary for effective circadian stimulus can be labelled as biologically dark and considered as zones where sustained occupancy over extended time periods may present a risk for disruption of the circadian systems"[2]. Consequently, a growing number of standards in the last few years added chapters and prescriptions for the daylight design aiming to the achieve the comfort of inhabitants.

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[2] K. Konis, "A novel circadian daylight metric for building design and evaluation", University of Southern California, USA, 2016

Along with the comfort issue, the design of buildings is increasingly considering also the aspect of the energy savings, moving towards NZEB. NZEB (Nearly Zero Energy Building) is a concept introduced in the directive EPBD (Energy Performance Building Directive) of 2010; the EPBD describes in Article 2 a nearly zero-energy building as a building having a very high energy performance. “The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby”. According to Annex I, article 1, “The energy performance of a building shall be determined on the basis of the calculated or actual annual energy that is consumed in order to meet the different needs associated with its typical use and shall reflect the heating energy needs and cooling energy needs (energy needed to avoid overheating) to maintain the envisaged temperature conditions of the building, and domestic hot water needs.”[3]

The design based on the achievement of this goal, will give space to a complete and deep analysis on the daylight aspect, since it will represent a mean not only of assurance of visual comfort, but also, if designed correctly, of energy savings. In fact, the exploitation of daylight is recognised as an effective means to reduce the artificial lighting requirements of non-domestic buildings. “In practice however, daylight is a great under-exploited natural resource. Significant amongst the various reasons for this may be the lack of realism of the standard predictive method: the daylight factor approach.”[4] For this reason, it was useful to introduce some parameters which will be useful to give a dynamic interpretation of the daylight analysis.

2.2.1 Definition of parameters

2.2.1.1 Daylight Factor (DF)

Daylight factor is the most common metric used when studying physical models to test daylighting in ‘overcast sky simulators’. It represents the ratio in percentage between the indoor horizontal illuminance and the unobstructed outdoor horizontal one. It is useful to assess the penetration of light in a room, but as it can be imagined, it is more reliable for climates having not a great deal of sun, since it is calculated in overcast conditions and the sun component is excluded from the scenario.

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[3] “Towards nearly zero energy buildings, Definition of common principles under the EPBD”, European Commission

[4] A.Nabil, J. Mardaljevic, “Useful daylight illuminances: a replacement for daylight factors”, 2006

For this reason, this method has two disadvantages:

- It does not depend on the building orientation due to the symmetrical sky luminance distribution;
- It does not depend on the location, hence the climate, of the building.

2.2.1.2 Daylight Autonomy (DA)

It is represented as a percentage of annual daytime hours that a given point in a space is above a specified illumination level. It was originally proposed by the Association Suisse des Electriciens in 1989 and was improved by Christoph Reinhart between 2001-2004. It is a major innovation since in considers geographic location specific weather information on an annual basis. It also has power to relate to electric lighting energy savings if the user defines a threshold, based upon electric lighting criteria. The user is free to set the threshold above which Daylight Autonomy is calculated.[5]

2.2.1.3 Useful Daylight Illuminance (UDI)

The UDI has been developed by Mardaljevic and Nabil in 2005, as a modification of the concept of Daylight Autonomy, which "has been used by others to evaluate the illuminance predictions from climate-based analyses. Daylight autonomy is a measure of how often (e.g. percentage of the working year) a minimum work plane illuminance threshold of 550 lx can be maintained by daylight alone. In contrast, the UDI scheme is founded on a measure of how often in the year daylight illuminances within a range are achieved. Real daylight illuminances in buildings vary enormously, much more than is suggested by variations in predicted daylight factors. Notions of illuminance uniformity that are a legacy of the traditional daylight factor approach are therefore inapplicable for realistic, daylit conditions. Likewise, the notion of simply achieving a threshold illuminance (i.e. daylight autonomy) has restricted value for two reasons. Firstly, daylight autonomy fails to give significance to those daylight illuminances that are below the threshold (for example, 550 lx), but which are nevertheless known to be valued by occupants and also have the potential to displace all or part of the electric lighting. Secondly, daylight autonomy makes no account of the amount by which the threshold

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[5] Patternguide.advancedbuildings.net (last visit, 26/08/2018)

illuminance was exceeded at any particular instant. This is significant because high levels of daylight illuminance are known to be strongly associated with occupant discomfort.”[6]

The UDI defines three ranges of illuminances:

- Useful daylight illuminance (between 100 and 2000 lux)
- Below the useful daylight illuminance (lower than 100 lux)
- Exceeding the useful range (over 2000 lux).

2.2.1.4 Daylight Glare Probability (DGP)

CIBSE Lighting Guide LG7 defines the glare as a “condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or extreme contrasts”[7]. The definition of the calculation of the DGP (Daylight glare probability) has been studied by Wienold and Christoffersen in 2006 as:

$$DGP = c_1 E_v + c_2 \log\left(1 + \sum_i \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{c_4} P_i^2}\right) + c_3$$

Equation 1: DGP Calculation

Where:

- E_v is the vertical illuminance at the eye [lux];
- L_s is the luminance of the source;
- P is the Guth position index.

In order to calculate the DGP it is necessary to generate a suitable hemispherical fish eye image at each time step of the annual simulation, for a time step of 1 hour. It is then possible to evaluate the glare, according to some limits for the values obtained:

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[6] A.Nabil, J. Mardaljevic, 2006, “Useful daylight illuminances: a replacement for daylight factors”

[7] S. Robinson, “CIBSE lighting guide LG7”, CIBSE, 2005

	Imperceptible glare	*Perceptible glare*	*Disturbing glare*
95% DGPs limit	≤0.35	≤0.4	≤0.45
Mean DGPs	<0.38	<0.42	<0.53

Table 1: DGPs limits

2.2.2 Parameters used in the project

Due to the increasing attention paid on the daylight issues towards the NZEB, also the most renowned energy rating systems updated their terms and prescriptions about the Daylight. The one taken as a reference for this project is the LEED (Leadership in Energy and Environmental Design) certification, due to its widespread use all over the world.

LEED is a green building certification program that recognizes sustainable building strategies and practices. To receive LEED certification, building projects satisfy prerequisites and earn points towards one of the five rating systems – Building Design and Construction; Interior Design and Construction; Building Operations and Maintenance; Neighborhood Development; and Homes. Each rating system is made up of a combination of credit categories.

The version of LEED taken as a reference is the LEED v4, which is the most recent, published in 2015; the lighting part in this new release of the LEED saw a notable update. In particular, the "Daylight" credit under the Indoor Environmental Quality (IEQ) category has been updated in LEED v4 to incorporate new metrics. LEED 2009 provided a prescriptive compliance path to achieve daylight credit. This compliance option allowed the calculation of daylight in a space using the window design. These calculations lacked in accuracy as they did not account for project-specific performance factors such as building orientation, exterior conditions, interaction with interior finishes or time of day and year. Daylight Factor (DF) was previously used for assessing LEED Daylight Credit for buildings. The new version, LEED v4, however, accounts for annual hourly measurement of daylight in a space. This is more effective in capturing the dynamic characteristic of interior daylight illumination throughout a year. Three options have been suggested for assessing the LEED Daylight Credit. The first and second options are based on a computer simulation, while the third one has an experimental approach involving two illuminance measurements:

For the daylight simulations, LEED v4 states that:

- The first option features a new simulation called “Spatial Daylight Autonomy and Annual Sunlight Exposure.” *Spatial daylight autonomy (sDA)* is a standard requiring that 55% of the occupiable hours during the year are adequately daylit in a project (above 300 lux). *Annual Sunlight Exposure (ASE),* which is the percentage of square meters in regularly occupied spaces that has direct sunlight during the year, controls the upper limit for assessing glare issues. LEED v4 requires that illuminance values of 1000 lux and above must not exceed 255 occupied hours during the year and must not exist in more than 10% of the occupiable floor area.
- Second option adopts a simple-point-in-time approach, which is to demonstrate through computer modeling that illuminance levels will be between 300 lux and 3,000 lux for 9 a.m. and 3 p.m., both calculate on a clear-sky day at the equinoxes (15 days within September 21st and March 21st). Two points can be gained if these illuminance values are achievable for 90% of regularly occupied space, one point for 75% of occupied space. Option 2 only provides two points maximum, whereas option 1 provides three points maximum.
- Third option is based on measurement of the physical space rather than computer simulation. However, the requirement is similar to option 2 - Achieve illuminance levels between 300 lux and 3,000 lux. Three points will be gained if the illuminance value is achieved for 90% of occupiable space, two points for 75%. The Measurement can be taken at any hour between 9 a.m. and 3 p.m. Two measurements are required during a year – the first one can be in any regularly occupied month, and the second one, however, needs to be taken at least 5 months later to account for seasonal effects. Although option 3 can potentially lead to three points, the documentation process can be lengthy since the two measurements have to be taken at least 5 months apart.

Option 1 is the one the has been considered in this thesis since it adopts the Climate-based Daylight Modelling (CBDM) approach, predicting hourly daylight quantity on an annual basis. In fact, it provides the most accurate estimate of daylighting performance in a space. To assess the Daylight credits required by the LEED v4, Illuminating Engineering Society has developed a method titled “IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)” (IES LM-83-12).

Let’s see in detail the two parameters that will be considered:

2.2.2.1 *Spatial Daylight Autonomy (sDA):*

sDA is a metric that defines a percentage of area that meets minimum daylight illuminance levels for a specified fraction of the working hours per year. In case of LEED v4, $sDA_{300/55\%}$ indicates that a certain percentage of area must meet or exceed 300 lux for at least 55% of the working hours per year.

The threshold to achieve points through this compliance path is:

Table 2: sDA threshold

Percent of area meeting sDA requirement	*Points available*
55%	2 points
75%	3 points

However, spaces designed to achieve these high thresholds for sDA could result in too much direct sunlight in a space. This is measured using the metric ASE (Annual Sunlight Exposure).

2.2.2.2 *Annual Sunlight Exposure (ASE):*

ASE is a metric that identifies the potential for visual discomfort in interior work spaces. For LEED v4, no more than 10% of a space should have direct sunlight more than 1000 lux for a maximum period of 255 hours per year ($ASE_{1000/255}$).

2.2.3 Overview of other standards

Along with the LEED prescription, at the beginning of the process, other standards have been analysed in order to define which is the current direction taken by the most important and used standards.

2.2.3.1 *Well standard*

WELL Building Standard has been released by WELL building institute in 2014. The aim of this document is to marry the best practices in design and construction with evidence-based health and wellness interventions. It harnesses the built environment as a vehicle to support human health, wellbeing and comfort. This is achieved in part by implementing strategies, programs and technologies designed to encourage healthier, more active lifestyles and reducing occupant exposure to harmful chemicals and pollutants.[8]

A consistent part of this document is dedicated to light and to its relationship with human health; it states that its difference from the other guidelines is that it "looks not only at visual acuity and glare avoidance, but also to recognize the important role that the light [..] has in creating alerting and circadian phase-shifting effects."

As the assumptions followed in this project, the horizontal plane is placed at the same height equal to 0.76 m above finished floor; on this plane the lighting system should maintain an average of 215 lux, with tasks lights providing between 300 and 550 lux.

In the paragraph "Daylight Modelling", the WELL Building standard explores the same parameters used by LEED and used in this project. In particular:

- Spatial daylight autonomy ($sDA_{300,55\%}$) is achieved for at least 55% of the regularly occupied space.
- Annual Sunlight Exposure ($ASE_{1000,255}$) is achieved for no more than 10% of regularly occupied space.

2.2.3.2 BREEAM standard

The BREEAM Standard is another well-known and widely used standard for certification of buildings. As far as the visual comfort is concerned, it is organized in a different way from the one seen for the WELL standard and the LEED v4, since it distinguishes the intended use of the building and the thresholds for the parameters are different according to that. Moreover, the discriminant is not the values of ASE and sDA, but the Daylight Factor (DF).

Along with the Daylight Factor required also a percentage of floor is defined. As the reader can understand such a definition of parameters is not suitable for a tool for the design stage, since it goes

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[8] WELL Building Institute, "WELL Building Standard v.1", Washington DC, 2014

too much in the detail of the intended use and implies the use of many more parameters compared to the other two standards seen; for this reason, it has been decided to not consider it. Moreover, the DF is a measure which is tended not to be used, due to the fact it is not a climate-based parameter and it is a point-in-time calculation.

2.2.4 Why ASE and sDA?

As seen in paragraph 2.2.1 , the daylight parameters are many and their use (also combining them together) may be used to describe the internal conditions of a room. So, why choosing ASE and sDA? Obviously, LEED certification is one of the most used certifications for a building and a LEED certification increases its value; hence the importance to choose parameters that could be easily used if the user wants to certify the visual comfort achieved. Moreover, also the trend of the recent years is to move towards a dynamic daylighting matrics, which are specifically defined for the location (through the analysis of the .epw file) and they are not point-in-time simulations but can be done on a yearly basis.

Sefaira guidelines on the use of dynamic analysis state that these two parameters are powerful if used together, since sDA has no upper limit, and the purpose of the use of ASE is to balance it. The architect’s goal is to maximize sDA while keeping ASE in check. This result is difficult to be obtained due to the fact that adding glazed parts cause an increase of the two values, so in order to reduce ASE and increase sDA it is necessary to use and consider some other solutions, such as:

- “the shape and orientation of floor plates;
- the amount of glazing on different façades (e.g. north vs. south-facing);
- the shape of glazing (tall and thin vs. short and wide);
- the design of shading devices (which can be designed to block direct sunlight while admitting indirect light).” [9]

As it can be imagined, some of the previous listed actions impact also on the energy use and consumption of the building, as it will be further explained in paragraph 7.2.1

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[9] www.sefaira.com/resources (last visit 01.09.2018)

3. SOFTWARE COMPARISON

Since the very beginning of this work, one of the main questions was which software/plug-in could be the best to make daylight analyses, i.e. which one could give results as similar to the reality as possible, in a valuable time and why possible differences could occur.

Considering that the first goal was to evaluate ASE and sDA parameters because of all the statements explained in the previous chapter, it was important to make analyses with software based on the Climate-Based Daylight Modeling, that is a new approach developed in recent years to address the issues associated with Daylight Factor (DF). Moreover, since the environment of plug-ins that can be used for this scope is wide, it is important to define which among them is the more reliable.

This chapter shows in its first part a theorical comparison, which has been done through the study of different papers written by the developers of the different software, in order to make a comparison on the differences of calculation and accuracy; then, they have been tested on field, using a reference room with windows placed at different heights. The results have been compared with the outcome of the theorical part, also to verify if the models have been set properly.

As it will be seen, the different tools obtain values slightly different; consequently, assumptions on the differences due to the sky model and the values of direct and diffuse radiation will be addressed and explained.

3.1 CLIMATE-BASED DAYLIGHT MODELLING

Climate-based daylight modelling (CBDM), in fact, “is the prediction of various radiant or luminous quantities (e.g. irradiance, illuminance, radiance and luminance) using sun and sky conditions that are derived from standard meteorological datasets and therefore is dependent upon both locale and orientation, in addition to building configuration and composition.”[10]

Compared with the traditional Daylight Factor approach, CBDM has the following advantages:

- Predicts absolute measures of daylight illumination using realistic descriptions for the sky and sun conditions;
- The evaluation usually lasts for a year to capture variations in meteorological conditions;
- Solar and sky conditions are evaluated together;
- Building location and orientation are taken into consideration.

The term climate-based daylight modelling was first coined by Mardaljevic and does not have a formally accepted definition yet.

CBDM takes sun and sky parameters found in the standard meteorological data files which contain hourly values for a whole year, considering that an evaluation period of an entire year is needed to get all the variations in conditions that are represented in the climate dataset. Perez All-Weather Sky Model is the sky considered to calculate the sky luminous distribution for direct and diffuse irradiation of a given sky condition.

“The two principal analysis methods are cumulative and time- series.

- A cumulative analysis is the prediction of some aggregate measure of daylight (e.g. total annual illuminance) founded on the cumulative luminance (or radiance) effect of (hourly) sky and the sun conditions derived from the climate dataset. It is usually determined over a

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[10] B. Gherri, “*Assessment of daylight performance in buildings: methods and design strategies*”, WIT Press, 2015

period of a full year, or on a seasonal or monthly basis, i.e. predicting a cumulative measure for each season or month in turn.

- Time-series analysis involves predicting instantaneous measures (e.g. illuminance) based on all the hourly (or sub-hourly) values in the annual climate dataset. These predictions are used to evaluate, for example, the overall daylighting potential of the building, the occurrence of excessive illuminances and in assessing the performance of daylight responsive lighting controls."[11]

Evaluations founded on the cumulative approach have the potential to influence the design of the building form at the very earliest stages of conception. Even if the evaluations have to be done for an entire year, only data for the occupied periods (e.g. the working day) needs to be considered.

3.2 DEFINITION OF TOOLS

The analysis on the daylight performance for indoor spaces is a topic which has seen relevant advances in the last 15 years, with the use of increasing reliable software for the calculation and the introduction of restrictive parameters also in the requirements for the certifications of a building. These analyses are made increasingly performing with the introduction of dynamic methods for the simulation, which allow to consider also transient conditions, dynamic system, dimming devices and sensors for the control of the lighting.

Despite all the progresses that have been made in the last years in this field of research, it has not yet arrived at an established path and scheme for a general method of analysis. Reinhart and Wienold[12] stated their list about the elements that obstacle the achievement of this goal:

- "No single simulation environment;
- Simulation time;
- Too complicated simulation processes;

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[11] https://www.researchgate.net/publication/301543455 (last visit 11.09.2018)

[12] C.F. Reinhart, J.Wienold, "The daylight dashboard – A simulation based design analysis for daylit spaces", Harvard University, June 2010.

- Outdated rating schemes;
- Inability to interpret simulation results.”

The first three points are strictly related with the analysis done using software for the calculation, since in the majority of the cases, they will result difficult for the user to be used and they become more time consuming than expected. Moreover, as a result of the third and fifth point, the simulation process tends to be complicated, especially if the user is a beginner and the lack of experience cause problems in the interpretation of the results.

On the heels of what has been stated before, in this project the evaluation of energy performance and daylight conditions have been performed with the use of a dynamic simulation software. As explained before, the aim of this study is a comfort-based form-finding process, which will lead to an analysis of many models, implying different solutions for the façade, which will be evaluated according to the requirements established by LEED. For this reason, there was a need for a flexible tool in terms of modelling. That’s the reason why Grasshopper, that is described below, has been used as the main tool for modelling in this study. It gives the possibility to quickly modify the models through parametric design. There are also plug-ins for Grasshopper that can perform energy and daylight simulations on the same model, share inputs and results.

The whole model has been built using Grasshopper and all the simulations were performed, at least for an early-stage approach to this topic, using the different plug-ins described below. Grasshopper is a graphic algorithm editor tightly integrated with Rhino’s 3D modelling tools. The model is generated by adding and connecting different components (commands) into a canvas and an illustration of the model is previewed in Rhinoceros.

3.2.1 Ladybug and Honeybee

Ladybug and Honeybee are two open source plug-ins for Grasshopper and Rhino3D that help explore and evaluate environmental performance. M. Roudsari, the developer of the two software describes Ladybug as a tool for Grasshopper, which imports standard EnergyPlus weather files (.epw) into provides a variety of 3D interactive graphics to support the decision-making process during the initial stages of design. On the other hand, Honeybee joins together four validated simulation engines - specifically, EnergyPlus, Radiance, Daysim and OpenStudio - which evaluate building energy consumption, comfort, and daylighting[13]. These plug-ins enable a dynamic coupling between the flexible, component-based, visual programming interface of Grasshopper and validated environmental data sets and simulation engines.

3.2.2 DIVA

DIVA is a tool developed by SOLEMMA LLC[14], which describes it as a highly optimized daylighting and energy modelling plug-in that allows users to carry out a series of environmental performance evaluations of individual buildings and urban landscapes including radiation maps, photorealistic renderings, climate-based daylighting metrics, annual and individual time step glare analysis, LEED daylighting compliance, and single thermal zone energy and load calculations. DIVA uses Radiance as an engine to perform the daylight simulations. Radiance is a suite of programs for the analysis and visualization of lighting in design, based on ray tracing techniques and it is widely used and validated. DIVA can be considered a further development of the program Daysim, which is based on Radiance algorithms and it calculates annual illuminance using a climate-based daylight modelling (CBDM).

3.2.3 Other tools

Other plug-ins for parametric daylight analysis are available for Grasshopper, as for example Geco or Gerilla, but DIVA and Ladybug/Honeybee are currently considered as the most complete and performing ones; here below a brief comparison table between the listed tools:

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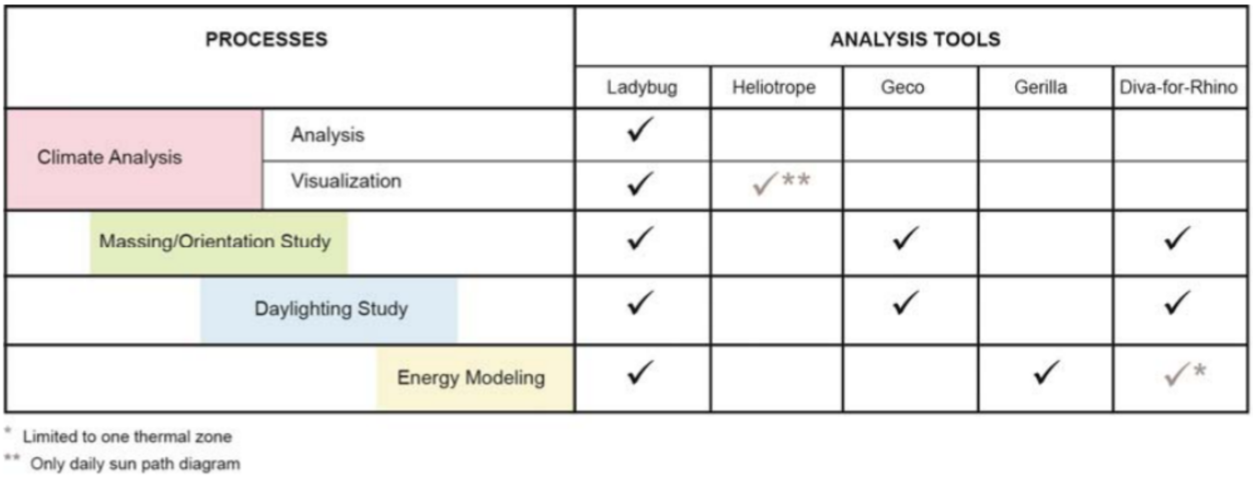
[13] M. Sadeghipur Roudsari, M. Pak, A.Smith, "*Ladybug: a parametric environmental plugin for Grasshopper to help designer create an environmentally-conscious design*", Gordon Gill Architecture, 2013

[14] www. Solemma.net (last visit, 13/08/2018)



PROCESSES		ANALYSIS TOOLS				
		Ladybug	Heliotrope	Geco	Gerilla	Diva-for-Rhino
Climate Analysis	Analysis	✓				
	Visualization	✓	✓**			
Massing/Orientation Study		✓		✓		✓
Daylighting Study		✓		✓		✓
Energy Modeling		✓			✓	✓*

* Limited to one thermal zone
** Only daily sun path diagram

Table 3: Comparison of the existing environmental analysis tools for Rhino/Grasshopper[15]

As it can be seen from the table above, Ladybug and DIVA are the most complete ones, which combine both daylight analysis and energy modeling; the other software tent to focus their simulations only on one of the two aspects. Ladybug in addition, offers a detailed analysis of the climate, which can be used also to carry autonomous simulations about the daylight parameters, as it will be explained in the next chapters.

3.3 CHOICE OF TOOLS FOR THE PROJECT

As explained before, this thesis starts as a prosecution of the thesis work done by one of our colleagues; the first approach was an analysis of the tools used in that work in order to create a sort of continuity also from the software point of view. For this reason, at least at the beginning, the chosen tool was DIVA, since it was the one used in the other thesis project and, also for its user-friendly interface. Nevertheless, also Honeybee and Honeybee+ have been considered, in order to understand if the results were comparable or if there were differences and, in that case, define which can be the differences and the reasons behind that.

3.3.1 Comparison between Honeybee and Honeybee [+]

The initial step consisted in creating a workflow for Honeybee and DIVA, but after the very first simulations, it was clear that the results were quite different and, moreover Honeybee does not have a component which calculates the ASE. After this, the possibility to use another plug-in came up and the same workflow has been modified to be suitable for Honeybee [+]. This new plug-in permitted to

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[15] C.F. Reinhart, J.Wienold, "*The daylight dashboard – A simulation based design analysis for daylit spaces*" Harvard University, June 2010.

understand that the methods implemented for annual daylight simulation in Honeybee have several limitations and, as explained from Mostapha Roudsari, the creator of these two plug-ins, some of the issues related to Honeybee, now solved in Honeybee [+] are the following:[16]

- Simplified calculation for direct solar contribution.
- Low resolution Tregenza sky model.
- No support for sub-annual simulations.
- No support for BSDF materials.

Honeybee Legacy runs annual daylight analyses using the Daysim engine, keeping the limitations due to use this Radiance-based simplified method. The introduction of Honeybee [+], in fact, is due to the fact that Daysim needed to be replaced with Radiance utilities, in order to have more accurate and precise analyses, keeping, at the same time, all the functionalities of Ladybug and all the advantages related to the use of it. Only a limited number of positions of the sun are modeled in Daysim during direct solar calculations. Honeybee [+], instead, follows the real position of the sun, considering each hour of the year when the sun is up in the sky and creating an accurate and precise analemma. This is made possible thanks to the combination of the functionalities of Radiance's -gendaylit and the sunpath created by LadyBug. Another limitation is that Daysim produces only the total illuminance values (i.e. diffuse + direct) that does not allow to calculate values of the ASE. Compared to it, Honeybee [+] keeps these values separated, in order to be accessible by the user. Moreover, the sky generated in Daysim is limited to 145+1 patches while Honeybee [+] uses Radiance's -gendaymtx which has no limitations on generating skies, implying higher resolutions.

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[16] https://github.com/ladybug-tools/honeybee (last visit 12.09.2018)

In Figure 3-1 there is explained a comparison about different methodologies to divide the sky for annual daylight analyses.

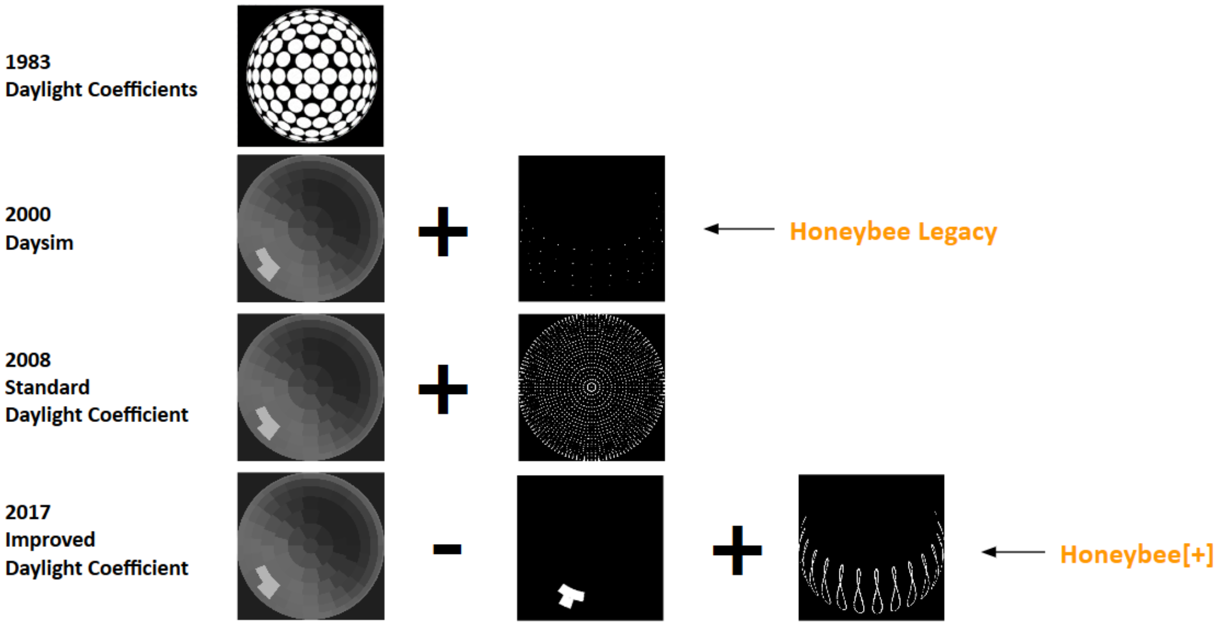

Figure 3-1: A More Accurate Approach for Calculating Illuminance with Daylight Coefficients. Proceedings of the 2017 Annual IES Conference. Portland, Oregon, USA.

Another important limitation of Daysim is that it is unable to support monthly or weekly daylight simulations. If the user wants to have results of a simulation only for a certain period of the year, he has to run the simulation for the entire year. Honeybee [+], instead, is able to model the daylight for any custom list of hours during the year.

As the materials are concerned, Honeybee/Daysim does no support BSDF material, that stands for “bidirectional scattering distribution function” and means that the shader will scatter the light. In fact, the type of shader determines the distribution function, which determines how the light is scattered and how the material appears. This is a major limitation if the user wants to model Complex Fenestration Systems (CFS).

Finally, Daysim doesn't support multi-processing calculation which will be a major limitation for large scale simulations or simulations with dynamic blinds. Honeybee [+] uses Radiance utilities which supports built-in multi-processing calculation.

After all these considerations, Honeybee has not been considered in the calculations of sDA and the ASE and, through the use of an un-shaded best case, some comparison has been done between DIVA and Honeybee [+].

3.3.1.1 Radiance engine for Daylight Simulations

Both the Honeybee [+] and DIVA tools are based on the same calculation engine: Radiance, that is a free and validated lighting simulation tool used for climate-based daylight. It was first documented in scientific literature by John Mardaljevic, who was also the first that documented and validate the application of Radiance for calculating illuminance with Daylight Coefficients. The Daylight Coefficient Method helps to calculate illuminance varying sky conditions through matrix-based calculations (Tregenza and Waters 1983).

"Radiance uses a hybrid of Monte Carlo and deterministic ray tracing techniques to calculate radiance values (McNeil & Chadwell, 2012). Direct, specular indirect and diffuse indirect components are calculated in order to trace rays backwards from measurement-point to source (McNeil & Chadwell, 2012). It is commonly used through other programs, which allow the user a limited input and set-up most of the simulation automatically."[17]

This is precisely how Honeybee and DIVA work, allowing the user to set the geometry, sky and material properties, as well as Radiance parameters. The most accessible Radiance parameters are presented in Table 4. Changes in these parameters can have a significant impact on the quality of the simulation results, as well as the duration of the simulation.

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[17] N.Baker, "Modelling and Analysis of Daylight, Solar Heat Gains and Thermal Losses to Inform the Early Stage of the Architectural Process", Stockholm, 2017

Table 4. Radiance parameters for daylight simulation

RADIANCE PARAMETERS		*DESCRIPTION*
_ab_	AMBIENT BOUNCES	The number of diffuse bounces in the indirect calculation [2,3,6]
_ad_	AMBIENT DIVISIONS	The number of sample rays sent out into the hemisphere [512, 2048, 4096, …, 15500]
_ar_	AMBIENT RESOLUTIONS	Adjusts the limit beyond which the accuracy of the indirect calculation will relax. [16, 64, 128]
_as_	AMBIENT SUPERSAMPLES	The number of extra samples used for areas of high variability in the hemisphere [128, 2048, 4096]
_aa_	AMBIENT ACCURACY	The maximum error permitted in the indirect calculation. [0.25, 0.2, 0.1]

3.3.1.2 Radiance Calculation approach

In order to have a better understanding of the differences between DIVA and Honeybee [+] on the annual daylight analysis' approach with, it is important to explain how the two software learn from the weather file and discretize the sky-dome to analyze the direct and diffuse radiation.

Since Radiance analyses Illuminance through The Daylight Coefficient Method, it is important to introduce the Daylight Coefficient, a factor that basically depends on the geometry of the room, with the related values of reflectance and transmittance of the surfaces and on the context with the surrounding buildings. The luminance values for the skies used in the Daylight Coefficient Method are usually derived from TMY weather data for different geographical locations. These data contain hourly values for direct normal and diffuse horizontal irradiation in the specified location, that helps to create a continuous Radiance-based sky definition through the Perez All Weather Sky Model. Then, the sky model is discretized into luminous patches that approximate the hemisphere. Radiance generate a sky vector discretizing the sky using either the Tregenza or Reinhart division schemes.

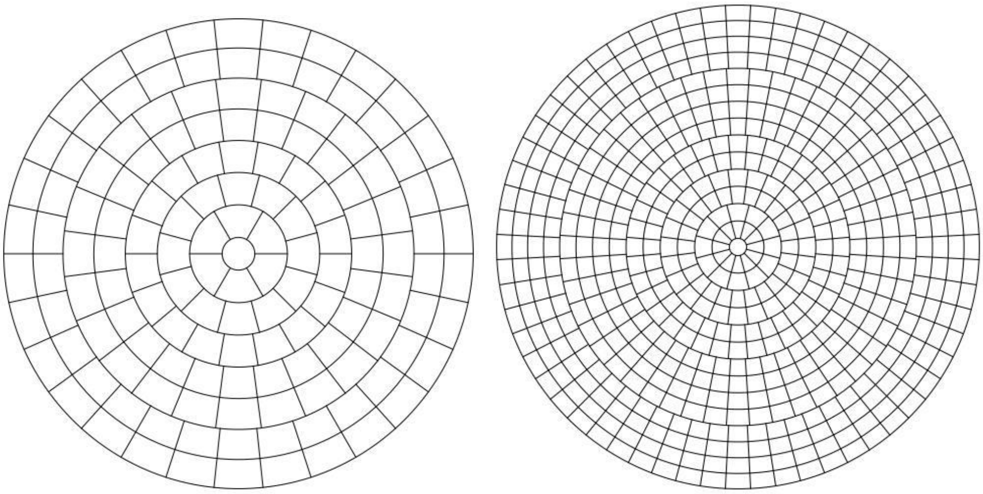


Figure 3-2. Ortographic projection of the Tregenza (left) and Reinhart (right) sky patches division

To understand better, a sky vector is a list of average RGB radiance values for each discretized patch of the sky. All the sky vectors create a sky matrix, that contains 8760 sky vectors, one for each hour of the year. In the pictures below is possible to see a continuous sky on the left, and then, how the sky is discretized for a Tregenza (145 patches) or Reinhart (580 patches).

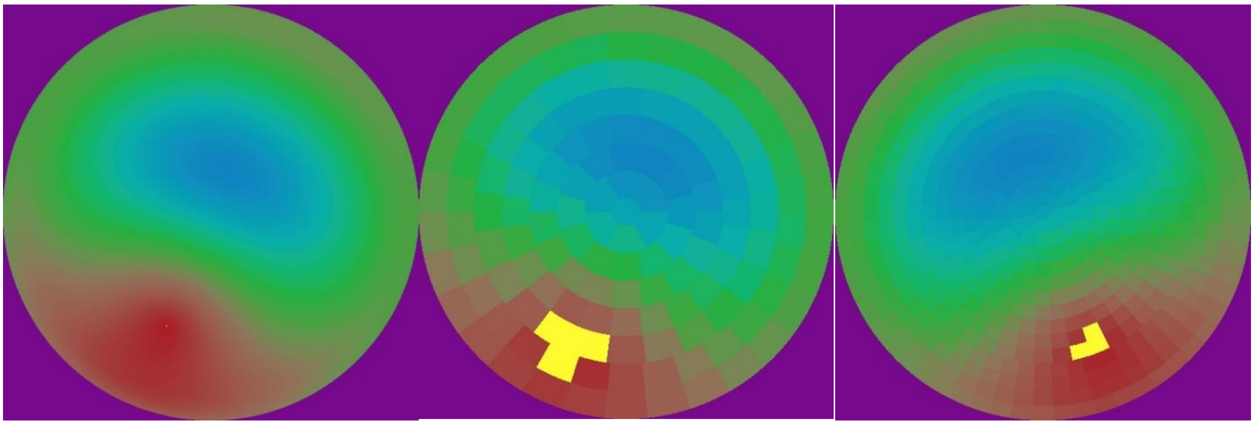


Figure 3-3. Representation of the sky vectors of a continuous sky model (left) and the Tregenza (middle) and Reinhart (right) discretized models

DIVA uses Daysim as engine for calculation. Daysim is Radiance-based, as previously said, but consider the discretization of the sky provided by Tregenza. On the other hand, Honeybee [+] allow the user to choose which sky discretization prefers the most, whether Tregenza or Reinhart. Obviously, considering that the first method divides the sky in a lower number of patches, the result will be provided faster, but the annual analysis will be less precise and accurate. As it is possible to see in Figure 3-3, for discretized sky models, at a certain time, the position of the sun in the sky in the

Tregenza model, and consequently in DIVA, is approximated to 3-4 sky patches respect to the Reinhart model, and so in Honeybee [+].

The contribute of the direct radiation is treated in different ways in DIVA and Honeybee [+], DIVA using Daysim has 65 sun position fixed to cover all the hour of the year, for each hour the contribution of the direct radiation is from the nearest point from the real sun position, Honeybee [+] uses the real sun position from the analemma for the analysis location for each hour of the year and so the contribution of the direct radiation is calculated in a more accurate way. This difference lead to slightly different ASE results.

3.4 SENSITIVE ANALYSIS THROUGH A BASE CASE

3.4.1 Default Windows

The basic case test building considered in this section (Figure 3-4) is a rectangular single zone (8m wide x 6m long x 2.7m high) with an external wall on the side with the windows and adiabatic partitions on the three left sides. It is 12 m^2 windows analyzed with different exposure conditions (S-E-W-N). The room is a base case taken from ANSI/ASHRAE standards.

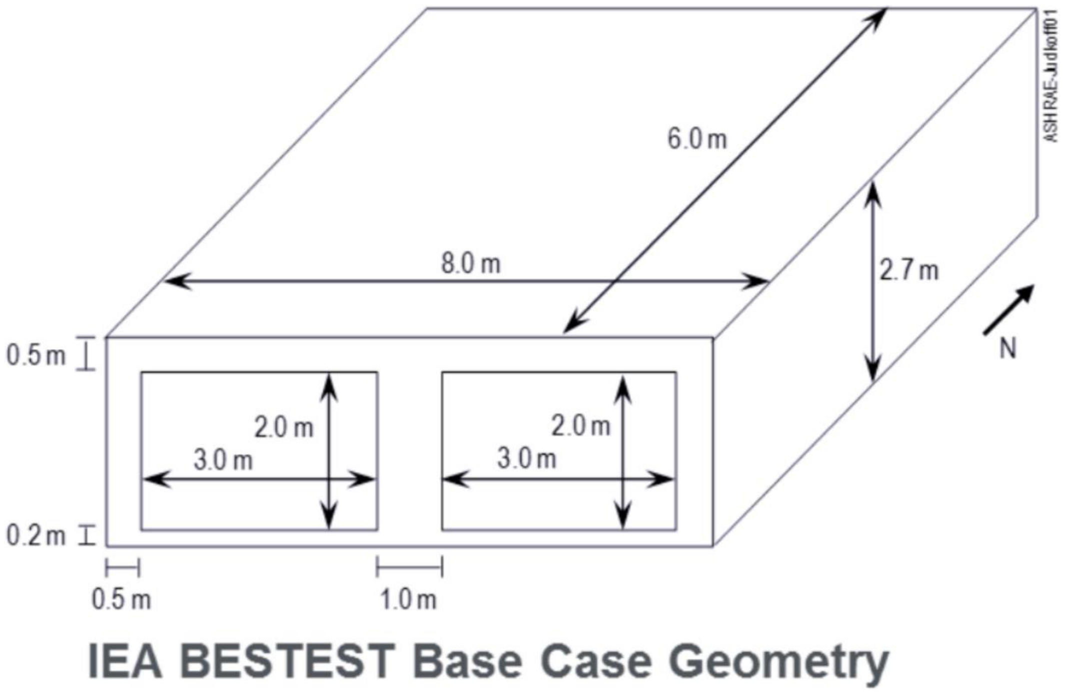


Figure 3-4: Base case geometry

The analyses have been carried out considering two different climate files, Milan and Miami, because of their different latitude. In this way it has been possible to analyze how the height of the sun influences the daylight and the feedback about sDA and ASE from the two different programs compared: Honeybee [+] and DIVA.

The above test case has been considered as a default case. Later on, the analyses were carried out also with smaller windows put at different heights on the façade.

According to this IES document the room for the analysis has been designed as follow:

- *Period of Analysis:* The designs are evaluated from 9:00am to 5:00pm during the working days.
- *Analysis Points:* the analysis grid is a 60cm x 60cm within an analysis area, at a height of 76cm above the floor.

The external surface where the windows are located have been designed as follow:

- Windows with 70% of light transmittance
- Opaque wall with 55% of reflectance

The radiance parameters to perform the calculations have been extrapolated from Honeybee [+] from an analysis at a medium level and have been set in DIVA as follows:

RADIANCE PARAMETERS used in the simulation		
_ab_	AMBIENT BOUNCES	5
_ad_	AMBIENT DIVISIONS	1024
_ar_	AMBIENT RESOLUTIONS	64
_as_	AMBIENT SUPERSAMPLES	2048
_aa_	AMBIENT ACCURACY	0.2

Table 5: Radiance parameters set for the sensitive analysis

In a first attempt the decision was to set and run the simulation for the annual daylight analysis considering the default RadParam of each program at medium quality. After comparing some preliminary analysis results, it came up that the sDA results differed considerably between the tools.

The simulations have been repeated in DIVA using RadParam coming from Honeybee [+]:

SOFTWARE COMPARISON									
DEFAULT WINDOWS		*MILANO*				*MIAMI*			
		South	East	West	North	South	East	West	North
Honeybee [+]	*Computational timing*	1.2min	1.2min	1.2min	55.7 s	1.3min	1.5min	1.5min	1.2min
	ASE	28.1%	19.2%	11.4%	0.0%	23.4%	22.9%	13.5%	0.0%
	sDA	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
DIVA	*Computational timing*	45.2 s	42 s	43.2 s	39.2 s	46.7 s	40.7 s	41.7 s	35.4 s
	ASE	34.9%	17.7%	18.2%	0.0%	30.2%	22.4%	24.0%	0.0%
	sDA	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 6: Results of software comparison - Default windows

In the two graphs below, it is easier to understand the differences:

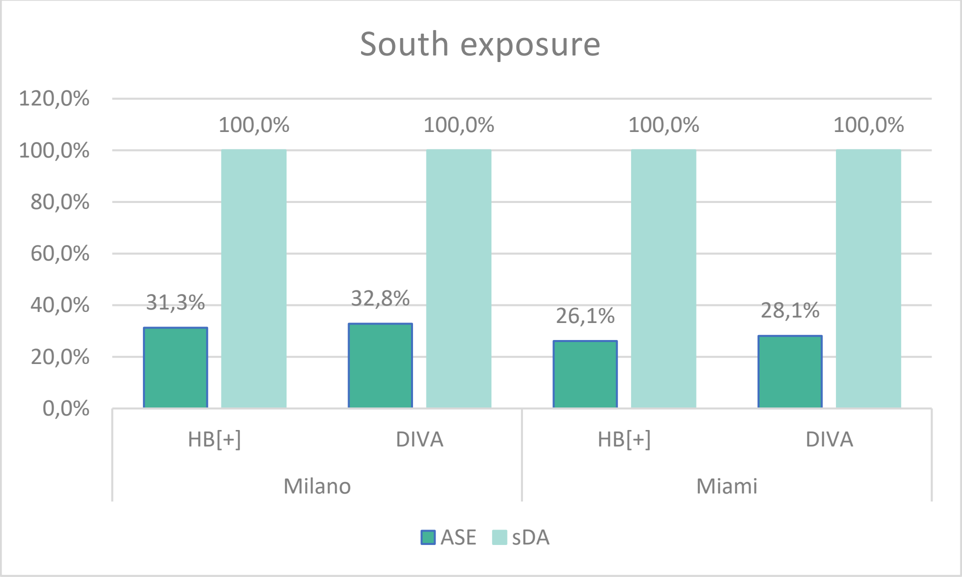


Figure 3-5: Results comparison - South Exposure

For the south exposure, where the sun hits the room for the majority of the hours, even if at different heights, and with no shadings, considering Milan or Miami, there are not relevant differences between the results of the two software.

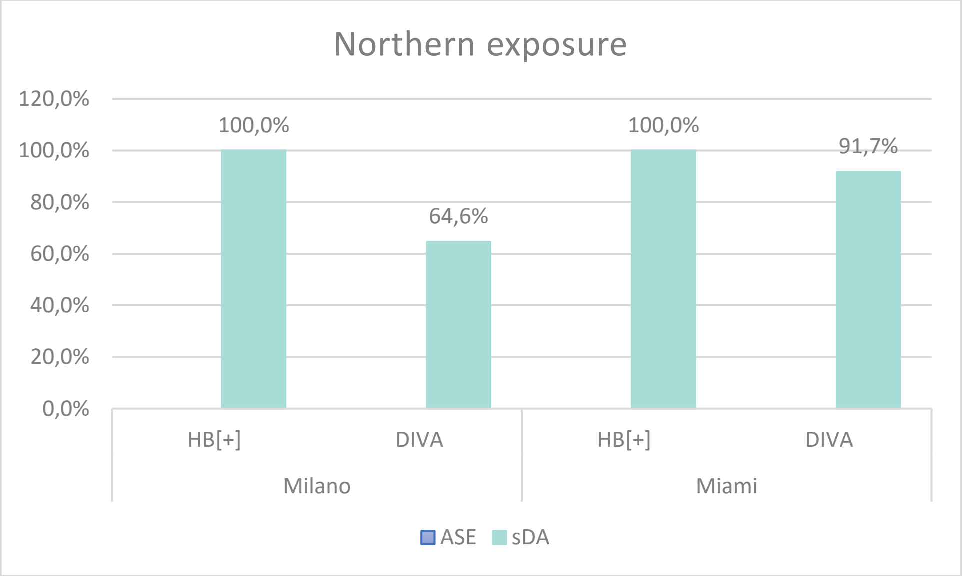


Figure 3-6: Results comparison - Northern Exposure

On the other hand, the northern exposure of the room gives different results. That means that the diffuse light entering the room is captured in different ways from DIVA or HB [+]. In Miami, where the sun is higher than in Milan because of its latitude and there is a higher amount of light entering the room, the differences between the software are about 9%, while in Milan, where the sun is lower in the sky, the light going inside the room is less and differences between the software are around 35%.

3.4.2 Comparison with windows at different heights

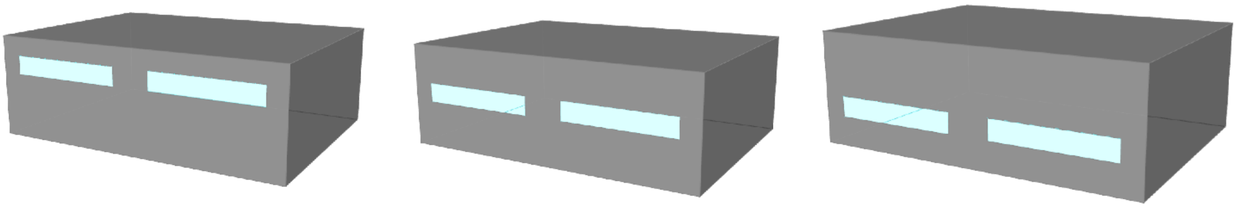


Figure 3-7. Test case with different configurations of the windows in facade

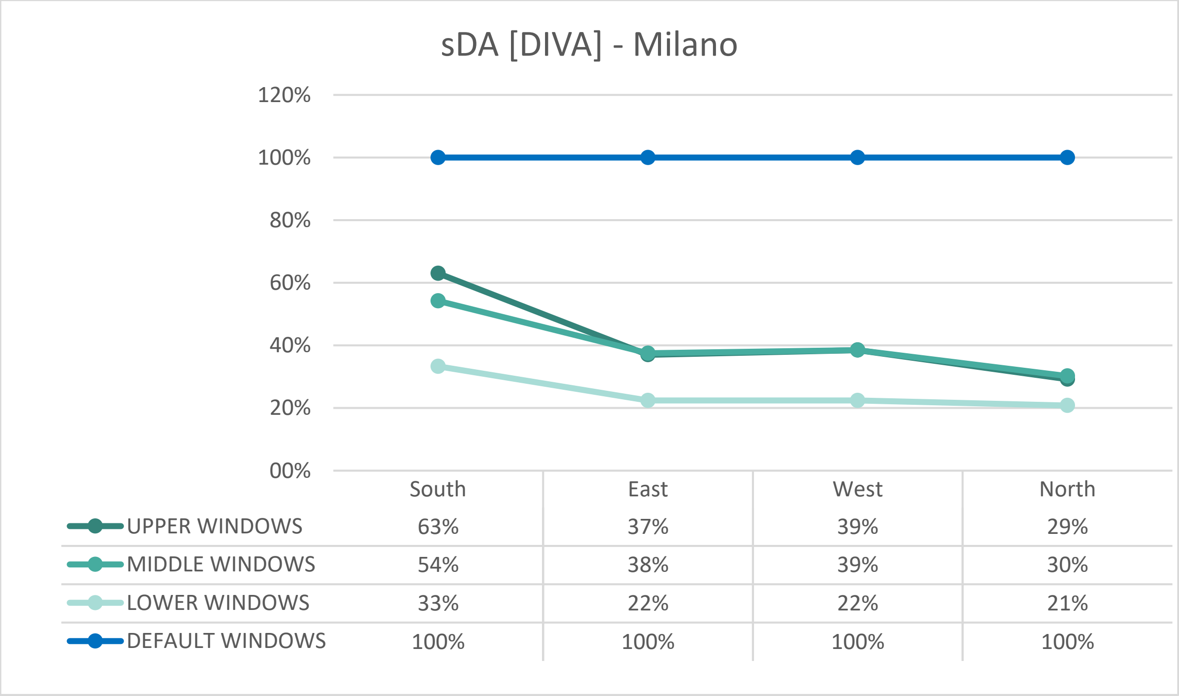
The test with the base case with windows at different heights on the façade has been introduced in order to have a better understanding on the variation of the values of the ASE and sDA due to the software, the orientation, the position of the sun in the sky and its discretization. The width of the windows has been kept the same, while the height has been decreased from 2m to 1 m. It has been tested for both Milano and Miami.

SOFTWARE COMPARISON									
UPPER WINDOWS		*MILANO*				*MIAMI*			
		South	East	West	North	South	East	West	North
Honeybee [+]	*Computational timing*	1.3 min	1.2min	1.2min	54 s	1.3min	1.5min	1.5min	1.1min
	ASE	0.0%	0.0%	0.0%	0.0%	5.2%	0.0%	0.0%	0.0%
	sDA	73.4%	53.6%	48.4%	43.2%	73.4%	69.3%	60.4%	51.6%
DIVA	*Computational timing*	55.6 s	45.8 s	46.6 s	41.3 s	49.7 s	45.7 s	44.8 s	41 s
	ASE	13.5%	0.0%	0.0%	0.0%	18.7%	5.2%	11.5%	0.0%
	sDA	63.0%	37.0%	38.5%	29.2%	63.0%	52.1%	55.0%	41.1%
MIDDLE WINDOWS		*MILANO*				*MIAMI*			
		South	East	West	North	South	East	West	North
Honeybee [+]	*Computational timing*	1.1 min	1.1min	1.1min	52.4 s	1.1min	1.5min	1.5min	1.2min
	ASE	10.4%	3.1%	0.0%	0.0%	11.5%	10.4%	4.2%	0.0%
	sDA	63.0%	55.0%	47.9%	44.3%	55.0%	60.9%	53.6%	65.6%
DIVA	*Computational timing*	47.9 s	44.2 s	44 s	40 s	39.1 s	42.5 s	41.1 s	49.3 s
	ASE	19.8%	9.4%	4.2%	0.0%	14.6%	11.5%	9.4%	0.0%
	sDA	54.2%	37.5%	38.5%	30.2%	39.1%	41.7%	42.2%	55.0%
LOWER WINDOWS		*MILANO*				*MIAMI*			
		South	East	West	North	South	East	West	North
Honeybee [+]	*Computational timing*	56.5 s	58.9 s	59.2 s	55.7 s	1.2min	1.5min	1.5min	1.1min
	ASE	7.3%	6.3%	5.2%	0.0%	6.3%	6.3%	5.2%	0.0%
	sDA	40.6%	32.3%	27.6%	24.0%	45.8%	39.0%	32.3%	30.7%
DIVA	*Computational timing*	48.2 s	40.4 s	40.9 s	35.8 s	47 s	39 s	39.4 s	36.9 s
	ASE	10.4%	6.3%	6.2%	0.0%	6.2%	6.2%	6.2%	0.0%
	sDA	33.3%	22.4%	22.4%	20.8%	31.2%	25.0%	23.4%	22.9%

Figure 3-8: Results of software comparison - Windows at different heights

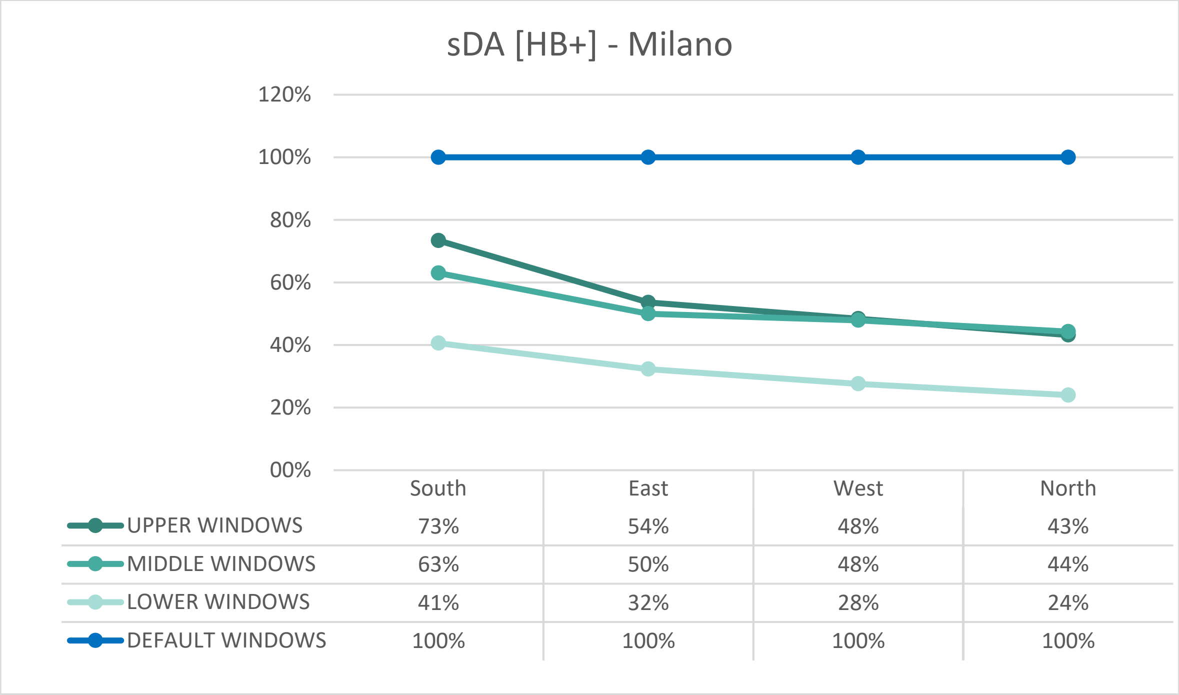
3.4.2.1 sDA Comparison

sDA considers both the direct and the diffuse radiation incident on the floor. As it is possible to see from the table, the trend shows that the percentage of the sDA increases increasing the height of the windows along the façade. This can be explained because the windows in the upper part face the most luminous part of the hemisphere. Vice versa, the windows in the lower part face the darker part of the hemisphere. As it will be showed later on with the geometry studied, (see. Chapter 6.2) the same consideration can be done if a surrounding context is considered. Of course, the windows in the upper part will not be covered by the surrounding buildings and will get higher percentage of radiation and, as a consequence, the sDA will be higher. Same results will be obtained for the case with the default windows. Since the example considered has not a context in front of the façade, the sDA is the higher between the four cases, because the windows cover a greater part of the façade, but the context will make this value decrease a lot.



	South	East	West	North
UPPER WINDOWS	63%	37%	39%	29%
MIDDLE WINDOWS	54%	38%	39%	30%
LOWER WINDOWS	33%	22%	22%	21%
DEFAULT WINDOWS	100%	100%	100%	100%

Figure 3-9: sDA results with Diva - Milano



	South	East	West	North
UPPER WINDOWS	73%	54%	48%	43%
MIDDLE WINDOWS	63%	50%	48%	44%
LOWER WINDOWS	41%	32%	28%	24%
DEFAULT WINDOWS	100%	100%	100%	100%

Figure 3-10: sDA results with Honeybee [+] - Milano

In the figures reported below, it will be shown the internal distribution of the light inside the room for the climate of Milano, with the façade facing south.

In the first case with the default windows the distribution of the light is widespread inside the room and the sDA is 100%, also because there is no context, no shadings and the façade is almost totally glazed. The other three cases are more relevant in order to understand how the position of the windows affect the façade: the more they are positioned towards the top part, the higher will be the sDA value, because the light entering the room hits deeper part of the room.

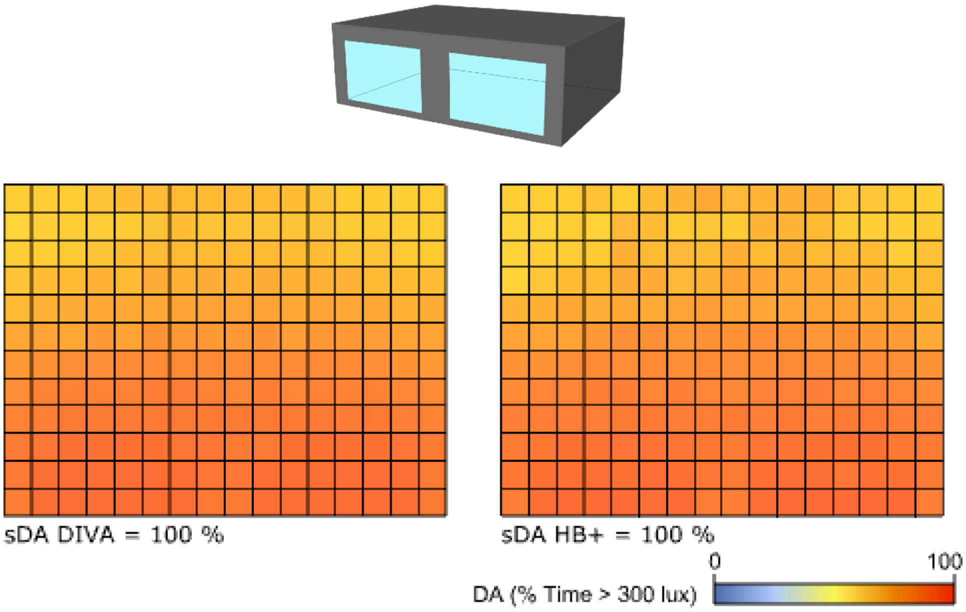


Figure 3-11. sDA distribution in the case with default windows

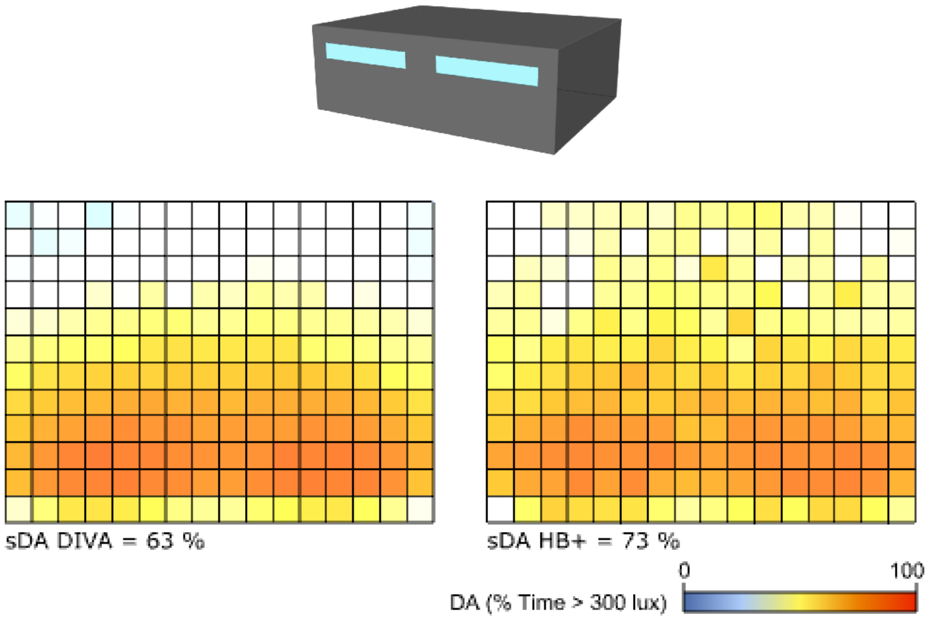


Figure 3-12. sDA distribution in the case with upper windows

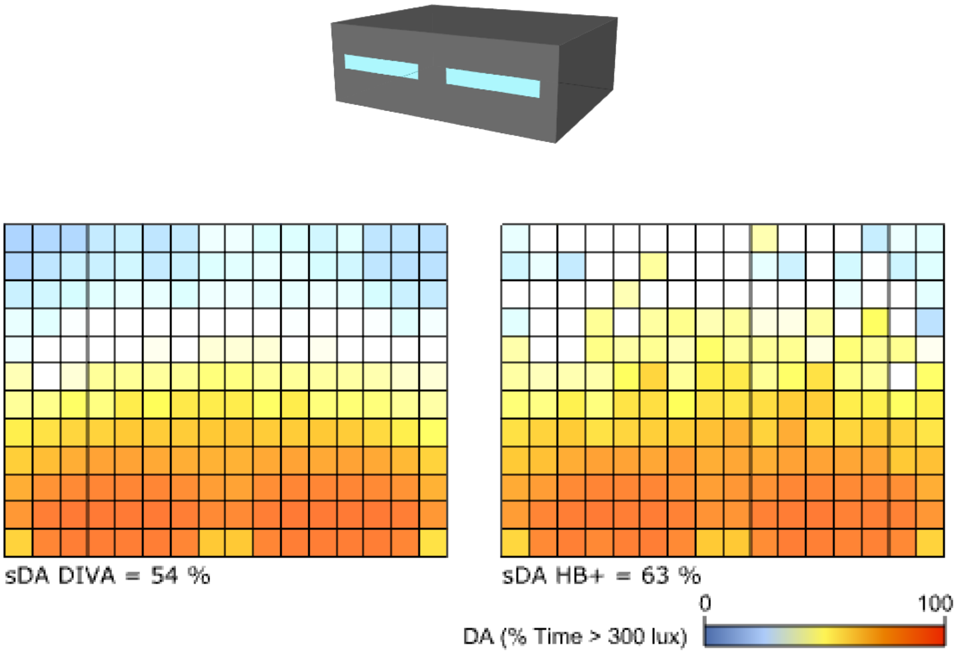


Figure 3-13. sDA distribution in the case with medium windows

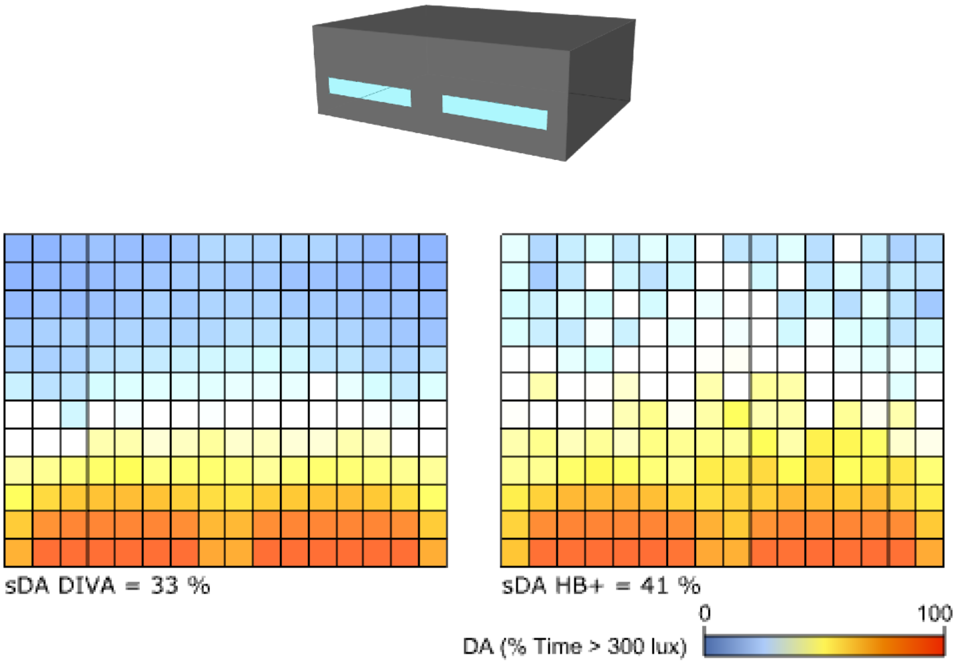


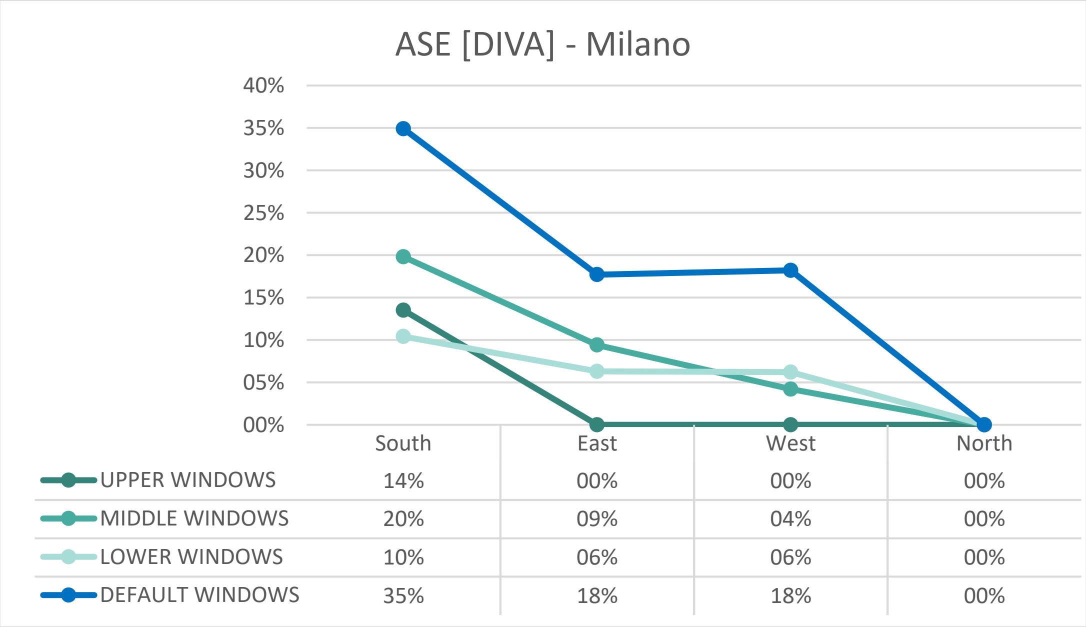
Figure 3-14. sDA distribution in the case with lower windows

Moreover, some considerations on how DIVA and Honeybee [+] obtain the results can be done: as explained in the first part of the Chapter, they have been analyzed with a different discretization of the sky dome. DIVA, through Daysim, discretizes the sky in 145 patches, while for Honeybee [+] has been chosen to perform the calculations discretizing the sky with Reinhart sky, i.e. division in 580 patches. Since both the software have been set using the same five main Radiance Parameters, as explained at the beginning of this section, what influence the most the results is the difference in discretization of the sky and, consequently the accuracy of the results. Honeybee [+] obtains more accurate results and this can be seen in the previous pictures, considering the distribution of the light onto the analysis grid.

Since the trend is always the same between the two different climates considered and between the various orientation, the other analyses will be shown in ANNEX II.

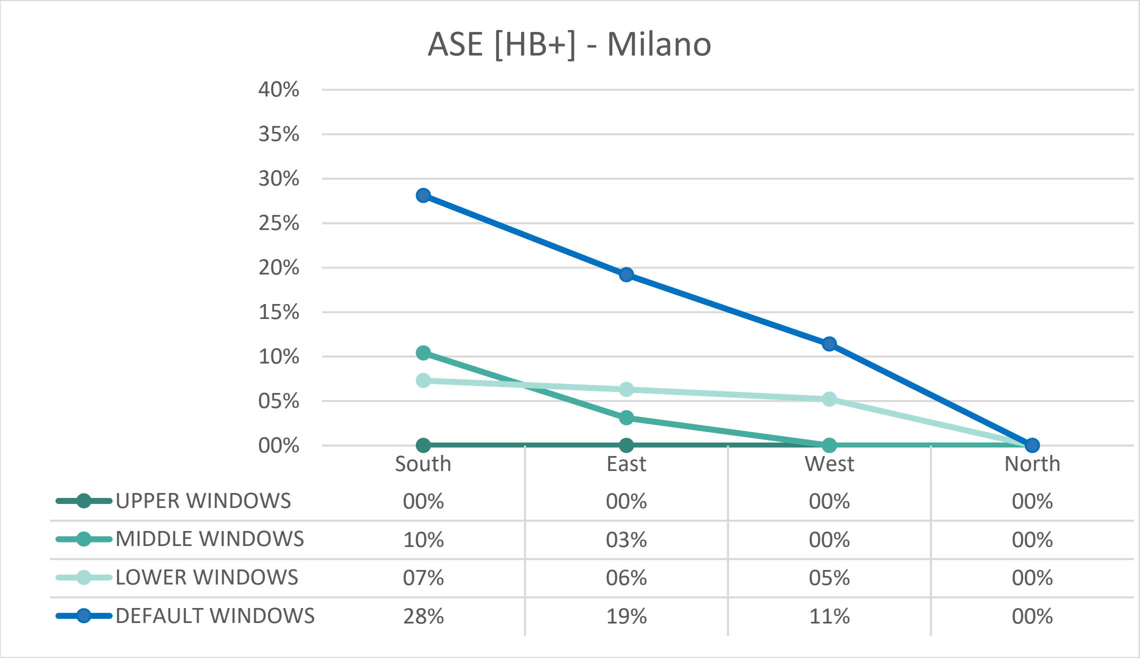
3.4.2.2 ASE comparison

ASE represents the contribution of the direct light hitting the floor, and consequently the grid of analysis considered.. The more relevant results are presented for the south orientation, since when the facade is oriented to north there will be no direct light hitting the pavement. The case considered is the one with the façade oriented towards south, always hit by the sun. Ideally the windows close to the top of the building should give low values, because the radiation hitting the pavement is spread in a wide area, so a higher number of points of the analysis grid on the floor are hit. Differently, for windows positioned closer to the floor, the direct radiation hits few points onto the grid for a larger amount of hours and the ASE increase. The same reasoning can be done for the windows positioned in the middle, since many points on the grid receive direct light for a large number of hours, the value of ASE will be the higher between the three configurations.



	South	East	West	North
UPPER WINDOWS	14%	00%	00%	00%
MIDDLE WINDOWS	20%	09%	04%	00%
LOWER WINDOWS	10%	06%	06%	00%
DEFAULT WINDOWS	35%	18%	18%	00%

Table 7: ASE Results with DIVA - Milano



	South	East	West	North
UPPER WINDOWS	00%	00%	00%	00%
MIDDLE WINDOWS	10%	03%	00%	00%
LOWER WINDOWS	07%	06%	05%	00%
DEFAULT WINDOWS	28%	19%	11%	00%

Table 8: ASE Results with Honeybee [+] - Milano

As already explained in the first part of the chapter, the differences between DIVA and Honeybee [+] have to be researched in how they consider the direct light from the sky. DIVA provides a simplified method, since the position of the sun is interpolated from 65 representative solar positions, and this is translated in a geometric loss of accuracy. Instead, Honeybee [+] considers the real position of the sun, point by point. As a consequence, it can happen that in DIVA one point over the grid is hit more times and for more hours than it should be, because of the approximation of the sun. This is translated in an increase of the percentage of the ASE. In fact, as it is possible to see from the tables and figures above, the values of DIVA are always higher than those in Honeybee [+], that is way more accurate.

In fact, as from the figures representing how ASE values change between DIVA and Honeybee [+], it is interesting to notice how wide are the differences in percentage if the upper or the lower windows are considered: in the first case DIVA provide a ASE of 13.5%, while Honeybee [+] of 0%; in the second case DIVA is around 10.4%, while Honeybee [+] 7.3%. Honeybee discretizes in a more accurate way the direct light, so when the windows are high, more points are considered hit and no one of them reaches the minimum value of 255h over 1000lux, while direct light in DIVA hits more points for a higher number of hours and the result is that in annual analysis a higher number of points of the grid is out of the range. In lower windows, where a lower number of points on the grid is hit by the direct light, in fact, the values of ASE between the two tools are almost the same.

4. GEOMETRIES

The aim of this thesis work is to design a tool which can give a shape to the visual comfort. This definition may seem abstract, but it can be a good explanation of what will be the final process, as it will be explained in the next chapters. The way in which the tool “shapes” visual comfort is through a combination of different geometrical variables, which create different shapes combined with the use of opaque or transparent materials, in order to create a shading or let the light enter the room, according to the boundary conditions, context, geometry, location, etc..

Even though the tool and the calculation methods, as it will be shown in the next chapters, are suitable and applicable to many different typologies of shading, the final plug-in has been originally studied for the optimization of a well-defined façade system. The system, as it will be explained later in Chapter 5, is complex since it is not a flat panel as usual curtain walls, but it is composed by different panels. The complexity is due to the generation of the geometry through the movement of different control points along different directions.

This chapter explains the process of generation of geometries, introducing also some hints regarding possible ways of juxtaposing them in order to create dynamic effects on the façade.

4.1 DEFINITION OF GEOMETRIES

The starting point for the definition of the geometries was the thesis work of one of our colleagues, Pietro Pavesi. As a matter of fact, this thesis work has been developed from the beginning as an automation and a continuation of his work.

In particular, his work started from different geometries which have been tested in the climate of Milano, in order to skim the ones that could not be satisfactory for that climate. The first effort of this work has been studying the geometries used in his thesis and define their main aspects. Then, the main aim was to extend the field of geometries and group them in families with similar properties, allowing each panel to be controlled by one or more control points. In this way, through the motion of the control points, it is possible to have a wide range of shapes and as a consequence, a higher probability of finding one that will adapt better to the internal needs mainly in terms of daylight comfort. This is due to the fact that the geometry will be then associated with opaque or transparent materials, which can create a different projection of shading inside the room, with relative changes in sDA and ASE results.

The base geometries are defined starting from two main geometric families: rectangular and triangular ones.

4.1.1 Rectangular Geometries

Independently from the kind of geometry analysed, the procedure for the definition of the subfamilies has been the same in all the cases. The main criterium has been to start from the easiest geometry, in terms of number of control points, going towards most complex ones.

In particular, rectangular families can be grouped under two subfamilies, both having three subfamilies. Ideally, R1 family can be imagined starting from R 1.a with only one control point that will split into two points free to move horizontally and vertically, creating respectively the subfamilies b and c.

Generally, all the points of family R1 can move in the three directions; moreover geometries b and c have the restraint that the points have to move specular (e.g. if one control point of geometry b moves towards the exterior towards left, the other one has to move to the exterior too, moving towards right; obviously, the displacement will be equal in module for both of them). On the other hand, points of family R2 can be imagined always as a development of R 1.a where the control point is split in 4 or 2 points, free to move diagonally; in addition to the movement along the diagonal, they can move also towards the z axis.

As it can be seen in Figure 4-1, the movement of the control points creates a non-planar geometry; to solve this issue, the panels have been divided in triangular panels, in order to create planar geometries. It is reasonable to deduce that this family of geometries will be more expensive than the other rectangular one; even if the surface of glass is comparable, the cut of glass is more complex and the number of cuttings is higher, in addiction there is a bigger area of frame needed and the construction is more articulated. Moreover, is preferable to apply this system to bigger surfaces, in order to reduce the visual impact of the frame.

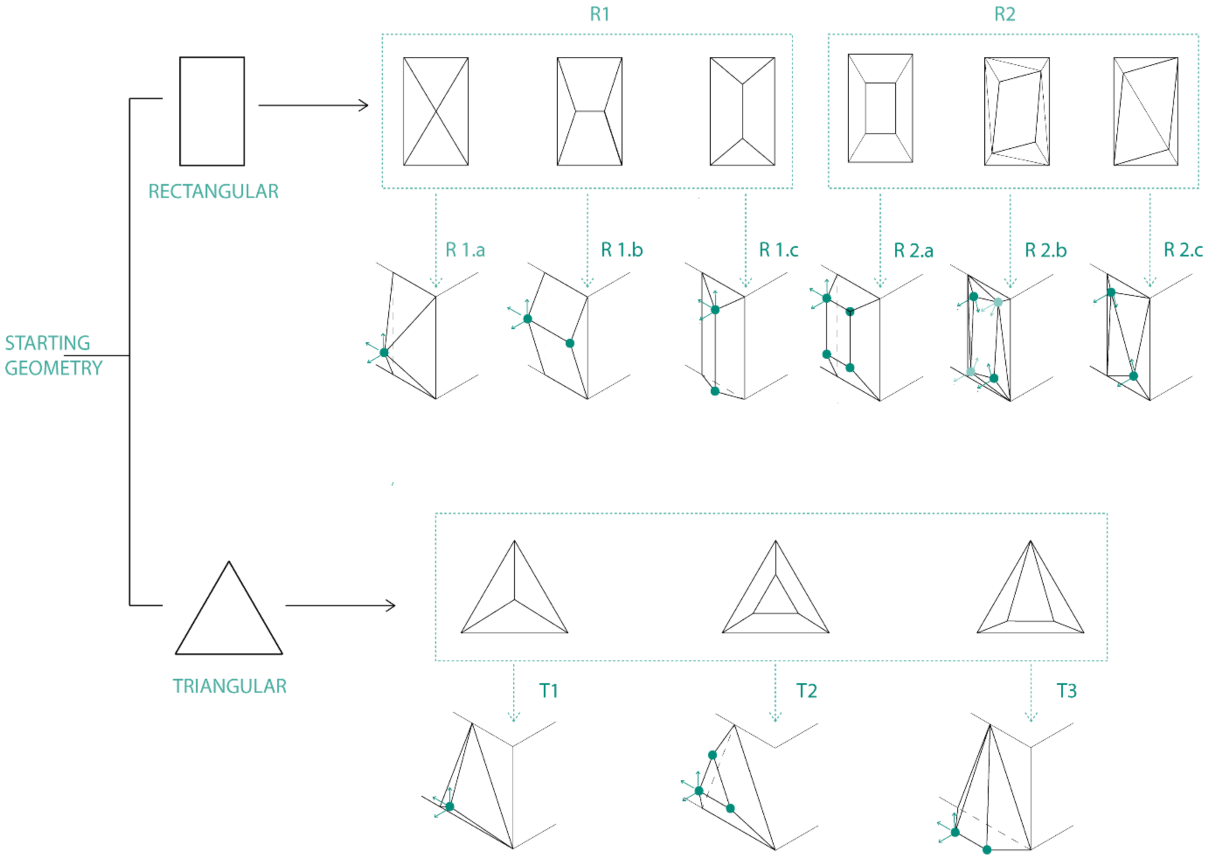


Figure 4-1: Geometries considered

4.1.1.1 Rectangular Subfamilies

As it can be imagined, the subfamilies have control points which are free to move in ranges which have been defined in the first steps of the modelling process in Grasshopper. The definition of the ranges is based on the study of existing systems, on the evaluation of the angles created by the intersection of the edges of the panels and the evaluation of the weight that the system can brought.

Family R1 is composed by three subfamilies, the first one with only one control point, creating only triangular panels and the second and third ones having two control points, which are basically the same geometry rotated of 90°.

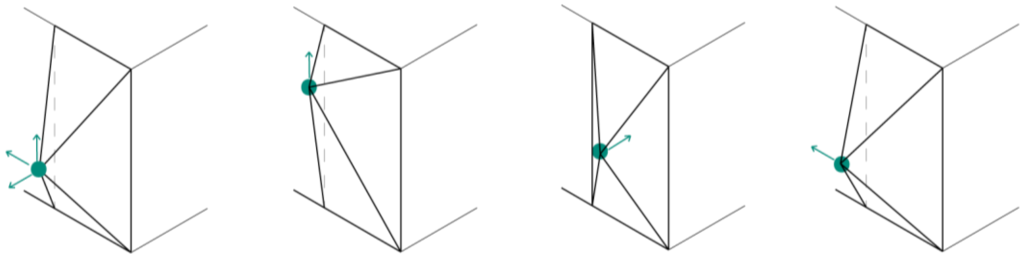


Figure 4-2: Movements of the control point of sub-family R1.a

The sub-families R1.b and R1.c are composed by trapezoidal and triangular panels. In each of them, the control points are free to move vertically, horizontally and away and towards the surface of the façade.

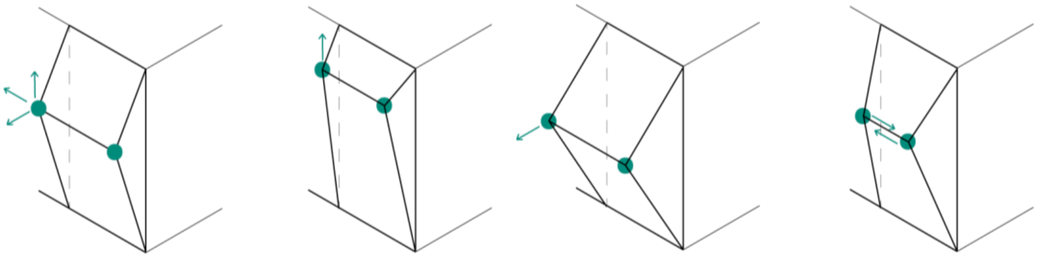


Figure 4-3: Subfamily R1.b

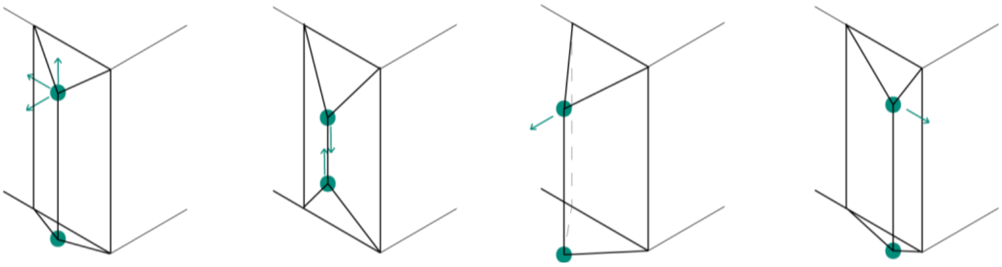


Figure 4-4: Subfamily R1.c

4.1.2 Triangular Geometries

As seen before, along the rectangular family, the triangular one has been considered too even tough triangular geometries are less used in façades respect to the rectangular ones; on the other hand, they allow to obtain particular and more complex shapes combining them together. In fact, this solution has been considered mainly to cover only a portion of the façade, in order to create a particular shape or pattern, or to create shading only in portions of the façade. The technological restrictions on the dimension of the panel, due to its weight and the installation procedure, allow to manufacture panels of modest size; this may lead to obtain a heavy redundancy if the pattern is applied to the entire façade.

Triangular family is composed by three different geometries. The T1 is the correspondent of R1.a for a triangular shape, it is composed by only one control point free to move in the three directions.

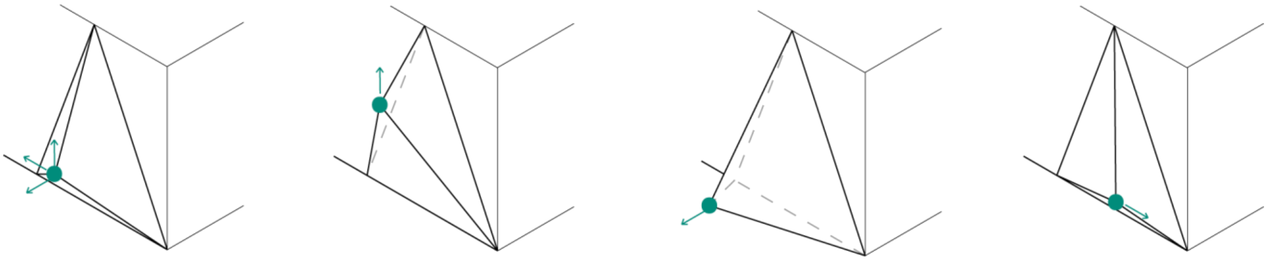


Figure 4-5: Family T1

T2 is composed by an extruded triangle placed in the middle of the panel, which is the bigger one scaled of a certain amount, corresponding to the R2.a.

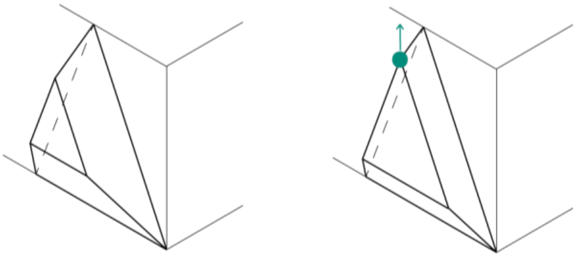


Figure 4-6: Family T2

This family has been thought in order to have a “more flexible” module, which can be rotated, used placed close to the others in order to obtain more complex shapes and patterns.

4.1.3 Tiling

Regarding the form-finding and the use of new shapes, Moneo[18] states that one of the main characteristics of the architecture nowadays is related to the representation issue; the new techniques go beyond the drawing and allow to have access to geometries that have been inaccessible until now. They are not only considered from the point of view of the architecture, but they become an exhibition instrument and a way to astound people with the virtuousness of the design. Another trend of the architecture is to use innovative materials, to combine different ones together, in order to create an impact through the juxtaposing of unexpected materials and shapes; as a consequence, the tendency is a design which moves towards the tiling, which allows the use of regular shapes that combined together can create a movement and break the regularity.

For this project the issue related to the shapes was a crucial point, but it was clear from the beginning that the tiling and the movement created along the façade had to be related to external parameters (e.g. the conditions to get a visual comfort) and it could not be only for their own sake. This was one of the biggest challenges for this project, since from the beginning the main concern was to push the tool definition beyond the limit to obtain a pleasant geometry, guaranteeing the comfort; the hardest goal to reach is to communicate through the geometry which are the indoor needs and viceversa, in order to explain the geometry according to what is required inside.

Along with the previous prerogatives, it is necessary to consider that this process cannot be completely automated and handled by a software, so a relevant aspect was to guarantee the user

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[18] R.Moneo, C. Diez Medina, “L’altra modernità, considerazioni sul futuro dell’architettura”, O.S. Pierini, 2012

the possibility to express preferences and to choose eventually a preferred configuration, guiding him towards a conscious choice in terms of comfort and energy consumption. The final façade will then be a combination of the computational part and the will and ability of the designer to choose a configuration and a distribution which allow to obtain pleasant geometries and shapes. The expected output of this plug-in will be to deliver to the user a geometry for the façade that will be customized as much as possible. The “customizing process” has been one of the hardest parts of the work, since it was not possible to give a complete freedom to the user, but it was necessary to give him choices that could cover at least part of his possible needs and requests, allowing him to express his will even through a pre-set path.

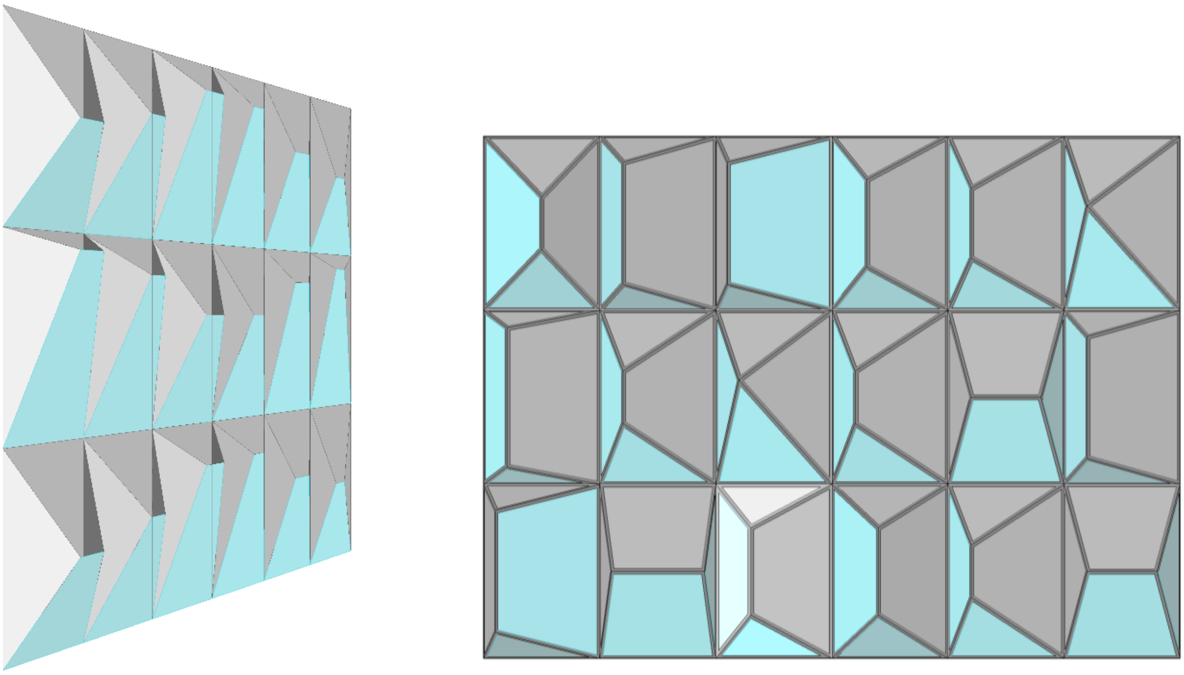

Figure 4-7: Geometries remapped and random distribution

Therefore, the user can choose the geometry (or more than one) that he prefers, decide how to combine it and also decide if he wants to set a trend for the distribution of panels; as it can be seen, the façade on the left has been realized ordering the geometries on the same floor according to an increasing/decreasing width, height or extrusion. On the other hand, the second picture, shows a random distribution of geometries belonging to different families.

A depth study on tiling will be required as a further step of this study, since some possibilities can be explored, also considering some technological issues which will be analysed afterwards. A possible option would be to attach the panels alternatively at the upper and at the bottom part of the slab, to create further movement to the façade:

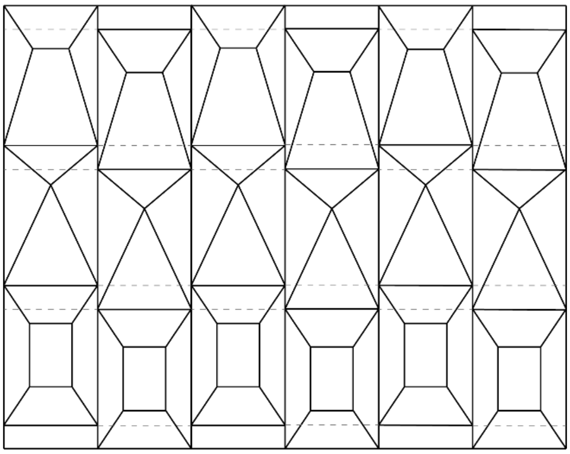

Figure 4-8: Different attachment of the panels

In this way, it is not required to have many different panels along the façade to create movement, but the panel along the floor can be the same only attached in a staggered way, respect to the adjacent one.

On the other hand, a limit of this configuration will be the fact that for the panels attached to the bottom part of the slab, will be visible from the outside, since in most of the cases the bottom panel of the geometry is transparent. The same can be said for the panels attached to the upper part, but this problem will be less relevant since in the major of the cases the upper panels will be opaque.

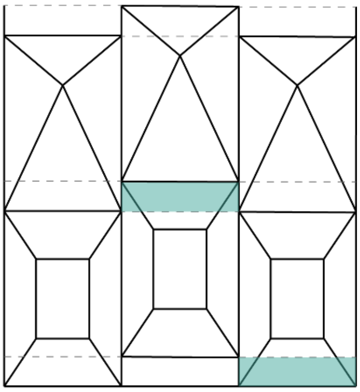

Figure 4-9: Sight of the slab through the panels

A solution for a disposition that has been rejected in this thesis work is the one where the panel is attached at half height of the adjacent one. This is due to the fact that the inhabitants inside will have at sight height the frame of the panel; moreover, this solution from a technological point of view is really difficult to be realized.

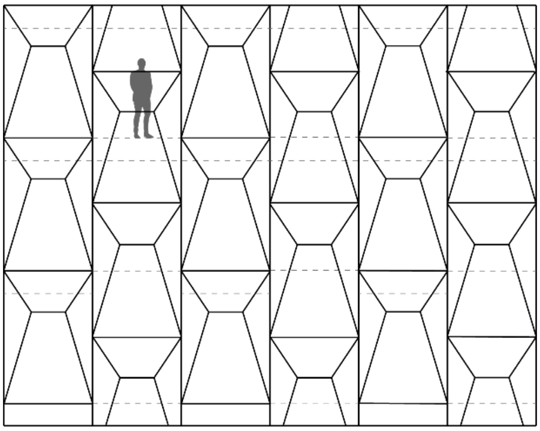

Figure 4-10: Staggered distribution

Nevertheless, this solution can be used in north orientations or in east/west façades where the panels are most likely transparent; otherwise it can be used in rooms that are not supposed to let the inhabitants to have a view of the outdoors, as conference rooms, museums, etc..

All these considerations involve a deep study on the tiling options, but mostly on the technological aspects related to the attachment of the façade cell to the structure; this thesis work, as it will be seen in the next chapter, considers a traditional technological system, with the attachment to the slab, since the main concern of this study was the definition of an autonomous process. Once the process will be defined and there will be no limitation on the side of the analysis tool, it will be possible to explore all the different tiling options and their related technological study.

5. TECHNOLOGY

The purpose of this study is to define a procedure and a flow for the preliminary stage design of façades and for the correct form-finding of each module towards the visual comfort. Even if the aim of the project is not the detailed analysis of a technological system of façade, some considerations on the technological issue must be done. In fact, as seen in the previous chapter, the type of geometry chosen is not easy to handle and design, since it departs considerably from the general guidelines usually followed for a curtain wall system. Consequently, the study of the technological part was fundamental at the beginning of the modelling part, because it was necessary to set some limitations to the control points.

It was important also to analyse the possibility of use of a PV integrated system and the changes that should be applied geometrically due to its use, its visual properties, but also its efficiency in order to evaluate it in the energy calculations.

Finally, the study on the technological part has been useful in order to define the costs of such a peculiar system, not only in terms of production, but also in terms of construction, installation and maintenance.

This chapter explores all of these aspects, firstly giving some information on the general structure of the module and the way to attach it to the slab; then it will be explained the glazed system used and the integration of the BIPV and lastly the maintenance and the costs.

5.1 UNITIZED SYSTEM

Once the geometries have been defined, it was possible to analyse the system from the technological point of view. This issue is fundamental for the further development of the project, since defining even in a general way which could be the procedure of installation is crucial to define approximately the price of the system and which can be the differences in price using different geometries in the same façade, both in terms of materials, production, transport, etc..

The initial question about the structure was about which main system to be considered, whether *stick* or *unitized system.* Many considerations have been done considering how long is the process to put them on site and the possibility to use or not the scaffoldings for the installation of the panels and, of course, the costs. The choice is relapsed on the use of a unitized system. Even if this method is more expensive, the installation is easier and safer, since there is no need to put scaffoldings on site. The modules will be lifted up through the use of a crane and then positioned directly on the façade where previously have been installed the brackets to host the unitized modules.

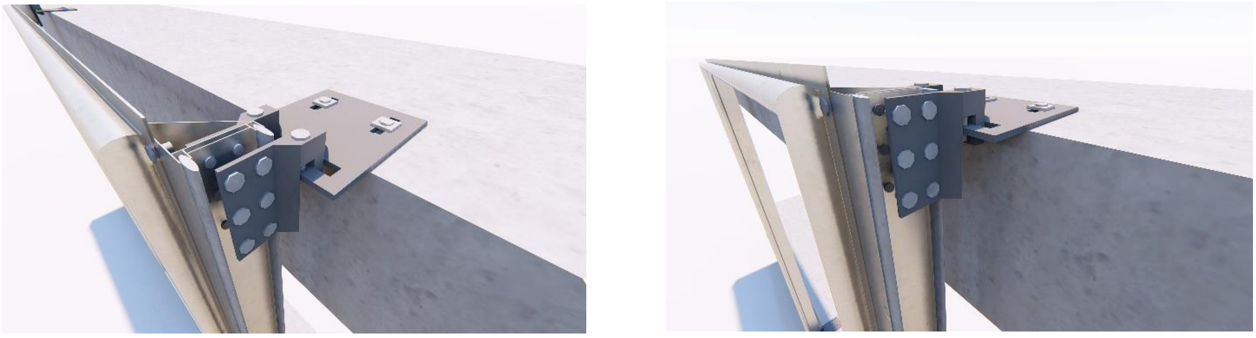

Figure 5-1: Brackets for the installation of the unitized system

The unitized system will be divided in two subsystems, as it can be seen in the following picture:

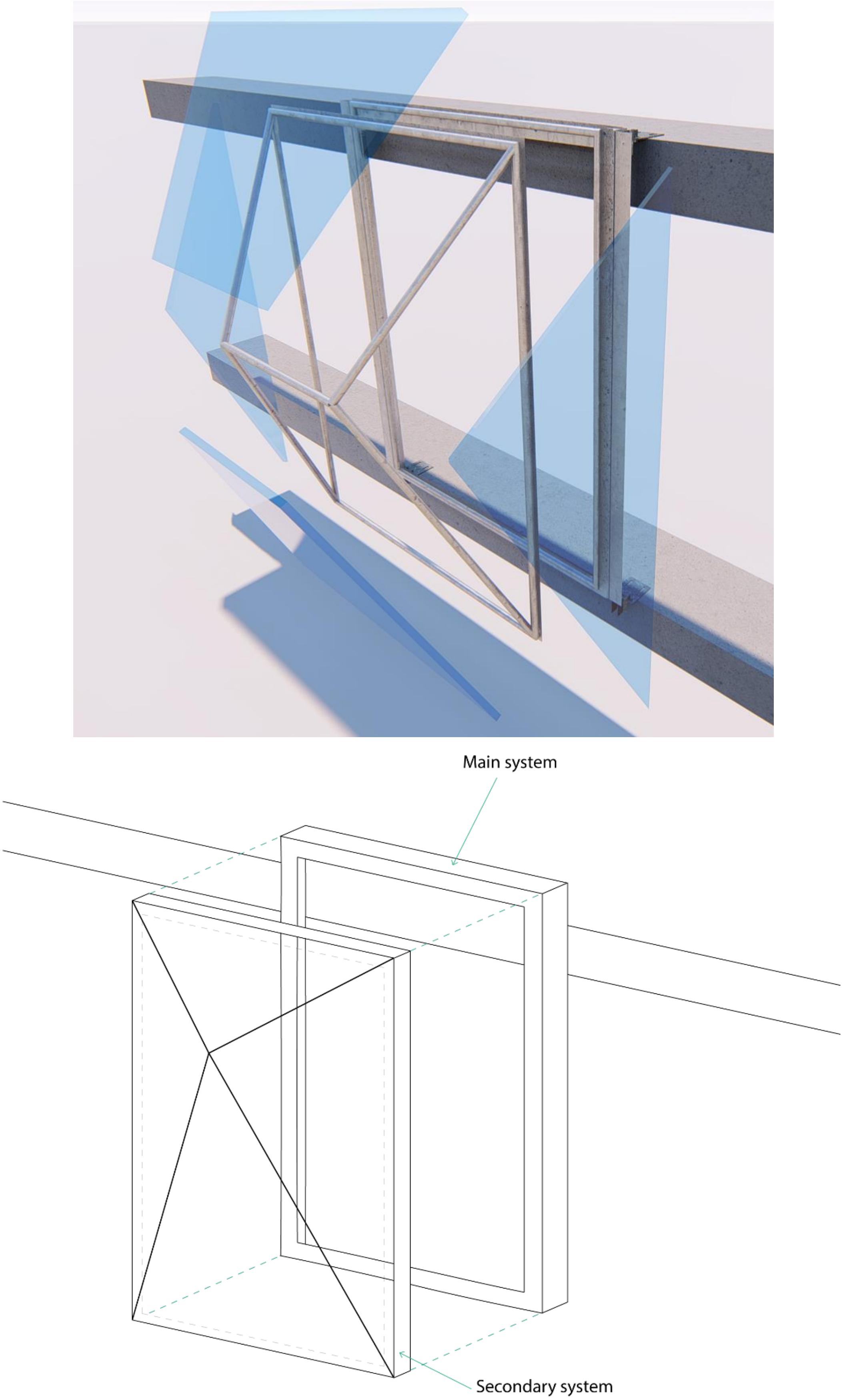

Figure 5-2: Scheme of the different structures of the unitized system

- The main system directly connected to the slab is a unitized module made of steel;
- The secondary system, the one that holds together the three-dimensional panels of the module consists of aluminum linear single bars and their connecting node points.

The entire individual module of the façade (main + secondary) will be assembled directly in factory. The geometry of the unit frame is adapted specifically to the load-bearing structure of the building. In order to understand and define which could be the limitations to be assigned to the system in the creation of the model phase, it was necessary to study the specifications of some systems which could be applied to the construction of such a peculiar panel. The best reference is the Schüco Parametric System, which is a non-flat façade system; analysing this system and making some assumptions related to the features of the considered geometries, some geometrical limitations have been provided, such as:

- The minimum possible angle between two linear single bars will have to be higher or equal than 10°;
- The maximum possible three-dimensional extrusion will be of 1 m, while the minimum of 10 cm;
- Due to the weight and the difficulties in fabrication and transportations, it has been given a maximum dimension in height (4m) and width (1,5m) for each unitized module.

The last consideration has been done considering a maximum planar surface to be covered with the system equal to 6 m^2 ; this value takes into account the maximum weight that the system can bear, since it is calculated considering the system as flat, so it allows to be conservative and safer, since the inclined surfaces will have a higher area, with a higher weight.

Since the maximum height considered of the modules is 4m, anytime the inter-storey is higher a spandrel panel will be provided.

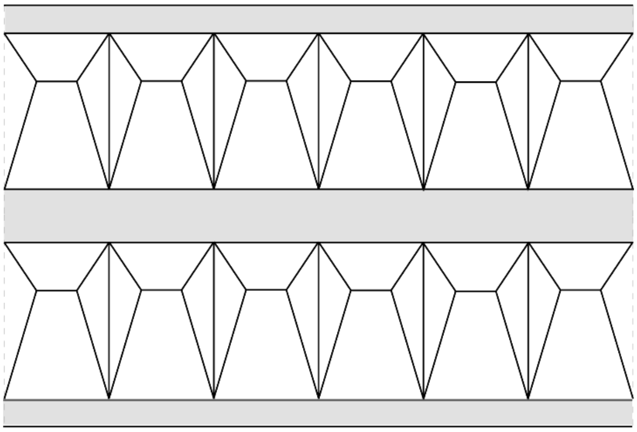

Figure 5-3: Use of spandrel between panels

5.2 INSULATED GLAZING UNIT MODULES

The system considered in this thesis work for the glazing modules is an insulated glazing unit (IGU). It has been planned to use a double-glazed unit; the air cavity between the two glasses will be fulfilled with argon (90%). The table below reports some parameters considered during the modelling part, both for the solar protection and the thermal insulating properties:

Description	*Light*		*Solar Radiant Heat*				*U-Value [W/m^2K]*
	Light transmittance [%]	Reflectance	Direct transmittance	Reflectance	Absorptance	g-value [Total transmittance	Argon (90%)
6 + 16 + 6 (low-E)	**73**	0.16	0.38	0.47	0.15	**0.39**	**1.0**

Table 9. IGU properties

Some similar systems provide a triple-glazing unit, which allows the system to be more performing, but, at least for the analysis, it has been decided not to consider it; nevertheless, the parameters considered can be easily changed to adapt to a triple-glazing unit.

According to the technical specifications considered of different manufacturers, the insulating thermal properties of these typology of modules, due to their geometrical and technological complexity, have to be analysed with particular attention. Due to their three-dimensional extrusion and their possible geometrical customization, it is important to consider also the U-value at the attachment of the module to the unitized façade and the attachment of the central unit between the two or three different glazing panes: the two frames will have different thermal transmittances. As it can be deduced, this difference is due to the inclination of the modules and, consequently, the angle between the panes: the thermal transmittances of a frame with an angle of e.g. 16° and 120° will be considerably different. The same assumption can be done if the glazing unit is considered with two or three panes. For thermal calculations (see Chapter 7.2), it has been considered an average of the values given by different producers' technical sheets:

- U-Value at the attachment with the unitized façade: 1,6 W/m^{2}K
- U-Value at the center outer corner of the unit: 1,1 W/m^{2}K

5.3 BUILDING INTEGRATED PV

The use of BIPV to generate renewable energy on buildings is future-oriented, particularly with regard to the expected implementation of the "EU Buildings Directive" 2010/31/EU concerning the total efficiency of buildings in the EU member states by 2020.

The choice to consider a Photovoltaic system inside the façade has been taken in order to increase the performance and create shadings against the light incoming inside the building. PV panels, in fact, allow the façade to act like an energy generator. Since the modules of the façade are three-dimensionally extruded and the panels are tilted between 10° and 80°, depending on the configuration, the efficiency of the panels increases rather than in flat facades, like curtain walls. Depending on the daylight analysis provided by the tool, it is possible to have more than one opaque panel on a single module. The possibility to integrate a PV panel will be evaluated depending on the inclination of the panel and the hitting radiation.

Moreover, the inter-storey spandrel panel, when provided, could be integrated with PV panels, even if this solution needs to be carefully evaluated according to the dimensions of the upper panels, which could project their shadow on the spandrel panel.

There are two commonly used framing systems for a PV integrated curtain wall: pressure plate and structural silicone glazing.

- *Pressure plate system:* the glazing unit is held mechanically by a plate put on the front with an extruded cover. The mullion cover has to be kept to a minimum to avoid the shadow produced by the system on PV cells.

- *Structural silicone glazing:* some or all of the glazing edges are glued together with the framing system. Moreover, the application of a structural silicon seal between PV glazing units eliminates shadowing effects but can lead to durability problems for PV panel edges.

The intent is to let the designer choose which solution is the best for his purpose.

There are different technologies to produce PV cells:

- *Monocrystalline silicon:* silicon cells that are usually manufactured from a single crystal ingot of high purity. The diameters are about 12.5/15 cm. It is applied a thin anti-reflection coating in silicon nitride or titanium oxide, in order to increase the light absorbed and, as a consequence, the current.

- *Polycrystalline silicon:* the starting material is melted and cast in a cuboid form. Large crystals with grain size from few millimeters to few centimeters are formed once the silicon is solidified. The efficiency is reduced slightly because of the grain boundaries. The ingot is cut into bars and, later on, sliced into thin wafers used to make cells. This solution is cheaper than the monocrystalline one, but its efficiency is also lower.

- *Thin-film:* the construction comes by applying thin layers of PV materials onto the front glass, i.e. the superstrate, or onto the module backside, i.e. the substrate. The PV module and the connections between the cells are made at the same time during the fabrication, since it is an integrated system. The active semiconductor materials used are amorphous silicon, cadmium telluride (CdTe) and copper indium diselenide. Compared to crystalline silicon technology, this solution has a lower efficiency. That means that to reach the same efficiency is required a larger unit area. Amorphous silicon and CdTe thin-film modules are made in similar way onto the glass superstrate, while CIS thin-film modules are normally fabricated onto a substrate: glass, metal or plastic. CdTe is a very stable, non-toxic compound, even if cadmium is a heavy metal with environmental issued. Moreover, among the thin-film technologies, CdTe modules have the lowest production costs.

- *High-performance:* there is a wide range of new technologies, but here will be mentioned one of the most well established in production: *HIT* (heterojunction with intrinsic thin-layer). It is a PV cell hybrid construction made combining a thin-film silicon cell with a crystalline one. In this configuration amorphous silicon is coated onto both front and rear faces of a monocrystalline silicon wafer. The name “heterojunction” is due to the fact that the junction is created between two structurally different semiconductors. HIT cells are more efficient and have less degradation of efficiency than monocrystalline silicon. These types of PV cell are assembled into glass-glass laminates, in order to allow the module to be more efficient, using both the front and the rear to absorb light and generate at least 10% more electricity than the standard mono-facial type. In building application this type of modules works because the backside of the panel benefits from the ambient and reflected light. Obviously, the maximum gain is achieved with reflective or white objects behind.

It is very important that the front glass, the one facing the sun, has a very high transmission efficiency. Typically, a white glass is used, since it has a low percentage of iron oxide. Transmission efficiency is basically around 92%, with 8% of reflection that can be reduced around 3% thanks to the use of an anti-reflection coating in the front. As a standard, the front glass is 3-4 mm thick, but can be increased to 10 mm for larger modules

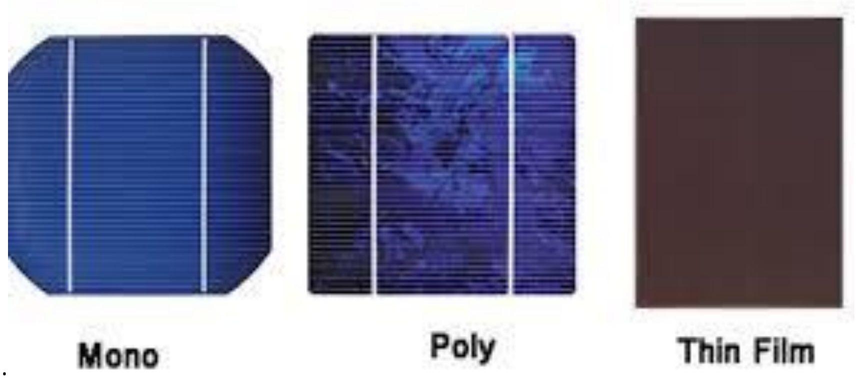

Figure 5-4. https://www.solaris-shop.com/blog/crystalline-vs-thin-film-solar-panels[19]

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[19] https://www.solaris-shop.com/blog/crystalline-vs-thin-film-solar-panels/ (last visit 12.09.2018)

TYPE	*TYPICAL MODULE EFFICIENY*	*AREA REQUIREMENT*
High-performance hybrid silicon (HIT)	17-18%	6-7 m^2/kW_P
Monocrystalline silicon	12-15%	7-9 m^2/kW_P
Polycrystalline silicon	11-14%	7-10 m^2/kW_P
Thin-film (CIS)	9-11%	9-11 m^2/kW_P
Thin-film (CdTe)	6-8%	12-17 m^2/kW_P
Thin-film amorphous silicon	5-7%	14-20 m^2/kW_P

Table 10. Efficiency of PV modules[20]

In this thesis work a crystalline silicon panel has been considered, thanks to its higher performance among the other typologies. Thin-films PV have great potentialities, but they still have to be studied to increase their performance. As said in the table above the current efficiency to convert solar energy into electricity is around 9-11%, even if tests in laboratory revealed that efficiency could reach values higher than 20%.

The other advantage of using thin-film than crystalline is due to the fact that thin-films are considerably thinner, about 1-2 micrometers (µm), against a much greater thickness of about 160–190 µm required for crystalline silicon.

Finally, installation costs will differ significantly between thin film and typical PV because thin film panels are very easy to install and require much less labor.

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[20] N. Guariento, S. Roberts, Building Integrated Photovoltaics, Birkhauser, Berlino, 2009

5.4 MAINTENANCE AND COSTS

5.4.1 Maintenance

As it can be seen in the next chapters, the final façade can be composed by different geometries in order to make the most of the combination of different shapes and materials to obtain the set goal. From the point of view of the costs, this can represent a potential problem. Consequently, a further analysis on the technology has been required, mainly to define if It was necessary to set some limits on the maximum number of different panels along the façade, to avoid excessive costs.

Firstly, it has been investigated more in the detail the way the secondary frame is attached to the primary one and how it was possible to change the panels in case of breakage. This issue is crucial not only in terms of extraordinary intervention, but also thinking about the construction of the façade. Let's think for example to a façade composed by all different panels; if one of them breaks during the transport and the construction advances by rows, it will not be possible to continue until the same panel is produced again and reaches the construction site, causing a considerable increase of the costs due to the delay.

Through a study on different systems, it is possible to define the structure as composed by three parts: the primary frame and the secondary one, which is composed in turn by a frame which in case of substitution is not removed and stays attached to the façade, while only the IGUs is removed and reapplied. As said in paragraph 5.1, during the construction phase the module arrives at the construction site already assembled in factory, with the primary and secondary frames mounted together and sealed. They are fixed at the slab, through the use of a plate, which has holes in order to allow the cell to be attached using some hooks.

In case of need to change the glasses or the opaque panels for maintenance, the primary frame is always attached at the slab; the structure of the secondary frame, which is screwed to the primary one stays in place. It is then possible to break the structural sealing and to remove the glass and the gaskets. The new glass is replaced, the gaskets substituted and the sealing is done on site.

5.4.2 Costs

In terms of costs, as the reader can imagine, this solution is expensive since it is a custom geometry, which is also complex from the point of view of the technology. The aspect which influences considerably the price is the higher amount of materials compared to the ones needed for a flat façade. In fact the secondary frame has big profiles in order to allow the tilted geometry and also due to the higher resistance that a system like this has to provide to resist to the external forces (e.g. wind, snow..). Through a comparison with flat façade system, the price of this system can be assessed as four times higher, which is a considerable difference. On the other hand, this system allows to improve the production of energy, due to the inclination of the panels, to increase the comfort and reduce the gains through the envelope; it can represent an efficient tool to save and produce energy, which can return in the years as a pay back of the initial expenditure. Nevertheless, in order to constitute a payback, it needs to be properly designed.

It is possible to state that fortunately, this system, since it is customized, does not present relevant differences in terms of price to obtain different panels for the same façade, which is crucial and fundamental to obtain the best optimization of the façade.

6. PRELIMINARY ANALYSIS

This chapter finally goes deeply on the first approach to the world of daylight and energy simulations using the façade system explained in the previous chapter. As this work aims to develop a more autonomous flow for the design of energy efficient and visual comfortable façades, it was crucial at least for an early approach to this world, a study on the basis and on the main factors which can drive this research.

The first part of the chapter "Model Setting" explains the basic principles of modelling followed to define a building model, simplified as a room, which can be used by the different daylight tools. The correct definition goes through the proper setting of materials, which are both required by DIVA and Honeybee. Finally, a brief explanation on the use of the solver is reported, mainly to explain which are the functions used to optimize the geometry, in order to obtain the best geometry.

The second part represent a tracking shot of the most important and relevant group of simulation performed, highlighting to what extent they have been useful for the final definition of the plug-in. Lastly, the final paragraph explain to the reader which have been the reasons which lead to a definition of property methods of calculation, which will be explained in detail in Chapter 7.

6.1 MODEL SETTING

In order to carry out the different analyses, it was necessary to define a model of a building, with the properties set for the materials both for the daylight and thermal properties. The reader will see in the next paragraphs that the analyses have been carried out with different software; each one requires particular precautions about the modelling. Nevertheless, the principles have some characteristics in common, which are going to be explained in this paragraph since they all are based on the same assumptions, declining them in different ways.

6.1.1 Geometry

First of all, the software requires a geometry to be tested; the decision for the preliminary analysis was to use a shoe-box geometry, with standard dimensions as stated in the ASHRAE prescriptions (as seen in Chapter 2). Crucial for the simulations is the definition of transparent and opaque surfaces, which comprehend the shading too; obviously, for the daylight analysis they will have to compose a closed volume. The decision fell on the use of a single room, in order to reduce the time for the simulations and to start making assumptions on the behave of the tools considered.

Along with the room itself, also the definition of the façade panels has been done, defined as parametric modules. As a matter of fact, each geometry (as shown in Chapter 4), has its own control points which are free to move along different directions, creating different geometries. The movement is defined with some sliders controlling the points.

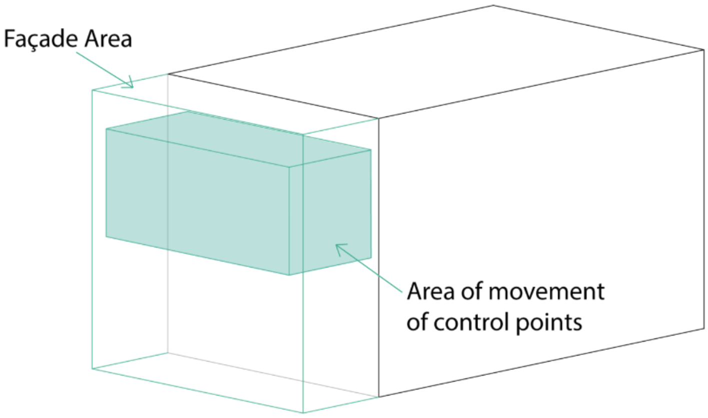

Figure 6-1: Area of movement of control points

The values of the sliders have been set considering some geometrical constraints, which are mainly due to some technical limitations, as explained in Chapter 5. The limitations given from the technological analysis have been translated in possible ranges for the movement of the sliders, translating the maximum and minimum thresholds into percentage of the total dimension of maximum and minimum movement. The main restraint is addressed by the minimum possible angle between the parts of the frame, which is 10°.

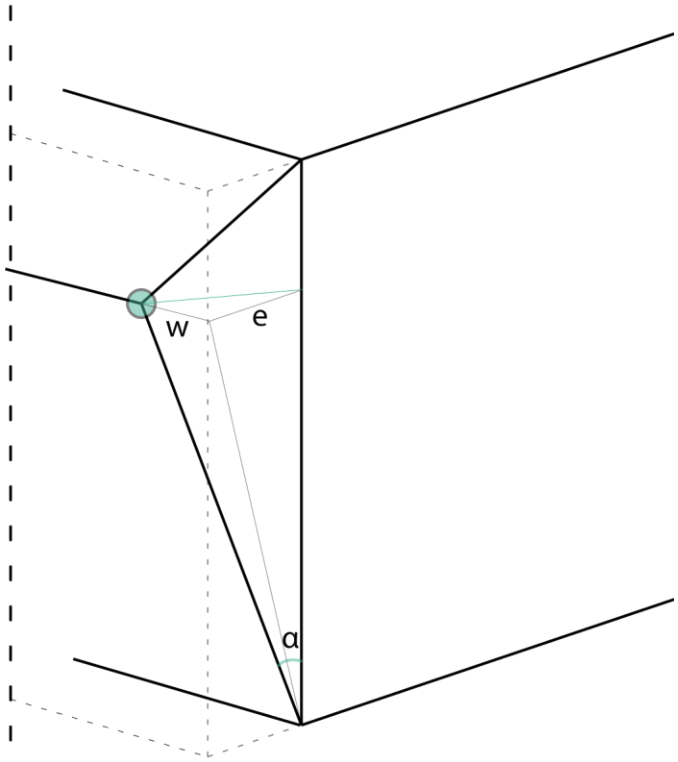

Figure 6-2: Calculation scheme for calculation of limitations

As it can be seen in picture Figure 6-2: Calculation scheme for calculation of limitations, the angle considered is α, which can be 10° minimum. From a simple geometric calculation, the case which has the smallest α is the one having the larger width (w) and the smallest extrusion (e), for that case it has been evaluated the minimum value of the extrusion, in order to obtain angles higher than 10°.

The obtained values for the room considered are the following:

	Minimum	*Maximum*
Extrusion	13cm/m	1 m
Height	1,6 m	2,7 m
Width	30 cm	1,5 m

Table 11: Ranges considered for the dimensions

These values have been set in the sliders as percentage of the total dimension considered of the panel, this method allowed to establish maximum and minimum extremes for each slider:

	Minimum	*Maximum*
Extrusion	1	10
Height	1	5
Width	2	9

Table 12: Extremes of dimensional sliders in Grasshopper

The creation of a geometry is a complex procedure, which has been developed in this project with a flow composed by different nested clusters, as it can be briefly shown in the following picture:

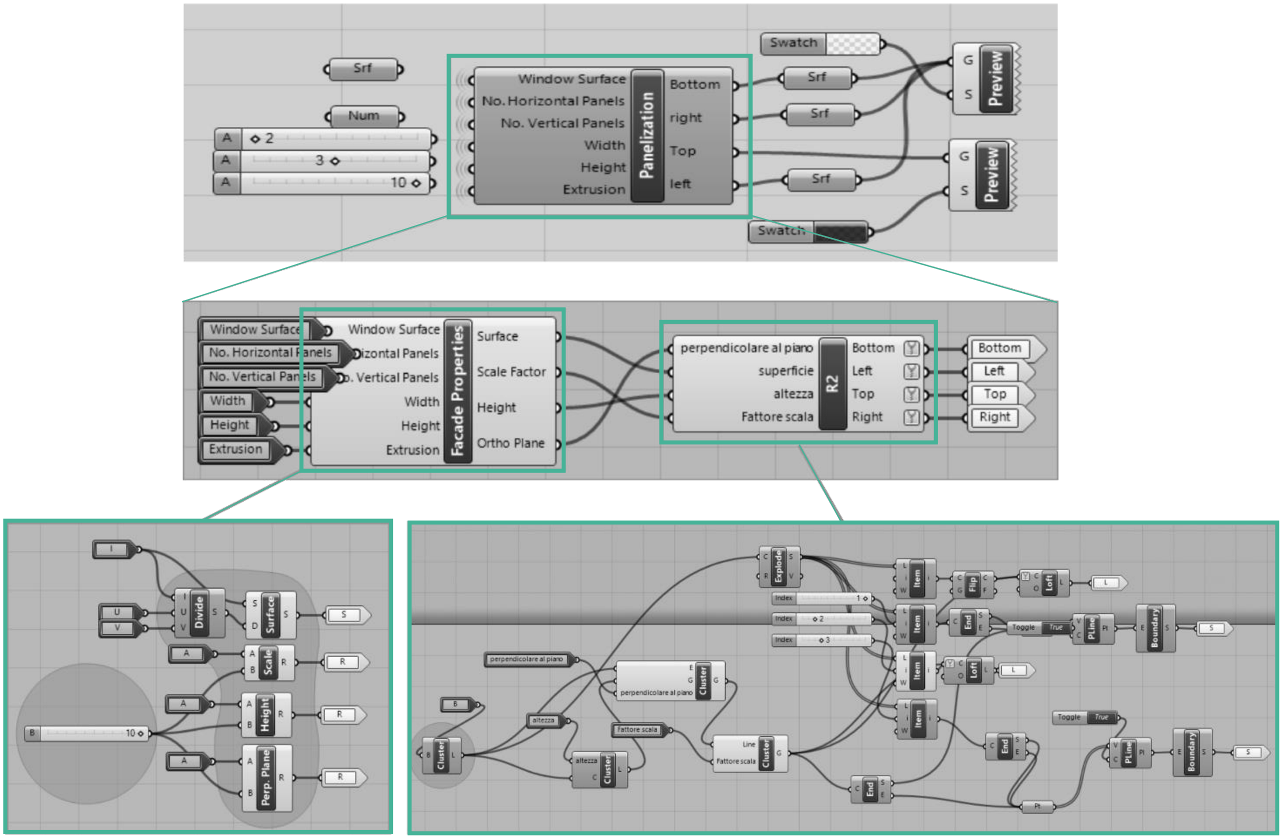

Figure 6-3: Geometry design flow

In the following picture, the reader can see how the geometry changes if the sliders change their value inside their range:

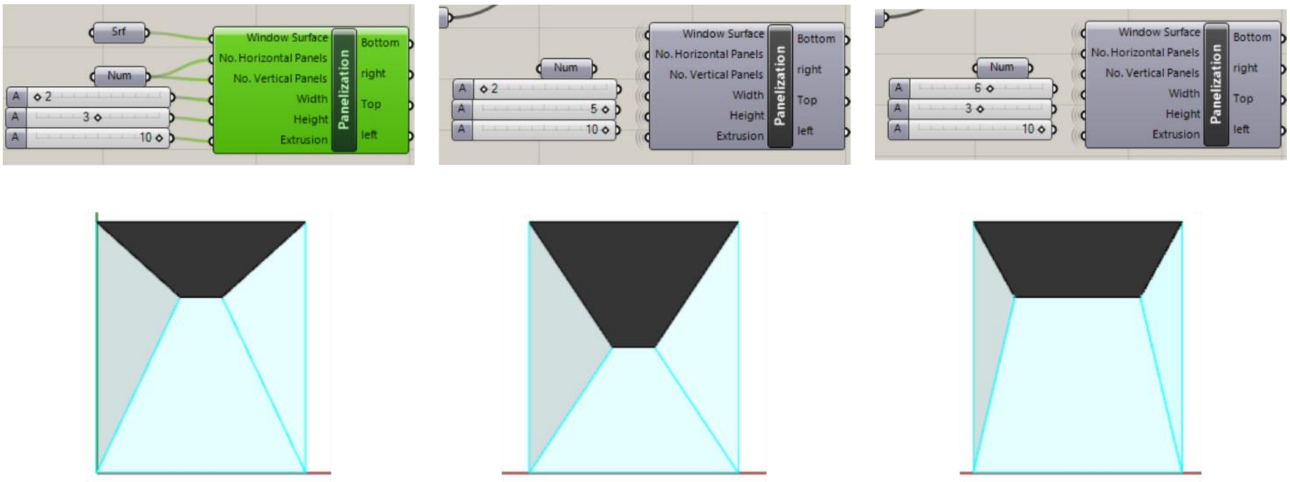

Figure 6-4: Dimensional sliders for the geometries

To generate a model suitable for a daylight analysis tool, it was important to make distinction between the opaque and the transparent surfaces, in order to apply the right material to the surfaces.

6.1.2 Materials

The definition of the properties of the materials is the same for DIVA and Honeybee, since they both allow the user to use the radiance library. “One often cited quality of Radiance is that it is physically based and capable of simulating complex geometries with flexible reflection and transmittance material properties using a mixed stochastic, deterministic backward raytracing algorithm. The ability to model specular components constitutes an advantage over radiosity based simulation approaches which treat all surfaces as Lambertian diffusers. Radiance’s scientific reputation is further founded on a series of independent validation studies.”[21]

The two software, in order to carry out the daylight simulations, require the optical properties of the materials considered. Their definition has been done using the format of radiance, which uses different parameters according to the type of material considered. The preliminary simulations only

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[21] C.F.Reinhart, M. Andersen, “Development and validation of a Radiance model for a translucent material”, Energy and Buildings, 2006, Elsevier

consider transparent, translucent and opaque materials, defined following the Radiance guidelines for materials[22]:

6.1.2.1 Plastic/Opaque Material

Plastic is a material with uncolored highlights. It is given by its RGB reflectance, its fraction of specularity, and its roughness value. Roughness is specified as the rms slope of surface facets. A value of 0 corresponds to a perfectly smooth surface, and a value of 1 would be a very rough surface. Specularity fractions greater than 0.1 and roughness values greater than 0.2 are not very realistic.

```
mod plastic id
0
0
5 red green blue spec rough
```

The opaque material used in the preliminary analysis is a BIPV with an inner layer of insulation, having the following properties:

```
# material name: BIPV_insulation
# material type: opaque
void plastic BIPV_insulation
0
0
5 0.1 0.1 0.1   0 0
```

6.1.2.2 Translucent Material

Trans material is similar to plastic. The transmissivity is the fraction of penetrating light that travels all through the material. The transmitted specular component is the fraction of transmitted light that is not diffusely scattered. Transmitted and diffusely reflected light is modified by the material colour. Translucent objects are infinitely thin.

```
mod trans id
0
0
7 red green blue spec rough trans tspec
```

---

[22] http://radsite.lbl.gov/radiance/refer/ray.html#Materials (last visit, 24 July 2018)

The definition of translucent materials is complex because it considers different parameters related to the scattering effect the light is subjected to when travels through the layer. As a consequence, the translucent materials used in the analysis are materials already listed in the literature; the one chosen have properties that we can approximate similar to ones produced by well-known glass producers.

```
# material name: TRANS24%
# material type: TRANSLUCENT
void trans TRANS24%
0
0
7 0.48913 0.48913 0.48913 0.08 0 0.5333 0


# material name: TRANS16%
# material type: TRANSLUCENT
void trans TRANS16%
0
0
7 0.40446 0.40446 0.40446 0.08 0 0.435635 0
```

6.1.2.3 Glass

For glasses one transmitted ray and one reflected ray are produced. By using a single surface is in place of two, internal reflections are avoided. The surface orientation is irrelevant, as it is for plastic, metal, and trans. The only specification required is the transmissivity at normal incidence. (Transmissivity is the amount of light not absorbed in one traversal of the material. Transmittance -- the value usually measured -- is the total light transmitted through the pane including multiple reflections). To compute transmissivity (tn) from transmittance (Tn) use:

```
tn = (sqrt(.8402528435+.0072522239*Tn*Tn)-.9166530661)/.0036261119/Tn

      mod glass id
      0
      0
      3 rtn gtn btn
```

For the preliminary analysis we considered two different types of IGUs, having different type of glass, with different light transmittances:

```
# Glazing_IGU_SUNCOOL40_22_PROT:  U-Value= 1.1W/m²K
# visual transmissivity: 40%
void glass IGU_LOW_SUNCOOL40_22_PROT
0
0
3 0.4 0.4 0.4

# Glazing_IGU_SUNCOOL70_40_OW:  U-Value= 1.1W/m²K
# visual transmissivity: 74%
void glass IGU_HIGH_SUNCOOL70_40_OW
0
0
3 0.74 0.74 0.74
```

As it can be seen, the second one is clearer, having a transmissivity equal to 0.74.

6.1.2.4 Use of materials in the model

The preliminary simulations carried out mainly aimed to reduce the wide range of variables of each system to a narrow domain, to reduce the time needed to complete a simulation. In order to obtain this goal, the first analyses do not take into account all the combinations possible using all the materials, but they only consider transparent or opaque materials; subsequently, once it was clear the behaviour in terms of sDA and ASE of the system related to the use of the materials, the simulations will consider also the combination with other materials belonging to the same category. (e.g. the system is tested with a basic type of glass and then tested with more performing glasses, in order to define the difference in performance).

In order to understand the behaviour of the system, some assumptions about the materials used in the different panels have been considered:

	South	*West*	*East*	*North*
Bottom panel	Transparent	Transparent	Transparent	
Left panel	Transparent/opaque	Transparent/opaque	Transparent/opaque	
Top panel	Opaque	Opaque	Opaque	
Right panel	Transparent/opaque	Transparent/opaque	Transparent/opaque	

Table 13: Materials assignments for preliminary analyses

6.1.3 Solvers

The dimensional parameters considered have been set as sliders free to change in their domain; the combination of the areas created by the different values of the sliders and the type of materials will imply a change in the opaque/transparent ratio and as a consequence, on the daylight parameters.

The aim is to reach the values of sDA and ASE to satisfy at least the minimum requirement of LEED v4, which is ASE ≤ 10% and sDA ≥ 55%, (to obtain more points for the LEED certification, sDA should be higher than 75%). As the reader can understand, it was necessary to find a way to automatically test all the possible configurations (more than 7000 for each geometry combined with the different materials); the choice fell on the use of a solver.

“Generic solvers, despite being called generic, can only be applied to a subset of all possible problems. To understand the limitations of a solver, one needs to understand both its underlying theory as well as the algorithmic representation of any given problem. These must necessarily remain somewhat abstract as the dimensionality of a problem is dependent on the chosen formulation, which is often far beyond what mere humans can visualise.”[23] A solver calls the domain of all the possible configurations the “phase space” where are collected all the combinations of values defining one state. The aim of a solver is to define the best solutions among them; to do this, it needs a “fitness

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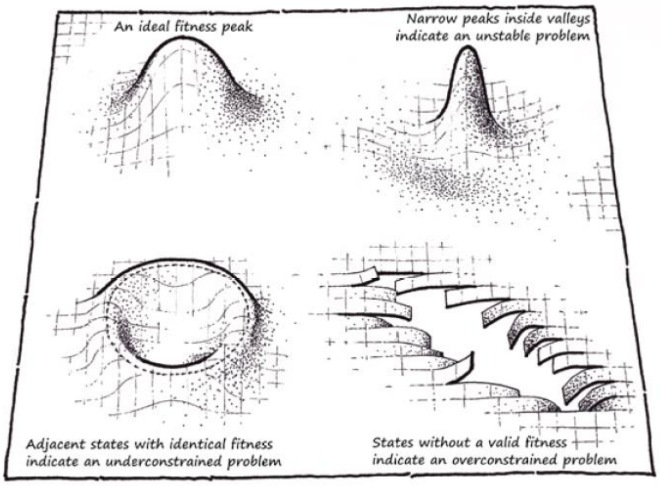
[23] D. Rutten,“Galapagos on the logic and limitations of generic solvers”, Architectural Design , 2013

function” which express the desirability of any given state and expresses that desirability as a single state.

Basically, it is necessary to define a “fitness function” which is obtained by all the values composing the “phase space”, then the solver will try to find the combination of values which maximize or minimize the fitness function, according to the will of the user.

The phase space is a 2D space, where the values of the fitness function are developed along a third dimension, creating peaks.



· *Figure 6-5: Landscape topologies*

The solver chosen for the preliminary stage is Galapagos, which offers two different kind of solvers:

- Evolutionary solver;
- Annealing solver.

The first one is based on biologic principles: the phase space is populated with individuals, then proceed to breed the highest ones in the hope that their offspring will be closer to a summit.[23]

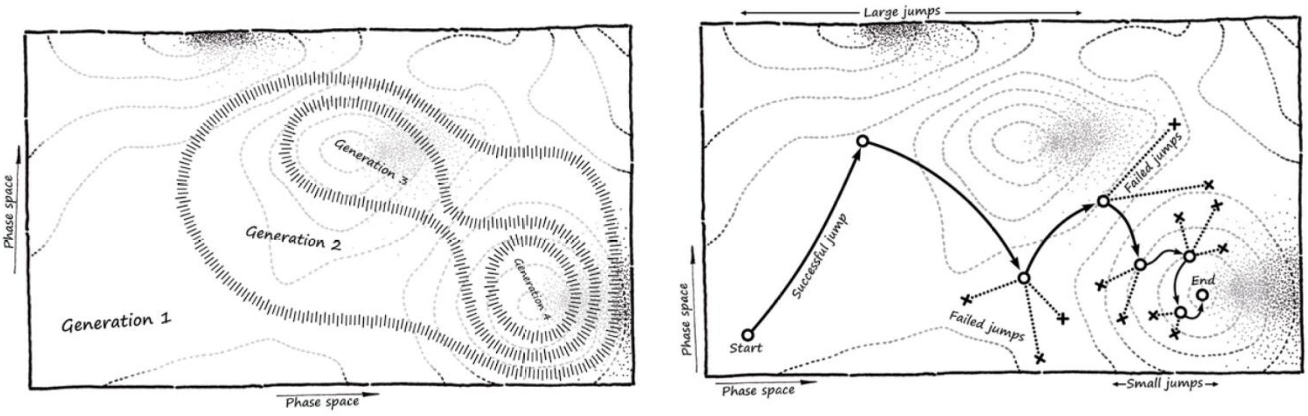


Figure 6-6: Evolutionary and annealing solvers

The second one is based on thermodynamics: when a crystalline matrix is formed during the cooling of a molten metal, the crystals grow as the temperature decreases. The solver tries combinations randomly in the space, doing decreasing steps; if the value obtained is worse than the previous one, it will revert to the previous value, not accepting the new combination.

The aim of the preliminary analysis is to define a certain number of possible configurations, guaranteeing acceptable values for the daylight comfort; as a consequence, the kind of solver chosen is the evolutionary one, since it does not provide the best value, but a group of suitable values.

6.1.3.1 Use of solvers in the model

Considering the way a solver works, as described by D. Rutten in his article about the limitations of the solvers, a solver needs a fitness function which expresses the *desirability of any given state*; the function needs to be expressed in a smart way, since the software will “learn” from the results of the processes and will plan the further attempts starting from them.

Different ways to express the fitness function have been investigated; the first main question was in which way the solver should learn that the results are not acceptable, distinguishing between the values that are close to be acceptable and which are completely out. Moreover, also inside the acceptable range it must be noticed that, even if values of ASE lower than 10% are good, the lowest is the value, the better is the visual comfort. The same could be said for the values of sDA, which should be higher than 55% or than 75%, according to how many points the user want to achieve from the LEED certification. These assumptions are the teachings that the solver has to learn.

The first challenge related to this setting was that the two values were on two different scales, so it was necessary to normalize the values on the same scale, to give them the same importance:

$$ASE_n = \frac{ASE\ value}{10}$$

$$sDA_n = \frac{sDA\ value - 55}{100 - 55}$$

Then, in order to make clearer to the solver the fact that the lower is the value of ASE, the better is in terms of comfort, the results higher than 11 has been transformed in negative number. Then the equation to be minimized was:

$$(1 - ASE_n) + sDA_n$$

This fitness function allows to give an important information to the solver: since the fitness function needs to be minimized, if the values of ASE are higher than 10% they are normalized and added in the formula: the smaller is the difference from the 10%, the lower will be the value of the fitness function, teaching to the solver that configurations having for examples an ASE equal to 12% have some good parameters which lead them to get close to being acceptable. This approach has been used in all the analyses that will be shown in the next part of this paragraph: the configurations are investigated trying to minimize the function set.

6.2 SENSITIVE ANALYSIS ON STUDIED GEOMETRIES

In this second part of the chapter, it is described the group of tests performed in order to evaluate different parameters that could have influence on the final geometry and on the decisional process. First of all, the sensitive analysis has been done considering the geometries studied, in order to understand if the behave descripted in Chapter 3.4 could be assumed also for more complex geometries.

The model has been analysed with the two tools using the same settings for Radiance Parameters and materials. This study has been necessary also for the analyses that will be explained later in Chapter 6.4, which lead to the definition of the bases to develop a method of calculation of ASE and sDA. As a matter of fact, at that part of the stage it was necessary to establish how and according to which parameters results could change from one software to the other, in order to predict the goodness of the obtained results.

Here below are reported part of the simulations carried out and the comparisons between the two software considered; the geometries studied are always composed by the same materials applied to the panels but trying the "most extreme" geometrical configurations.

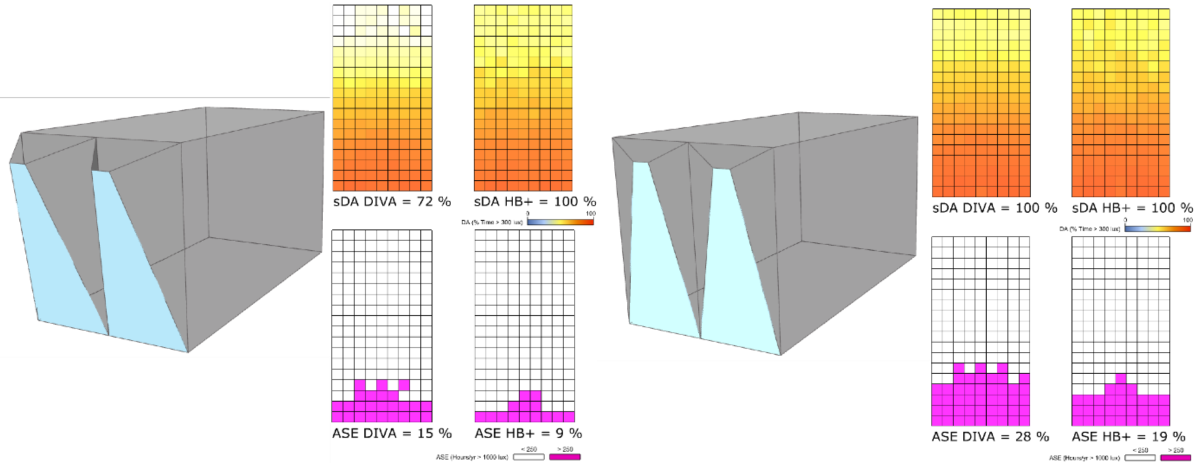


Figure 6-7: High height, high extrusion, small width and High height, small extrusion, small width

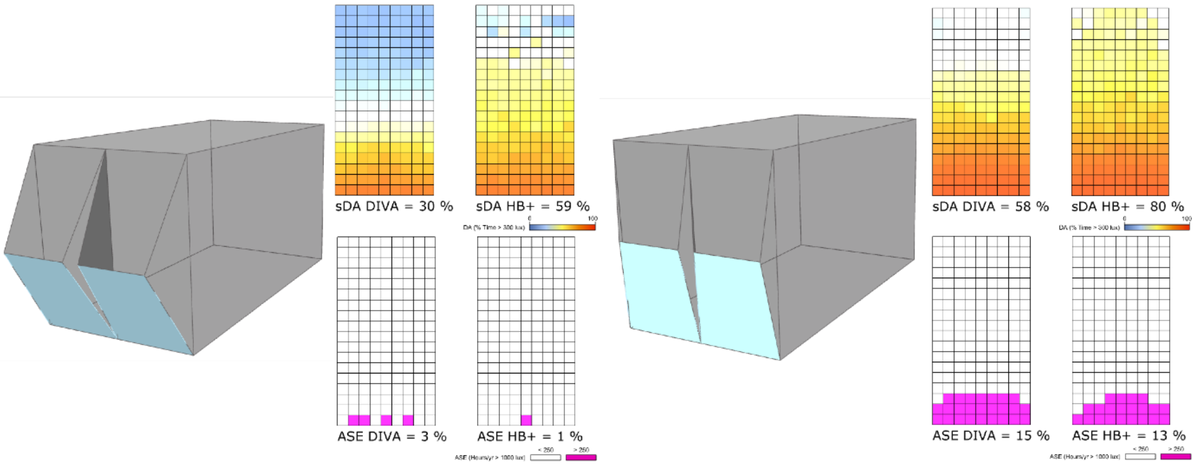


Figure 6-8: Low height, high extrusion, high width and Low height, low extrusion, high width

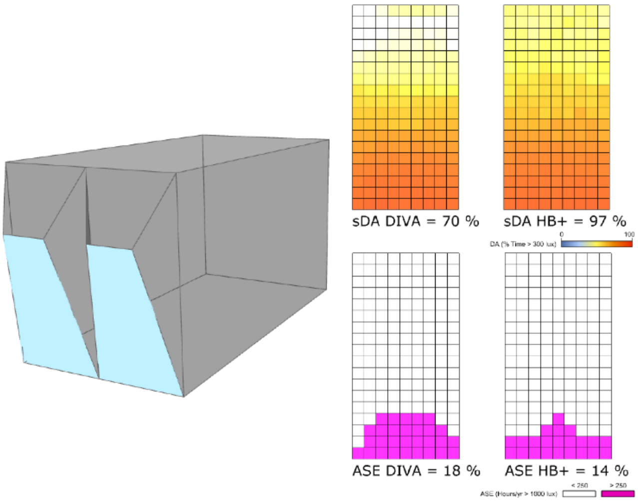


Figure 6-9:Medium height, extrusion and width

As the accuracy of the ASE is concerned, the simulation shown that the highest is the transparent surface, the lower will be the difference in the results of ASE between the two software. As previously explained in the chapter 3.4.2.2, the variation of ASE values between Honeybee [+] and DIVA is less valuable if the glazing part is in the lower part of the façade and the incoming direct light hits the grid analysis in the part of the floor closer to the façade. In this case, the three-dimensional more extruded shadings, i.e. in the cases 3,4 and 5 acts like windows placed in the lower part of the façade and, consequently there is not so much variation between the values of the ASE. Vice versa, where the glazing part is more emphasized and there is not so much shading, the difference in ASE between the software increases considerably.

Same considerations can be provided about the sDA. As already said in the chapter 3.4.2.1, the different discretization of the sky patches between the two software has a lot of impact on the results. Since in DIVA the position of the sun in the sky is approximated of 3-4 patches, if a shading is provided like in this case, the grid points that will be more subjected to direct and diffuse light will be those closer to the façade; deeper inside the room, even increasing the power and the bounces for the calculation, the results will never be accurate enough. This explains why the percentage of hours of illuminance overcoming 300 lux calculated in Honeybee [+] is high also in the intermediate area of floor of the room, while in DIVA this value rapidly decreases moving away from the window; in fact, looking at the figures from Figure 6-7 to Figure 6-8, it can be seen that the orange cells of the floor are similar until the first half of the room, then in Honeybee they tend to smoothly fade towards the end of the room, while in DIVA there is not a smooth transition, but it is quite abrupt compared to the other software.

In support of this theory, also the results of the Daylight Autonomy (DA) have been plotted and evaluated according to their distance from the façade; the following graph (Figure 6-10: DA trend moving from the façade shows the trend of DA moving away from the window in the two software, where it is possible to see that the higher is the distance from the façade, the higher is the difference between the results of the two software; it can be seen also that the values start to have considerable distances after the first half of the room.

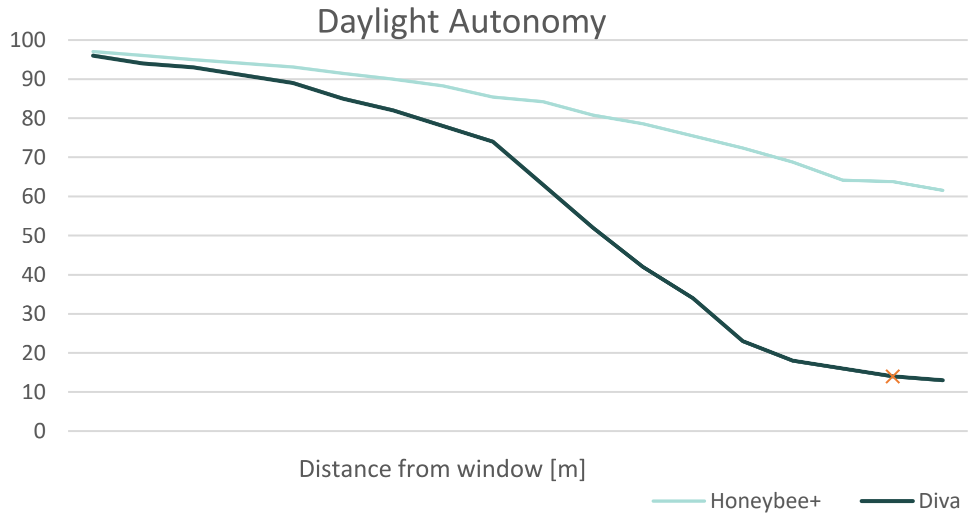


Figure 6-10: DA trend moving from the façade

6.3 RADIATION ANALYSIS

As seen in the previous paragraph, the very first group of simulations have been done on a default geometry, belonging to R1.b family to enrich and validate the sensitive analysis treated in Chapter 3.4; then the subsequent step was to run many simulations (around 200) on the room, trying to find the configurations which can optimize ASE and sDA. The room analysed was composed by two panels and the results have been obtained both considering a context and for the building alone. The first issue that catch the eye was the time needed to perform the simulation for a room, testing a high number of geometries; it was clear that a similar process for a façade composed by many rooms would turn out to be really time consuming and difficult to manage.

Starting from the definitions of the daylight parameters according to the LEED prescriptions, it was clear that the value that could affect the most the results would be the solar radiation, which as a consequence is the first one that has been analysed.

In order to simplify and make the simulations faster, the subsequent step was to study an entire façade, divided in as many panels according to the dimension of a standard panel and study the incident solar radiation on each panel, considering also the effect of the context.

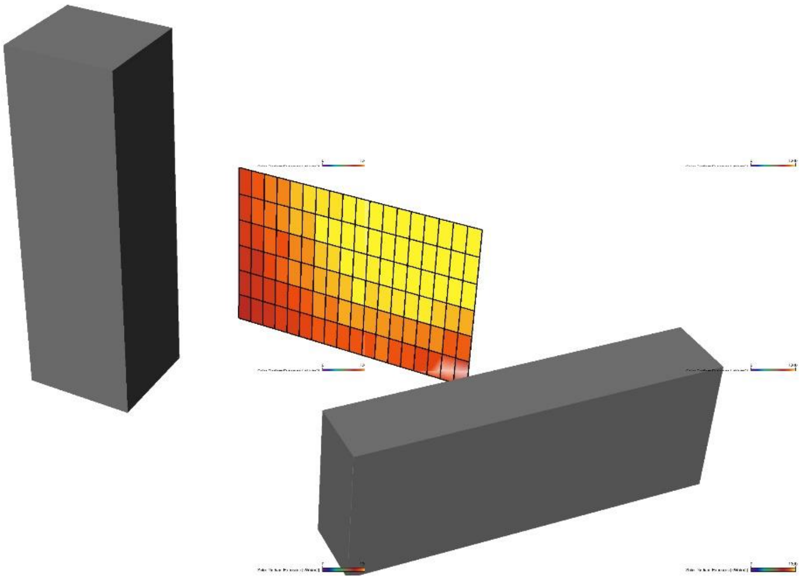


Figura 1_Incident radiation on the façade, related to the context

As it can be seen from the picture, this method allows to define in a reliable way the effect of the context on the façade along the entire year. Once the radiation has been calculated, how is it possible to design a proper geometry for each panel?

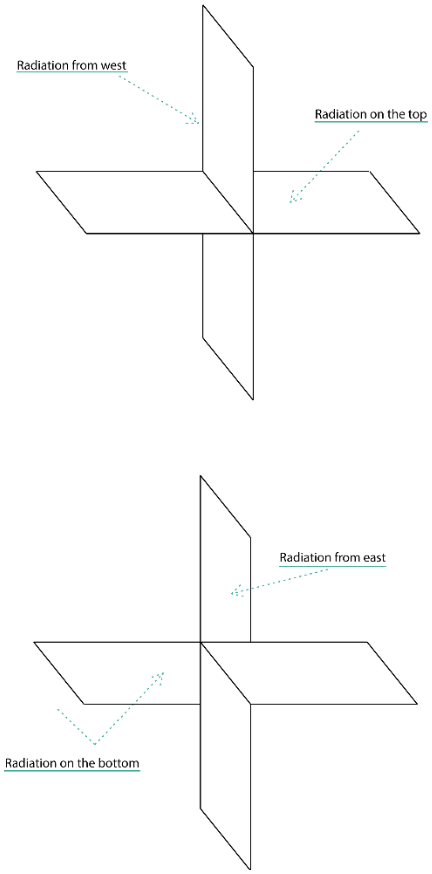


Figure 6-11: Scheme of the incident radiation on the faces of the cube

The solution proposed was to simplify each panel with a “cube” placed in the centre and for each face of the cube, the incident radiation has been calculated. This simplification entails a reduction in the time needed for the simulation and will give an approximation of the radiation coming from the different directions. Then, the energy on the different faces will be proportional to the ones reaching the top, bottom, right and left panels; the final value will be proportional to the radiation since the faces will be tilted and it will be affected by the angle of inclination.

In this way, there is no correlation with a geometry which can guarantee the achievement of good values for ASE and sDA, so at this step it has been decided to study two rooms of the façade: the one with the lowest incident radiation and the one with the highest radiation. The optimization of geometries have been defined using DIVA and a solver, using the equation shown in paragraph 6.1.3; the solver generates geometries which are tested with DIVA, until it does not reach for a certain number of attempts (the number can be set by the user) an improvement of the results (the limit in these simulations has been set equal to 100: if for 100 times the software does not get better values, it will stop the process). Once the optimization (in terms of ASE and sDA) has been done for the two rooms and an acceptable configuration has been found, all the others can be obtained with a remap of the results. This is due to the fact that the solar radiation smoothly changes along the façade and each change is related to a portion of area of the cube; a change in the geometry to satisfy the daylight requirements is correlated to a change in radiation, so the interpolation of these data may allow a reliable configuration of the façade, which obviously needs to be tested, to see if some rooms present some local issues.

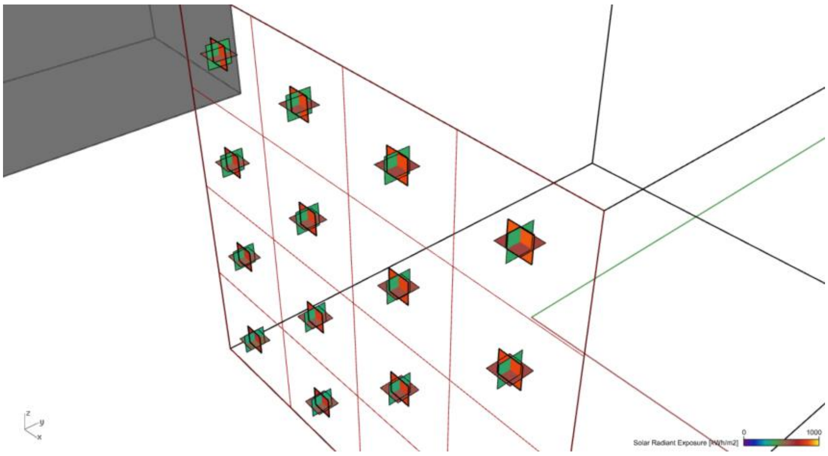


Figure 6-12: Solar radiation on each panel of the façade

The values obtained were used to remap and control the values of the sliders related to the parameters of the panel: extrusion, height and width. The width was related to the radiation incident on the two lateral sides of the cube, the extrusion to the top side and the height to the parallel side. As it can be seen, the result is that the shape of the panels and their dimensions varies along the façade, coherently with the context.

The interesting aspect of this solution is that this was an attempt to see it was possible to evaluate the geometry only for an optimized configuration for some specific rooms with particular values of incident radiation (highest, intermediate, lowest) and start from them to obtain all the other geometries.

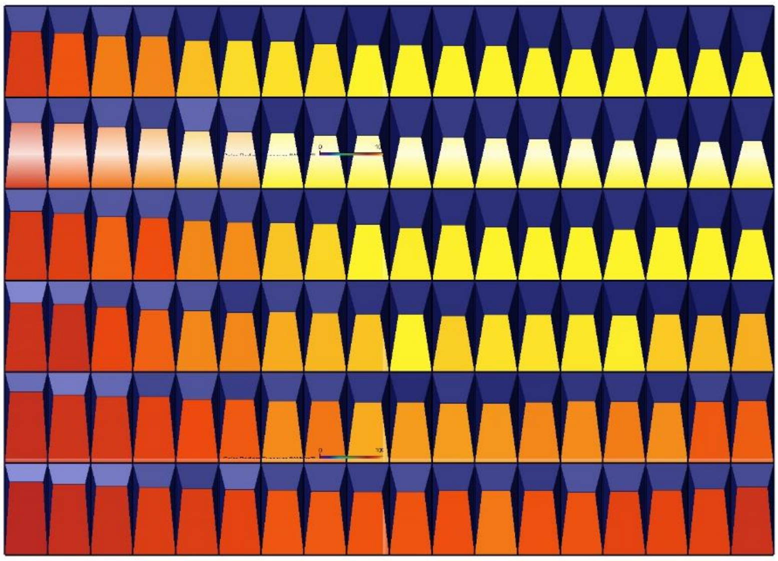


Figure 6-13: Correlation of final geometry with the incident solar radiation

Since the sun path depends on the latitude, we tried three different latitudes in order to see how the remapped ranges influenced the shape of the façade. We can see that the trend is similar along the façade; on the other hand, the dimensions of the panel change according to the latitude, due to the different height of the sun.

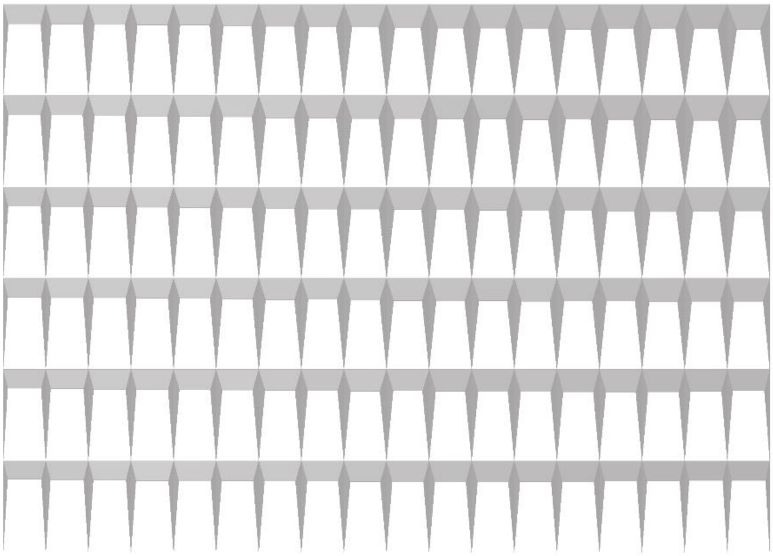


Figure 6-14: Results of the preliminary analysis for Alaska

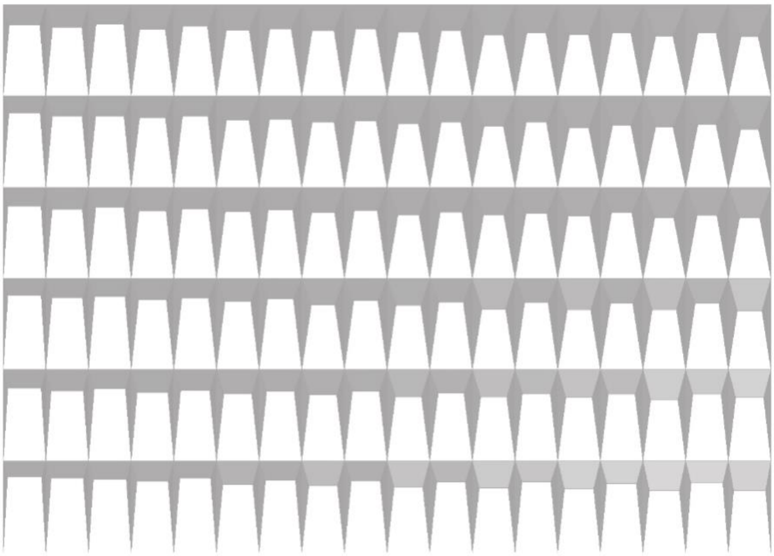


Figure 6-15 : Results of the preliminary analysis for Boston

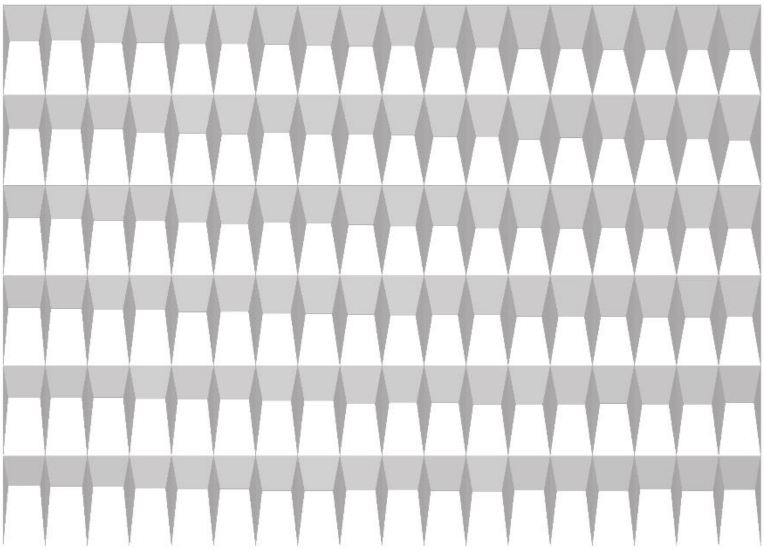


Figure 6-16 : Results of the preliminary analysis for Miami

This preliminary analysis was helpful since some aspects that have been underlined from the results, will be the starting point for further analysis process. Starting from the cons, the final façade is not obtained with a study for each room, but each value has been remapped considering few rooms and their relationship with the context. With this kind of simulation, it is not possible to be sure that all the configurations will be acceptable even if they are generated from acceptable configurations, so they will be tested for further verifications: this leads to a massive reduction of the time needed compared to the time needed to perform the research of the best geometry with the use of solvers. The heritage that has been left from this approach is that the results shown that the expected correlation between the geometrical values and the solar radiation is verified; moreover, the strategy used for the remapping process has been used in the option B of the final optimization process (see par. 8.4.2.2).

6.4 LATITUDE BASED ANALYSIS

After the study of the output of the previous analyses, it was clear that the solar radiation cannot be used as the only parameter to be considered for the purpose, because it is too affected by the context and it is not so easy to use it to make predictions. As it can be seen in Figure 6-14, Figure 6-15 and Figure 6-16 the results of the façades analysed with the same context are different; this means that the variations in the façades are due to the sun path and the height of the sun in the different locations. The position and orientation of the building influence the results, since related to that there is a change of the altitude and azimuth angles.

If this assumption is correct, the results and the output for façades in cities placed at different latitudes should be proportional to the change in latitude from one to the other. As a consequence, the main idea that drives this group of analysis is to carry out analysis on different cities at different latitudes in order to create a database for the simulations.

To simplify the process, the globe has been divided in five macro areas according to the latitude, in order to define the behaviour of the families related to the height of the sun.

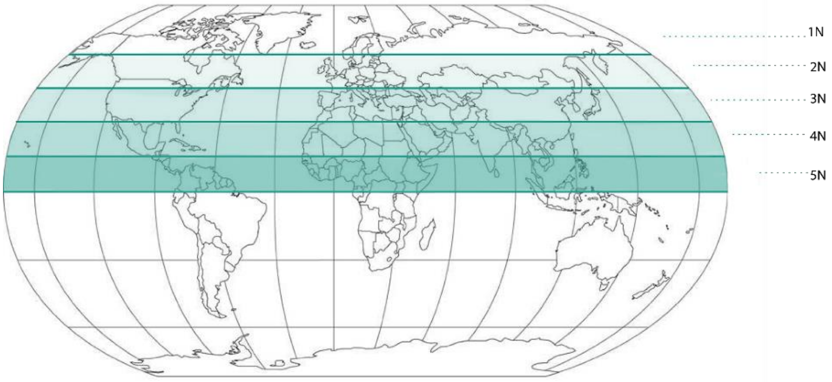


Figure 6-17: Macro areas subdivision of northern hemisphere

In each area has been chosen a city where the room has been placed in.

6.4.1 Database creation

The cities chosen are located at different latitudes with a difference in latitude approximately equal from one to the other. The cities chosen are Singapore, Bangalore, Miami, Milan and Stockholm. In order to make a rich database, the simulations for each city have been run for the façade exposed towards south, east and west and the simulation run both in DIVA and Honeybee+ to compare the results and define where the differences could lay between one and the other. This step is added to the one descripted in Ch. 3, in order to enrich the sensitive analysis.

6.4.1.1 Influence of orientation

As said previously, the orientation directly affects the incoming radiation and sunlight in the room. General assumptions may be done a prior according to the exposition of the façade considered, but they will be declined according to the latitude and height of the sun. Generally, the northern façade is the one receiving direct sunlight around the summer solstice therefore it may have a high percentage of the surface glazed. For this reason, analyses on this exposition have not been carried out. Façade towards east and west receives high amount of solar radiation, especially during summer, but with a shallow angle making it difficult to be shaded. Lastly, southern orientation receives the highest amount of solar radiation, with a steep solar angle.

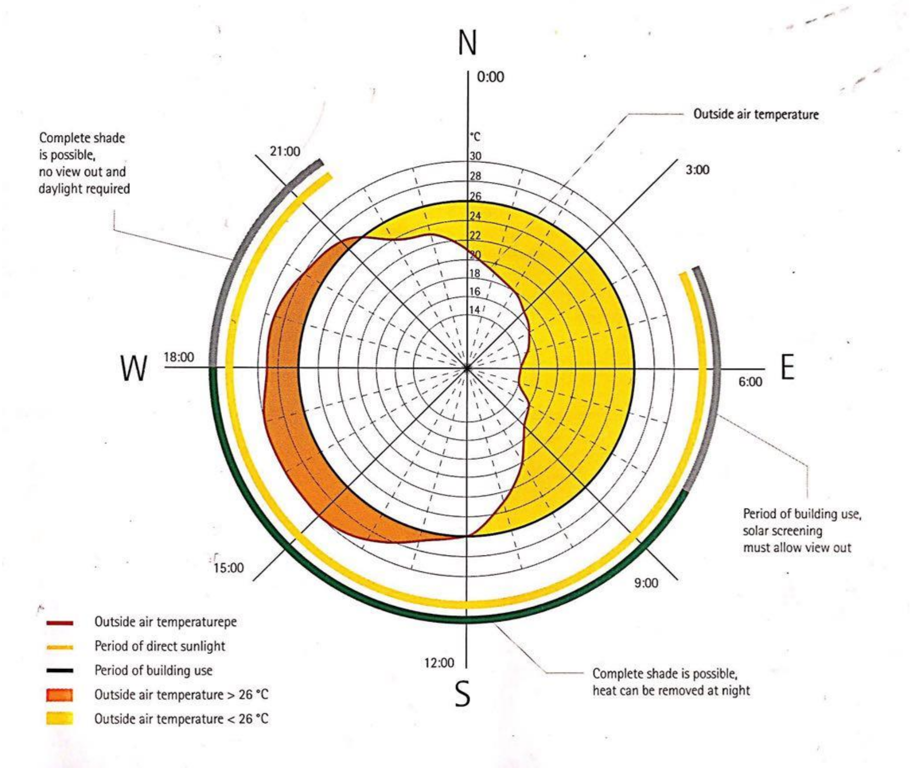
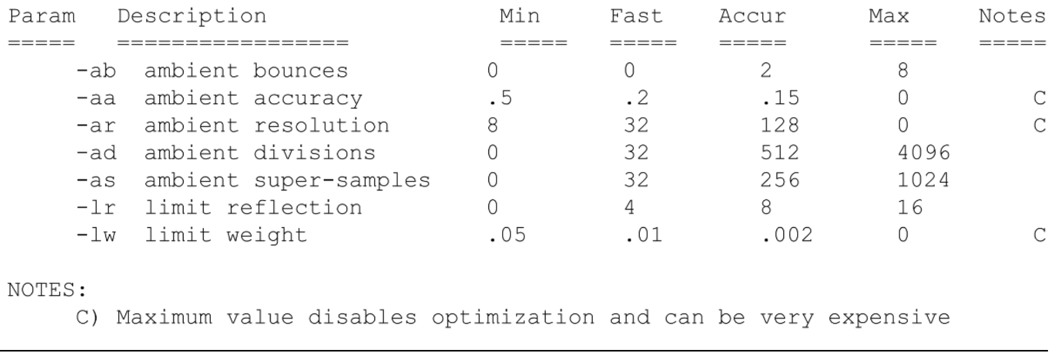


Figure 6-18: Effects of orientation of the façade

6.4.1.2 Simulation settings

The considerations made after the sensible analysis of the tools for the calculation on a base case of a shoe box, lead this process to be organized in different steps, each one characterized by an increasing level of detail. In terms of simulation, this has been translated in a different setting of the rad parameters; indeed, at the beginning the simulations have been run with the default options of DIVA and Honeybee, but results showed that there was not a quality of simulation of DIVA that could match to the one Honeybee. As a consequence, to compare the results, it was necessary to set the same -rad parameters to both of them. The rad parameters used are the same which have been set in Chapter 3.

As a reminder, they are reported below along with a brief scheme of their range, which can help also to understand the time needed to run the simulation.



```
Param   Description                Min     Fast    Accur     Max     Notes
=====   =================          =====   =====   =====     =====   =====
     -ab  ambient bounces        0         0         2         8
     -aa  ambient accuracy       .5        .2        .15       0         C
     -ar  ambient resolution     8         32        128       0         C
     -ad  ambient divisions      0         32        512       4096
     -as  ambient super-samples  0         32        256       1024
     -lr  limit reflection       0         4         8         16
     -lw  limit weight           .05       .01       .002      0         C

NOTES:
     C) Maximum value disables optimization and can be very expensive
```

Figure 6-19: Description of -rad parameters in DIVA

-ab	5	-dr	2
-aa	0.2	-ds	0.2
-ar	64	-lr	12
-ad	1024	-dj	0
-as	2048	-sj	1
-lw	0.004	-st	0.75

Figure 6-20: Used -rad parameters

The literature and the experience obtained from the simulations performed at the first approach to this topic showed that the two values considered are differently affected by the quality of the simulation, due mainly to their nature. ASE represents somehow the glare inside a room: it will be mainly affected by the direct solar radiation. sDA on the other hand represent the illuminance inside the space considered, so it will be a function of the direct and diffuse solar illuminance and it will depend also on the number of bounces considered.

To streamline the process, it has been decided to use a solver and run firstly the simulations in lowest quality to find all the configurations allowing to obtain a value of ASE between 0% and 10%, since this value is not affected by the quality. The lowest quality allows to save time, since each simulation takes around 20 seconds and the possible configurations for each family are 7200, considering the all the combinations of the sliders.

As a matter of fact, the variables could change between the following ranges:

	Range
Height	From 1 to 5*
Extrusion	From to 1 to 10*
Width	From 2 to 9*
Material right panel	Glass low transparency, glass high transparency, opaque
Material left panel	Glass low transparency, glass high transparency, opaque
Material bottom panel	Glass low transparency, glass high transparency

*values from 1 to 10 represent a percentage of the total, e.g. 1=10% and 10=100%

Table 14: Variables ranges

The output of this group of simulations is the collection of configurations which guarantee an ASE value acceptable. Inside this space, only the configurations with a sDA at least equal to 30% have been considered in the next step. This choice, as it can be seen in the following chart, is done considering that the value of the sDA increases passing from one quality to the other; configurations with 30% of sDA in low quality can reach an acceptable value in higher quality, (such as the one defined by the -rad parameters used) or at least getting closer to an acceptable value.

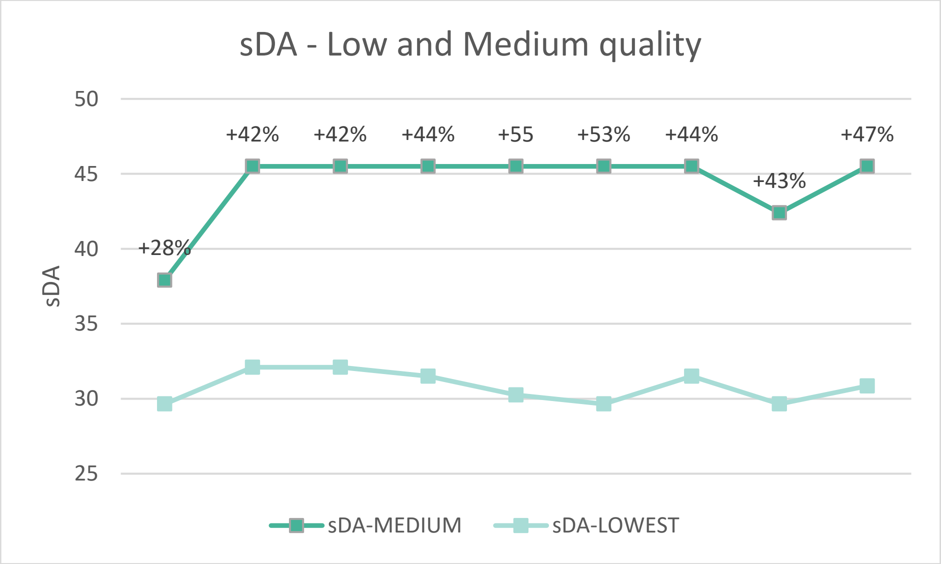


Figure 6-21: sDA comparison between low and medium quality

The results obtained from the previous two steps for all the expositions and all the climates considered, have been evaluated in function of the income of direct and total radiation, in order to make assumptions on the behaviour of the system and to restrict the domain of the variables. As not expected, the results pointed out that the values were only slightly affected by the total and direct radiation; this led to further researches to find a relationship between the results obtained for ASE and sDA and some geometrical functions. As said, the first correlation tried was between the radiation (total, direct, diffuse) on the transparent part and the daylight results:

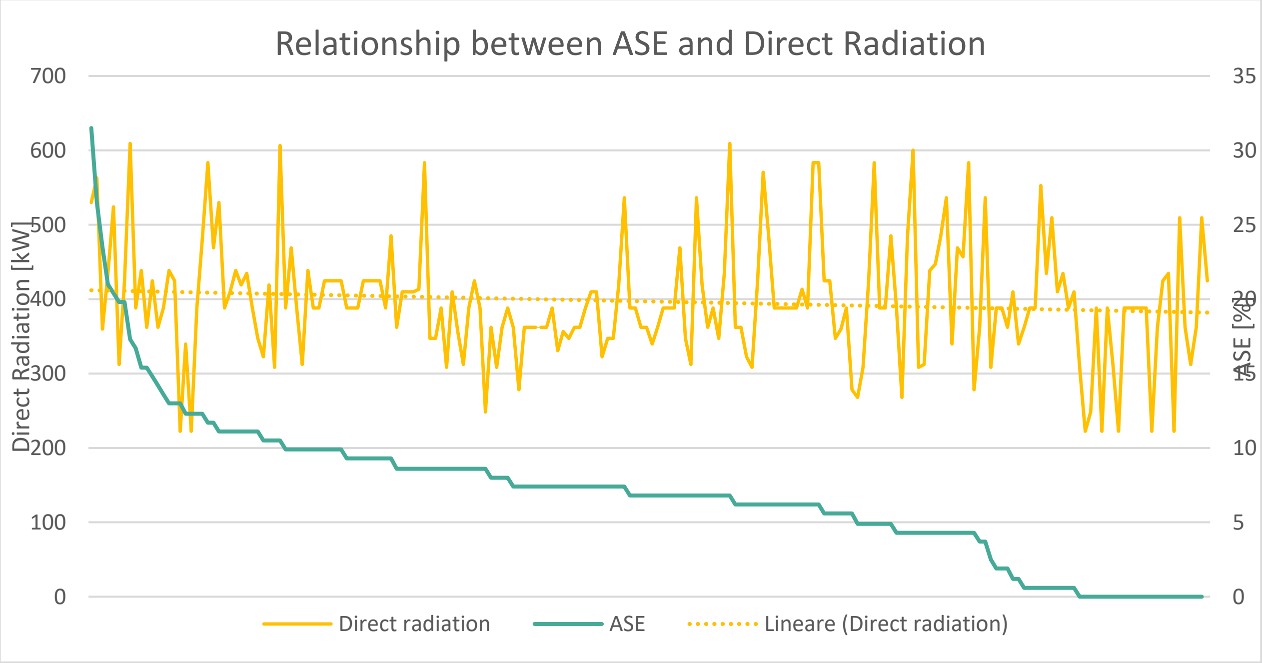


Figure 6-22: Relationship between ASE and Direct Radiation

As it can be seen from the previous graph, the relationship between the value of ASE is not as accurate as expected; the ASE is decreasingly ordered but the peaks of the direct radiation do not allow to establish a common trend between the two values considered.

Subsequently, the attempt was to find a relationship between the glazed areas and the ASE, but not even this evaluation was realistic of a trend:

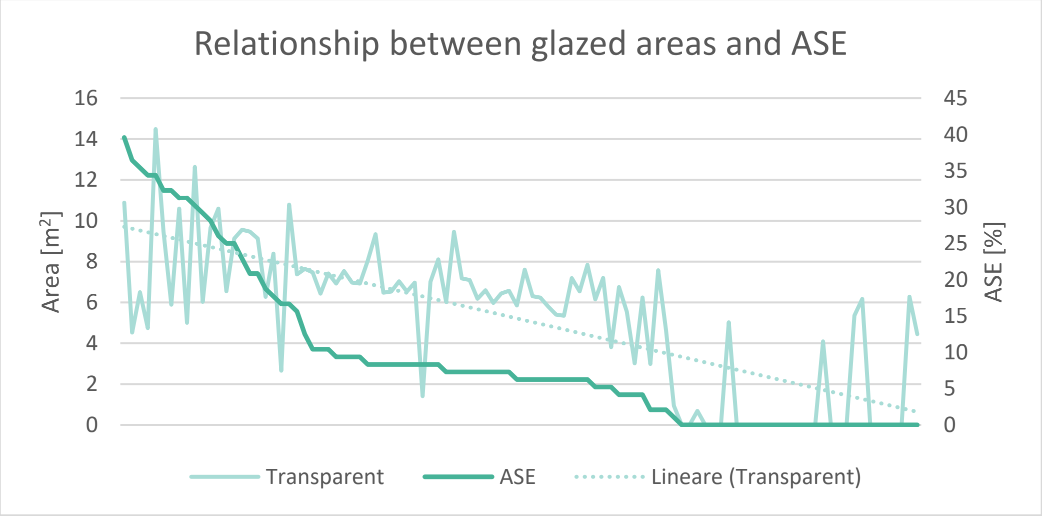


Figure 6-23: Relationship between glazed areas and ASE

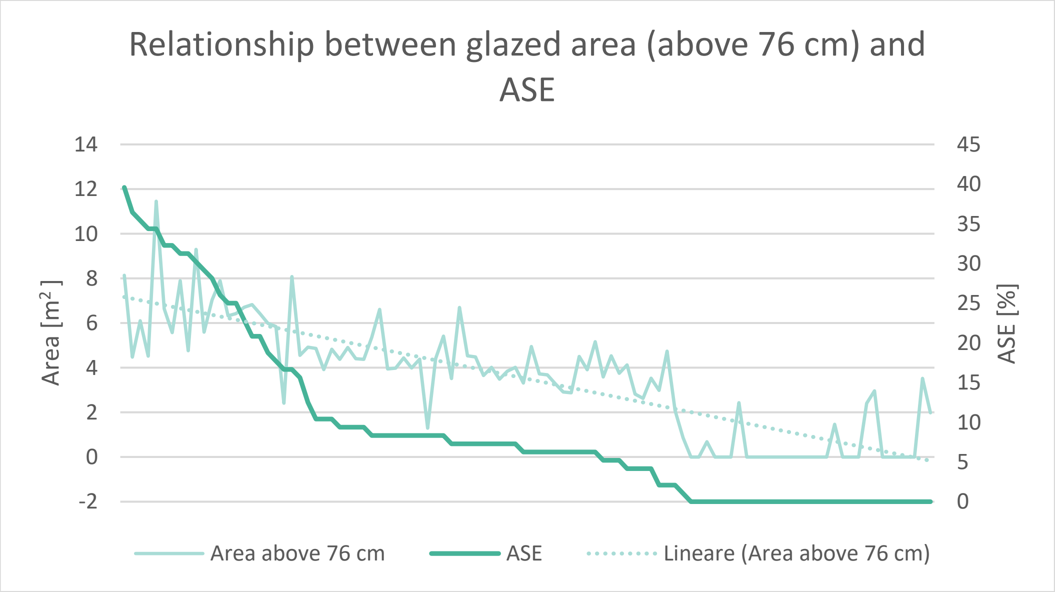


Figure 6-24: Relationship between glazed area (above 76 cm) and ASE

The areas considered in the two previous graphs are both the sum of glazed ones projected along the direction of the sun vectors; in graph Figure 6-23 the area is the entire glazed one and in graph Figure 6-24 the area considered is only the one above the grid. The linear interpolation of the values of the glazed areas is following the trend of the ASE, but the peaks that are visible imply that the correlation cannot be established only considering the sum of projected areas, showing that the ASE is not dependent by the quantity of the direct radiation but on how this radiation is distributed. In fact the projection of the area along the direction of the sun in the morning can lead to a really big projected area, since the sun height is low at the horizon, but most of the part of the room covered by this area is hit by the sun only during the morning, so it will not affect considerably the value of ASE; it can be imagined that the critical area of the room is the one in proximity of the window, since it is the one that is always reached by the solar radiation.

For this reason, the following step is to weight the projected area by the distance from the façade: this calculation is done to enhance the points under the window and less consider the points far from the façade.

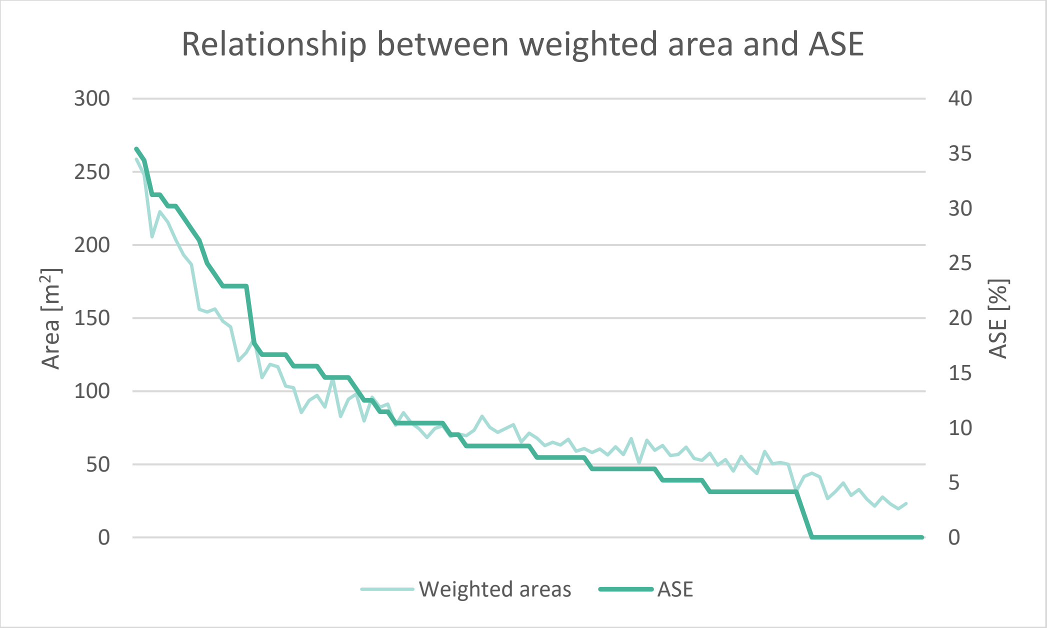


Figure 6-25: Relationship between weighted area and ASE

As it can be seen in Figure 6-25, the weighted area allows to approximate well the ASE values, even for configurations obtaining higher values, which means that are highly daylit.

These assumptions on the approximation of Annual Sunlight Exposure allow to develop a complete calculation method, as explained in the next chapter.

7. CALCULATION METHODS

In the previous chapter the reader has been introduced to some of the simulations performed at the beginning, as a first approach to the world of daylight. All the solutions explained allowed to get a better knowledge of the parameters considered and to make assumptions on the relationship between different parameters and the final results, which slightly got more closer to the effective ones. Moreover, as seen at the beginning of Chapter 6, the results on the geometry analysed for this project, show slight differences using different tools, confirming what has been explained in the sensitive analysis (Chapter 3).

Pairing this aspect with the long time needed for the analysis using existing software for the calculation, it appeared clear as a subsequent step of this work the definition of a proprietary method of calculation. In order to be effective this method should have some properties:

- Reliability on the goodness of results;
- Suitable for different geometries;
- Being CBDM;
- Faster than the competitors.

This chapter describes the methods of calculations which have been developed in the different field considered: daylight calculations (both for ASE and sDA) and energy calculation, addressing the reliability of the results comparing them with other tools and with the reduction of the time needed for each simulation.

7.1 DAYLIGHT ANALYSIS

The first calculation method described is the one used for the daylight analysis. It was clear from the beginning that the most used software in the daylight field can be used by the user for many different purposes; this will lead to really complex analyses, which are time consuming too. The reasons for the long time needed for the simulation can be explained in different ways: first of all, most of the plug ins are not performing a calculation for each component, but they tend to group more than one simulation in one component (e.g. Honeybee has only one component which performs UDI, DA, DF calculations). As a consequence, if the user needs a result for the ASE probably he is not able to obtain only that value, reducing the simulation only to the calculation of the ASE, but he will have a longer simulation which will calculate also other daylight parameters.

Another issue which lengthen the simulation time is related to the assumptions explained in Chapter 3.4, which is the discretization that the software does for the sky; the higher is the resolution, the higher will be the number of patches considered and as a consequence, the time needed for the simulation increases.

Since it was also clear that the main parameters that would be used as discriminants would be mainly ASE and sDA, all the other possible outputs coming from the calculation of other software would lead to a useless waste of time. As a consequence, it comes the decision of calculating these values directly in Grasshopper, without the use of other tools.

This decision has two main pros: beside the reduction of time needed for the simulation, there is the design of a flow completely developed by us; as a matter of fact, every time a flow in Grasshopper is realized with components of different tools, it cannot be used until the user downloads and install them: this is time consuming and makes more difficult the user experience. The tool that has been developed does not use any other component, but analyses autonomously the sky and its vectors and delivers in shorter time the results of ASE and sDA.

7.1.1 ASE

The ASE value represents the percentage of floor which has, for more than 255 hours, 1000 lux. This definition combined with the outputs of the preliminary analyses (see par. 6.4), has been used to develop the calculation. In fact, as the reader can remember, the aim of the preliminary analyses has been the research and the determination of the connection between the ASE with a geometrical value, considering also other aspects like for example the position of the sun, its height and the context.

The definition of the model followed the steps done for whichever other daylight tool: the room has been designed setting a grid of sensors at 76 cm of height from the floor with a certain spacing: the smallest are the cells, the higher will be the accuracy of the calculation since the result is a percentage of the floor and the evaluation will be done considering if the center point of the cell is hit or not. As it can be seen in Figure 7-1, even if the grid on the left-hand side has its fifth row partially covered, it will not be calculated, since the shades will not reach the midpoint. On the right-hand side, the spacing is smaller and the accuracy will be higher; the results of the two examples show a percentage of floor covered respectively of 66% and 45%. The difference is not slight and as for this extreme example, the grid must be chosen also considering the accuracy needed for the project.

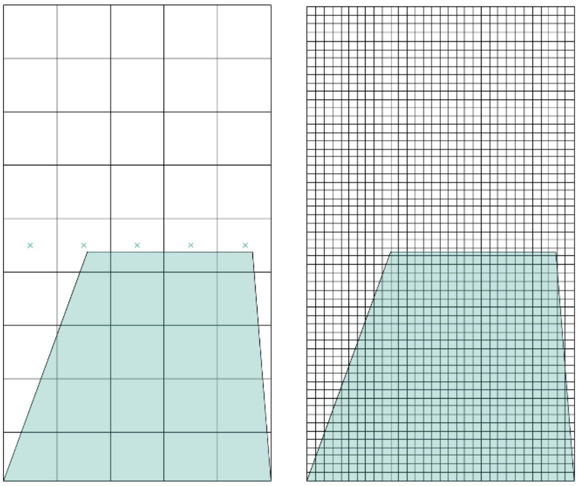


Figure 7-1: Difference of accuracy according to the size of the grid

Nevertheless, the spacing of the cell is defined by the standards, which usually give a minimum value; the one chosen for this work is 55 cm, respecting the requirements of the LEED. Through a study on the ASE, which has been done considering its definition and the results of the comparison of the available software, it is clear that it is dependent from the direct illuminance, while the diffuse one does not affect considerably the results. As a matter of fact, ASE is a different way to express the glare inside a room, so it should be more affected by the direct radiation than by the diffuse one; glare is usually expressed using the DGP (see par. 2.2.1.4), but in a work formulated as this thesis project, the evaluation of this parameter cannot be considered useful, since its calculation depends on different parameters that cannot be considered general and used as discriminants in an early stage design process. In fact, DGP is affected by the point considered, its closeness to the window, the position of the user, the direction the user is looking towards, etc..

In the most of the daylight calculation software, ASE is never computed alone, but it is always paired with the calculation of other parameters, which involve a different consideration of the illuminance and sometimes require longer time. The other values which are calculated take into account also the reflected light and the diffuse component, which are useful if the purpose of the analysis is to get accurate hourly values of the illuminance in each point of the test grid, but for the ASE this part of the calculation it is not necessary. Besides, the duration of this last type of analysis is affected also by the number of bounces, of reflections of the light and the other rad parameters considered by the software increasing considerably the time for a simulation, which could be really shortened. Another parameter that affects the value of the ASE is the direction of the sun rays, which can be derived from the position of the sun: it can be seen that it does not change significantly on a daily base, but it is a slow change where the visible differences can be seen on a monthly base; to reduce the time an average calculation can be assumed.

Starting from these assumptions, the aim is to develop a tool which can calculate the desired value, only considering the parameters and the calculation which are strictly related to the result that has to be obtained, avoiding the calculation of extra criteria which will lengthen the time needed for the simulation.

7.1.1.1 ASE Calculation method

The calculation of the ASE starts from the analysis of the .epw file, which contains all the available climate values for a location. Firstly, from the weather file it is possible to create the path of the sun on a yearly base for the chosen location and obtain the hourly values of the direct radiation for all the hours of the year of a reference year. Considering these data, it is possible to define the exact position of the sun along the year, which will be used in reference to the position of the room considered. Moreover, the hourly yearly values of the intensity of illuminance are reported in the weather data file taking into consideration also the weather conditions. For example, if the weather is cloudy, there will be a reduction of the direct illuminance, while the diffuse radiation will not be affected by the climate conditions.

7.1.1.2 Calculation of the sun position

The first step is the analysis of the position of the sun, which allows to calculate the direction of the sunrays. They are obtained considering the vector joining the point of the position of the sun with a point of the room considered; since the change in the position in during the day is slight it is reasonable to use instead of the hourly value of the direction of the sun an average value, obtaining a reduction of the time needed for the calculation.

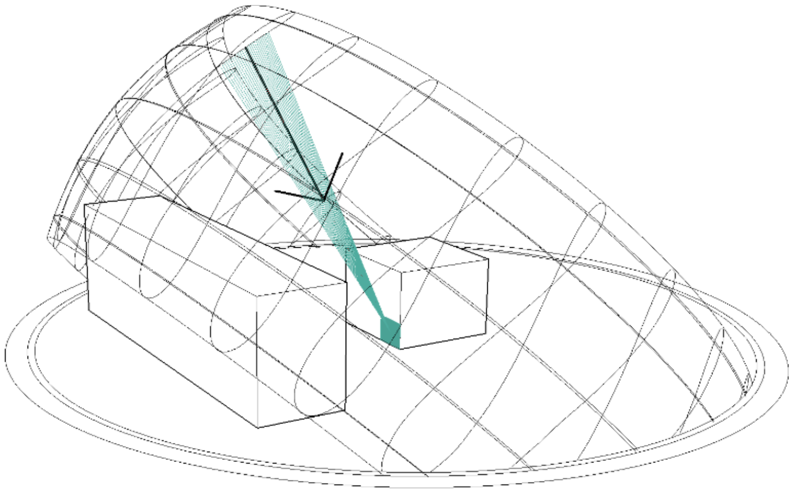


Figure 7-2: Sun direction of August at 12:00 am Milan

As it is possible to see from the Figure 7-2, the position of the sun at 12:00 a.m. during August, which is one with the biggest changes of position during the month, has not big variations and an average of these vectors is a good representation of them. The calculation of the average is the first step which goes towards a reduction of the time for a simulation; the approximation of the direction is reliable and the time saved for the calculation of the position is conspicuous.

7.1.1.3 Evaluation of the context

The subsequent step is to take into account the context in the solar vector definition process; each vector defining the position of the sun creates a line ending in the center of the considered panel.

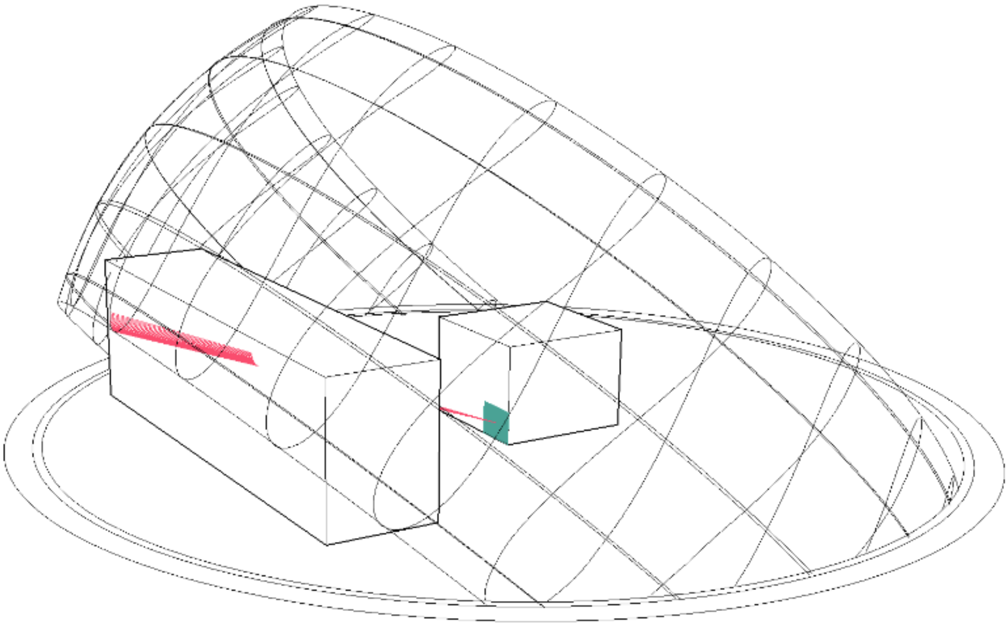


Figure 7-3: Sun direction of December at 12:00 am Milan

Each line is tested with the surrounding context to see if it is possible that the sun rays “meet” an object of the context and as a consequence, they are shielded by the context, as the reader can see in Figure 7-3. According to the month considered, the same context acts in a different way, since the sun path is different; in the case considered, during the month of December at 12:00 a.m. there will not be direct sunlight and there will not be an average vector.

Another possibility that can occur is when during the same month there are some days in which the sun vectors collide with the context and some days not; in this situation the average vector will be made taking into account only the vectors that do not collide with the context (Figure 7-4).

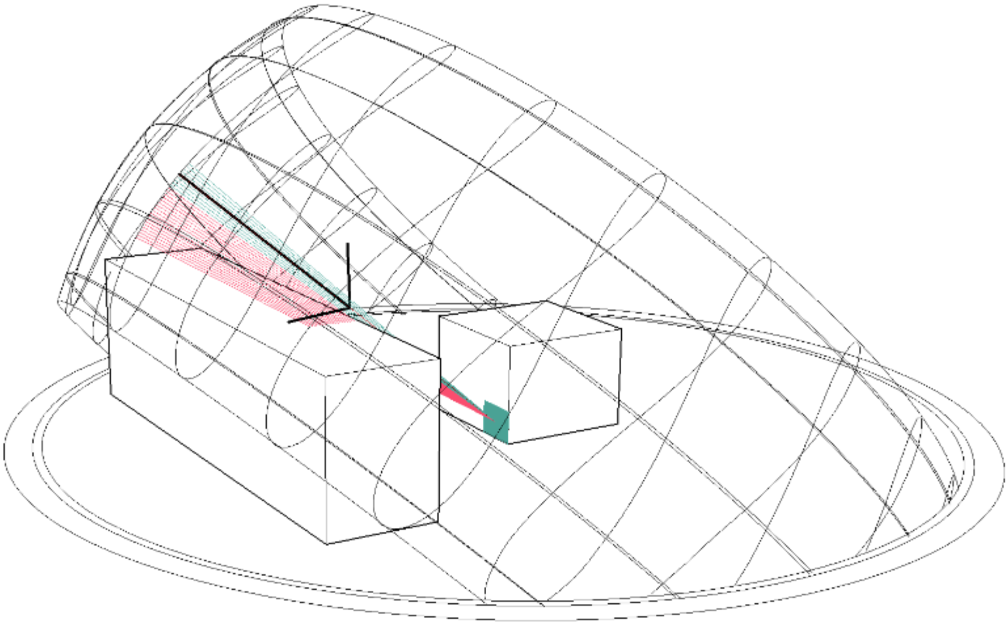


Figure 7-4: Sun direction of October at 12:00 am Milan

7.1.1.4 Evaluation of the schedule

Before the calculation of the average vector, the occupancy schedule is considered and used to cull the days when the building is not occupied. For example, a typical office schedule has occupancy equal to 0 during the weekends, so the vector that represent these days will not be calculated in the average (Figure 7-5).

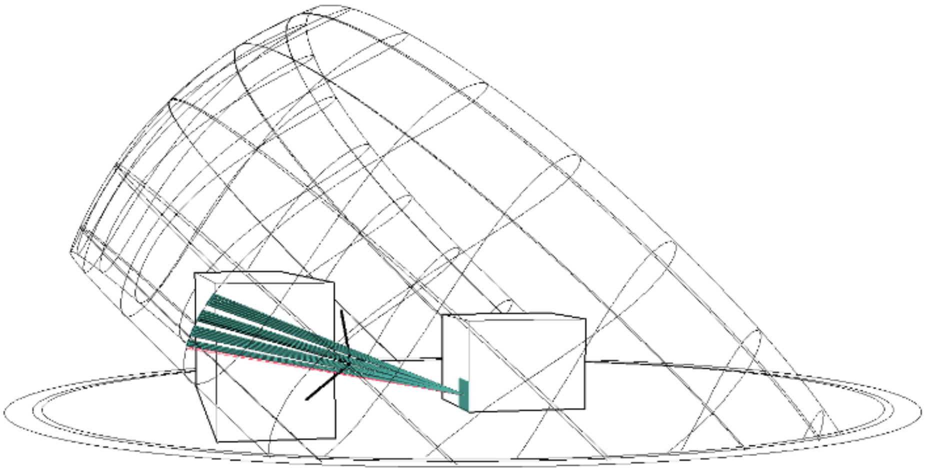


Figure 7-5: Sun direction of November at 9:00 am Milan working day

7.1.1.5 Evaluation of the direct illuminance

The last parameter that is considered is the climate condition and the illuminance; starting from the weather data it is possible to know the value of direct illuminance and consider only the days in which at that specific hour there is enough direct illuminance to have more than 1000 lux on the test point, (e.g. for a glass with VT = 0.7, they will be considered only the hours with direct illuminance equal or higher than $\frac{1000\ lux}{0.7} = 1428\ lux$.)

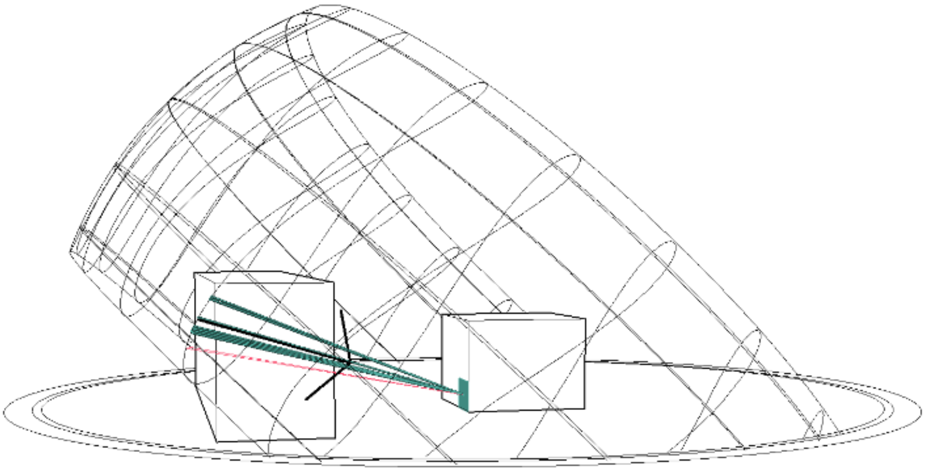


Figure 7-6: Sun direction of November at 9:00 am Milan

In Figure 7-6 it is shown the average vector of sun vectors for November at 9:00 in Milan taking into account of all the factors, while in Table 15 it is possible to see the details of the month considered.

	Day	***Direct illuminance (lux)***	***Context collision***	***Vectors for the average***
1	Monday	0	False	
2	Tuesday	7000	False	✓
3	Wednesday	31200	False	✓
4	Thursday	0	False	
5	Friday	0	False	
6	Saturday	29900	False	
7	Sunday	30100	False	
8	Monday	100	False	
9	Tuesday	0	False	
10	Wednesday	0	False	
11	Thursday	26800	False	✓
12	Friday	0	False	
13	Saturday	0	False	
14	Sunday	14200	False	
15	Monday	24550	False	✓
16	Tuesday	11600	False	✓
17	Wednesday	23400	False	✓
18	Thursday	23200	False	✓
19	Friday	0	False	
20	Saturday	4400	False	

21	Sunday	17300	False	
22	Monday	550	False	
23	Tuesday	0	False	
24	Wednesday	0	False	
25	Thursday	0	True	
26	Friday	0	True	
27	Saturday	14600	True	
28	Sunday	14700	True	

Table 15: Vectors for the average, November 9:00 am Milan

As it is possible to see from Table 15, during the month of November after the skimming process, there are only seven days in which the considered part of the façade is reached by a direct illuminance that can cause an internal illuminance higher than 1000 lux.

To each average vector is correlated the number of hours which are collected by that vector. Since the calculation of ASE is the amount of hours over 1000 lux, it is necessary to make an average of the direction of the sun in order to know how many hours each vector is representing; in the example of Table 15 the vector is the average of seven days along the four weeks.

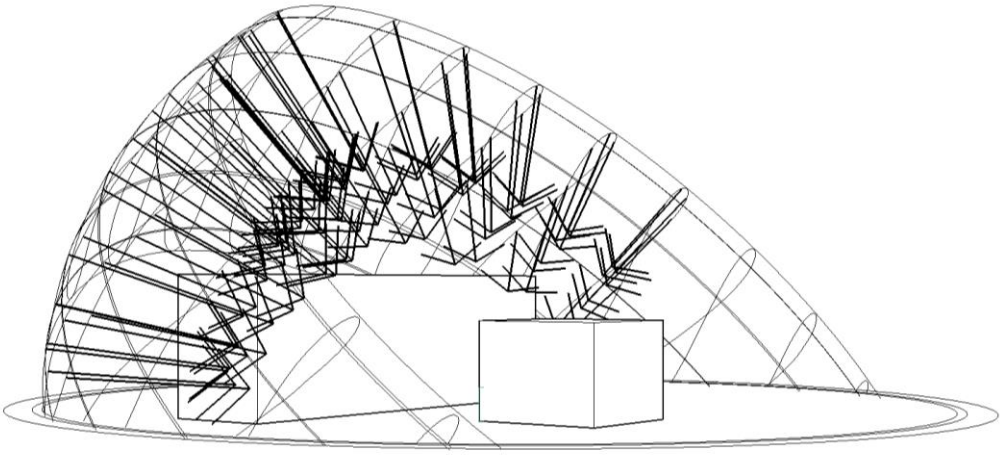


Figure 7-7: Average vectors

With this calculation, it is possible to pass from 2300 vectors of an office schedule (9-18 Mon-Fri) to 125 average vectors (Figure 7-7).

This procedure is useful because the calculated vector depends only on the location of the considered surface of the façade, but it is independent from its geometry in that point.

This type of simplification is as a good way to take into account of direct contribution of the sun since is an average made on the correct analemma of the selected location.

Comparing this type of method with the one used in DIVA and Honeybee (see Chapter 3.4), it appears clear that this kind of average on the vectors should be a better schematization for the direct part of the radiation, since both the software has 65 defined sun position for the direct part and instead of the real sun position is used the nearest of these standard points.

7.1.1.6 Projection of the façade

At this point, it is possible to project the transparent surfaces of the façade along the vectors on the test points. Starting from the portion of the façade selected, a test point grid is created behind the surface; the grid has an height equal to 0,76 m and a depth of 6 meters, in order to represent the dimensions of the floor of the reference room; the height of the grid is standard and it cannot be changed in the plug-in, while the depth of the room will be represented by the average depth of the room which is defined by the user before the preliminary analysis.

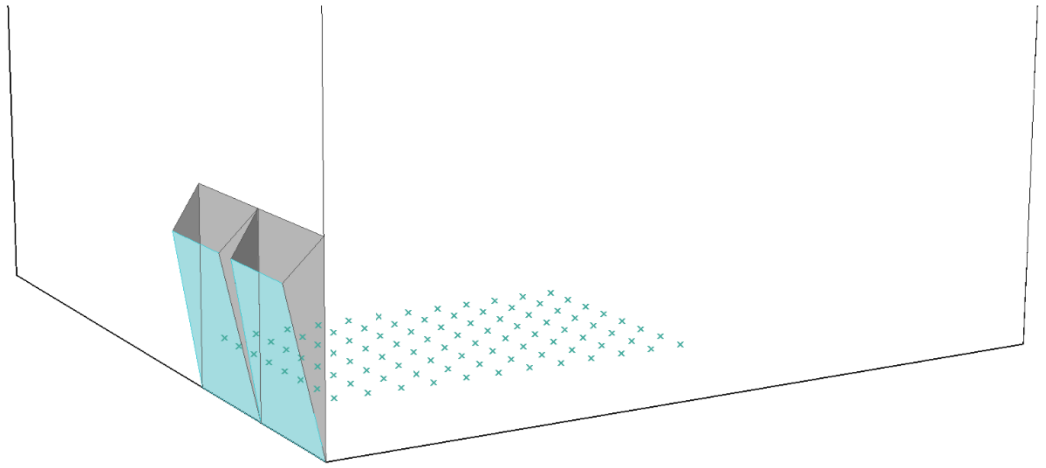


Figure 7-8: Test point grid for the selected part of the façade

The test point grid generated (Figure 7-8) has a spacing of 55 cm between each point. Then, the transparent part of the panel is projected along the average vector.

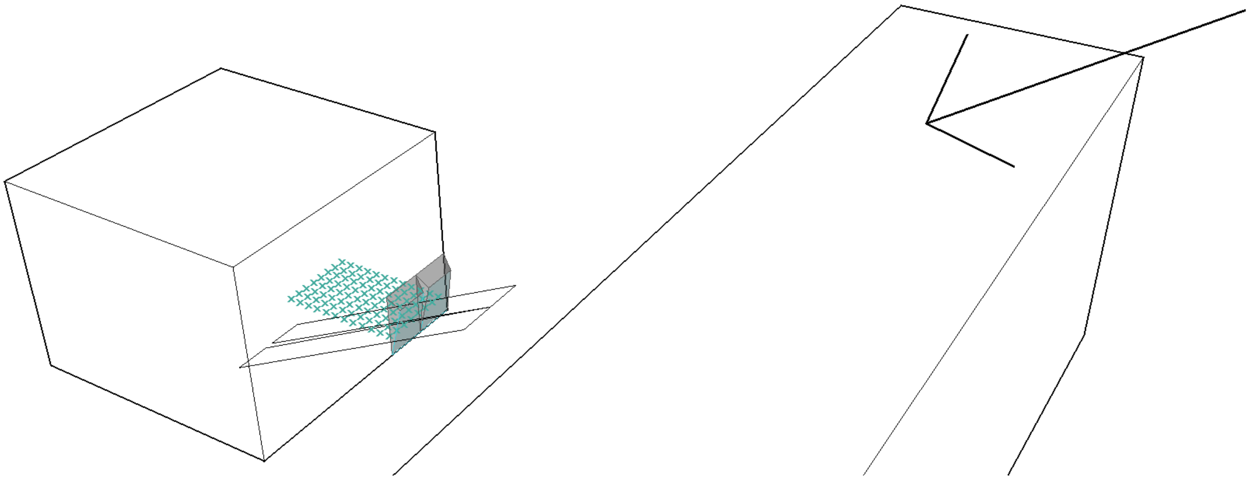


Figure 7-9: Projection of the transparent part, October 9:00 am Milan

In Figure 7-9 it is shown the projection along the vector previously calculated; once this step is done, it is possible to find how many points of the grid are covered from this projection, so this imply that they are hit by direct sun in the month of October at 9:00 am.

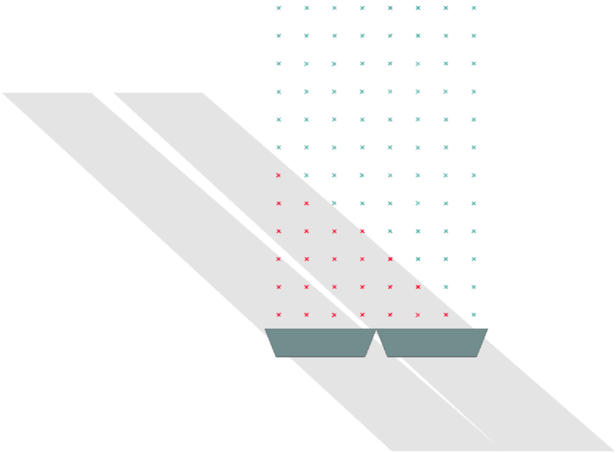


Figure 7-10: Grid point hit by direct sun

Knowing that the average vector of October, after the skimming, is the result of seven vectors, the points in Figure 7-10 in red for the month of October at 9:00 am have seven hours with more than 1000 lux.

At this point it is possible to repeat the calculation for all the average vectors and summing in each point the quantity of hours related to the vectors; in this way it is possible to know which are the points having more than 255 hours exceeding 1000 lux.

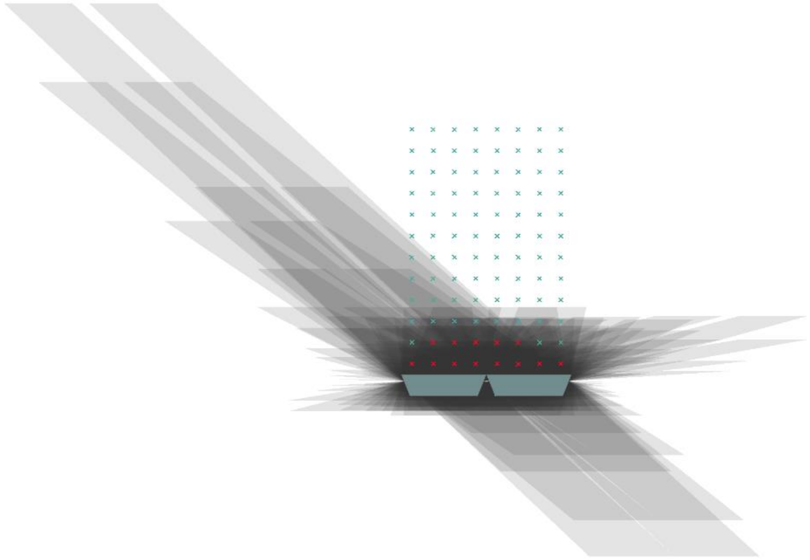


Figure 7-11: ASE points

In Figure 7-11 it is shown the result of the annual calculation and highlighted the number of points reached from the solar radiation for a number of hours higher than 255; the result of the ASE in this example is 13%, a bit out of the acceptable range.

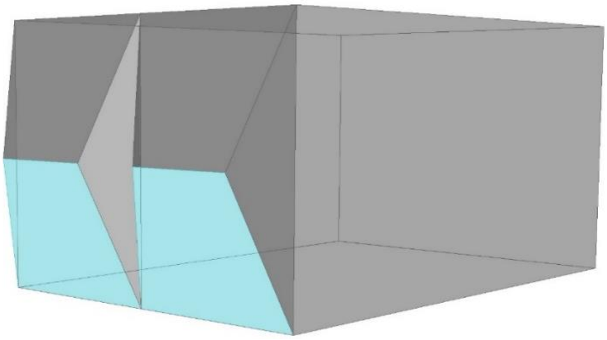
From this moment on, for convenience, this method will be called “Simplified method”.

7.1.1.7 Comparison between Simplified method and other tools

The configuration seen in par. 7.1.1.1 has been tested with other tools (DIVA and Honeybee+) in order to define if the Simplified Method has effectively a reduction in the time needed for the simulation. The analysis time of HoneyBee+ is 55 seconds, the one of Diva in the lowest quality is 10 seconds, with the Simplified method the result is given in 3 seconds, which is a reduction of time respectively of 94% and 70%.

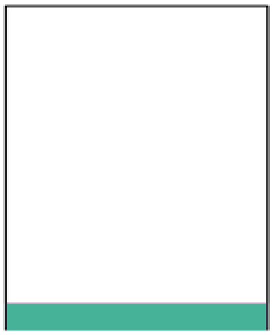
To compare the results not only in terms of time, but also in terms of figures obtained with the three different methods, different configurations in different climates have been analysed:

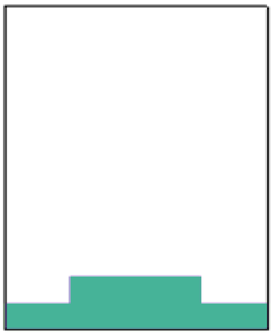
7.1.1.8 R 1.b Configuration, South Exposure

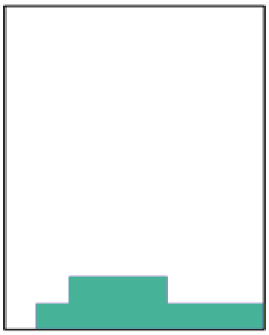


MILAN

Tool	Diva	Honeybee+	Simplified Method
ASE	8,3%	12,5%	10,4%
Time	10 sec	44 sec	3 sec

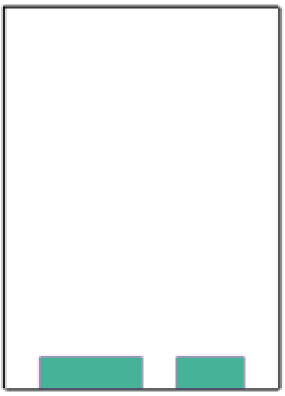


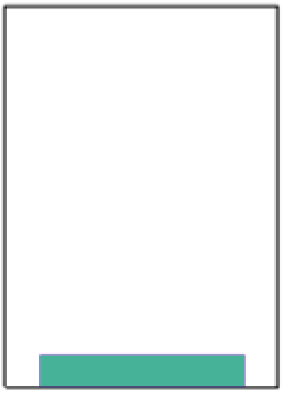


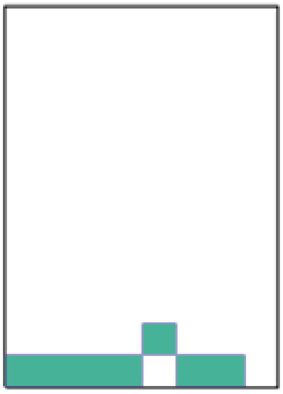


BERLIN

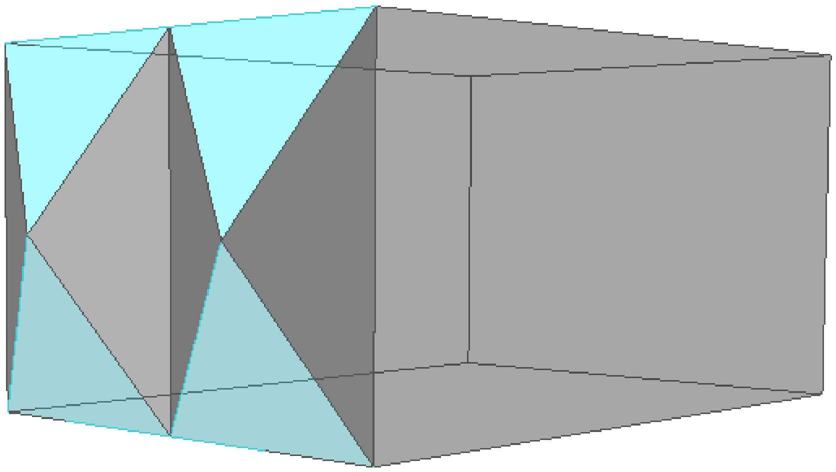
Tool	Diva	Honeybee+	Simplified Method
ASE	5,2%	6,25%	7,2%
Time	10 sec	43 sec	3 sec





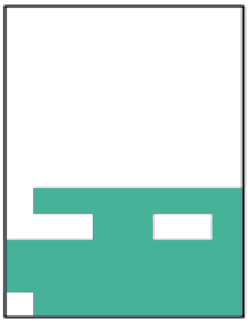


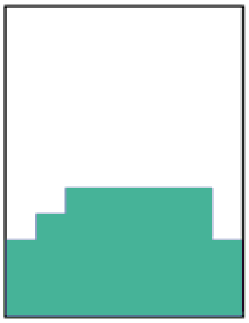
7.1.1.9 R 1.a Configuration, South Exposure

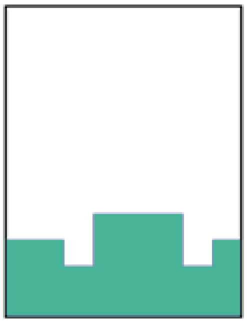


MILAN

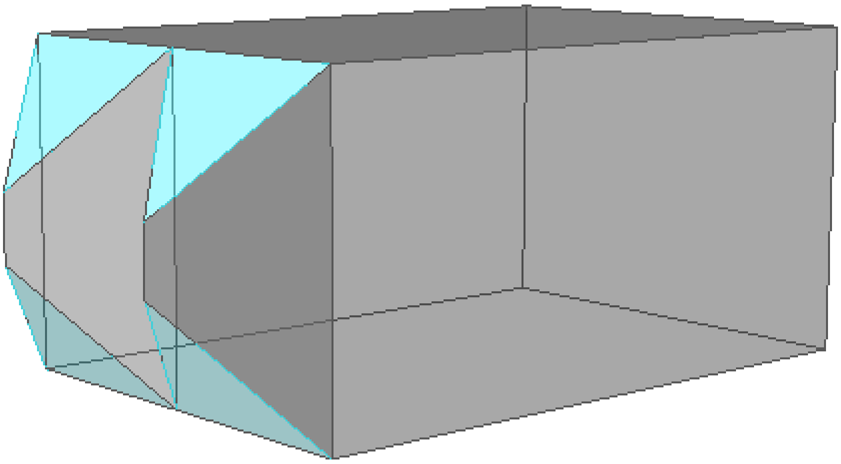
Tool	Diva	Honeybee+	Simplified Method
ASE	34%	36%	26%
Time	10 sec	43 sec	3 Sec





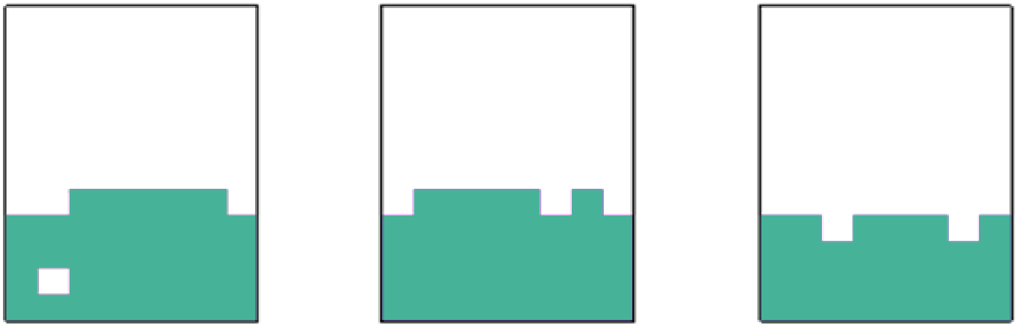


7.1.1.10 R 1.c Configuration, South Exposure



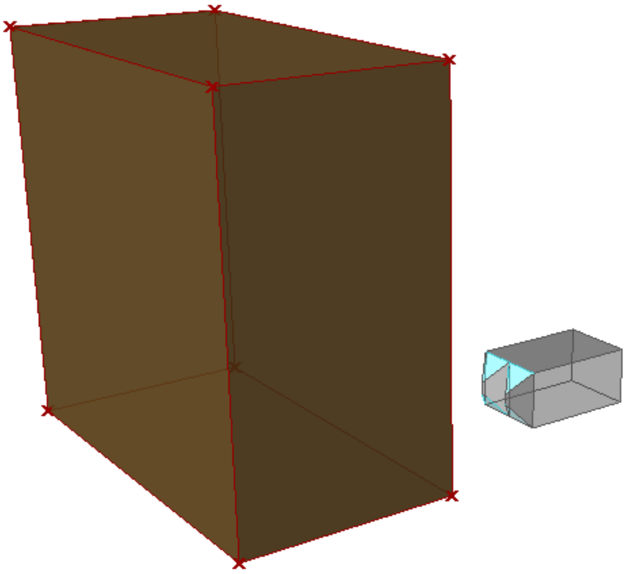
MIAMI

Tool	Diva	Honeybee+	Simplified Method
ASE	38%	38%	31%
Time	10 sec	43 sec	3 sec



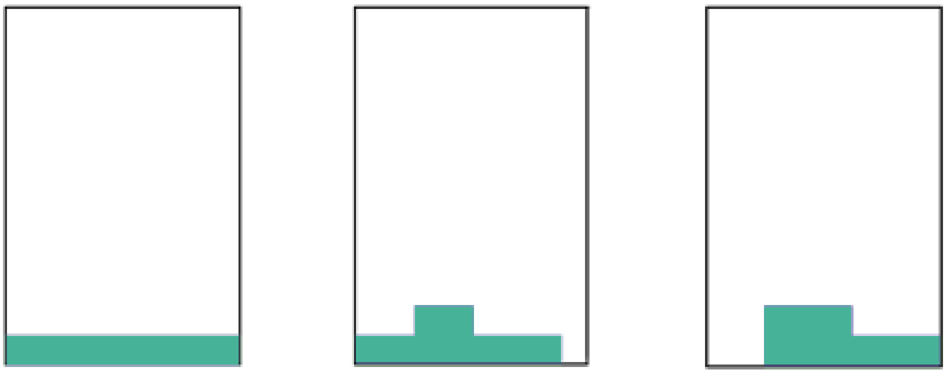
As said before, the simplified method can consider also the influence of the context on the results. This is evaluated since the sun path is analyzed considering the context as a blocking object: all the sun rays, intended as vectors joining the sun position and the center of the panel, that impact on the context before reaching the window, are culled from the vector list.

Here below, the comparison is done considering an "extreme context":



MIAMI

Tool	*Diva*	*Honeybee+*	*Simplified Method*
ASE	8.3%	9.3%	9.3%
Time	10 sec	43 sec	3 sec



To sum up, the Simplified Method can be considered as a fast and reliable tool to make the calculation of the ASE. This flow can try 20 configuration each minute, much more than the 10 considered in DIVA per minute and the ones with Honeybee+.

7.1.2 sDA

The calculation of the spatial Daylight Autonomy is more complex than the one of ASE, since the result of the analyses performed with other tools shown its dependence on the quality of the analysis, so it is difficult to design a method similar to the one for the calculation of ASE, which is only reduced to a geometrical calculation. In fact, an analysis carried out at higher quality gives better results of sDA, since the light is simulated with a more realistic behavior and the behave of the room is considered too. The goal is to develop a way to get a result of the Spatial Daylight Autonomy in a faster way compared to the other tools, since a single analysis with high quality can take up to 10 minutes.

As for the Annual Sunlight Exposure, the first step was to understand which could be the parameters that mainly affect the sDA results and if there were differences in results between the different software:

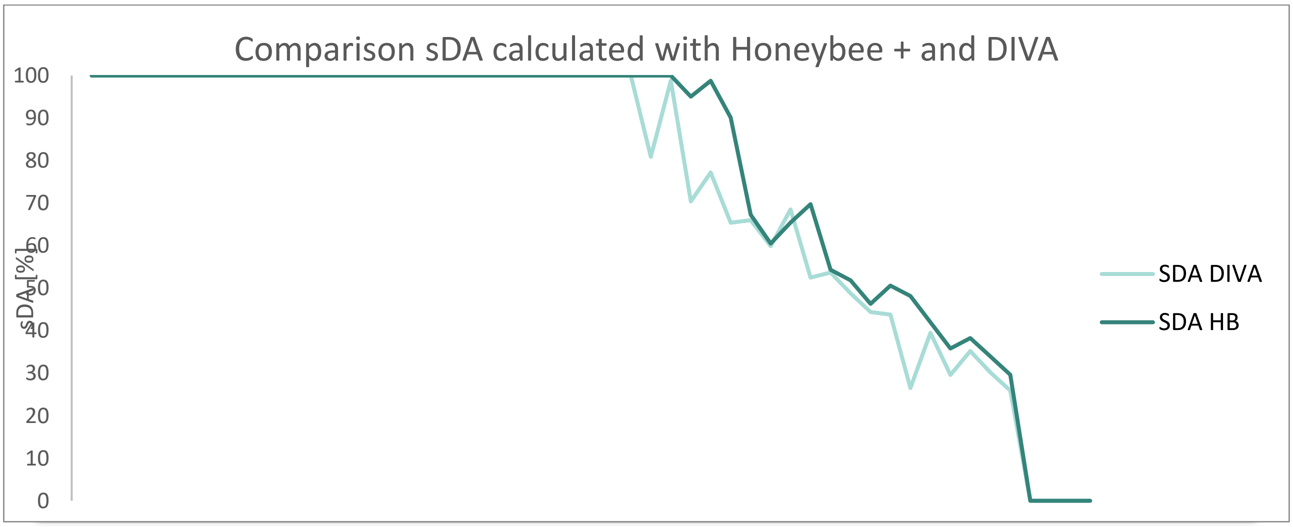


Figure 7-12: Comparison sDA calculated with HB + and DIVA

As it can be seen, the general trend of the two software results is the same, but the results obtained in DIVA present on average, lower values compared to the ones of Honeybee+, according to what has been explained in Chapter 3. Trying to find geometrical parameters which can approximate the sDA behavior, the first one considered has been the area of transparent part of the panel, since a bigger glazed area gives a higher value of sDA.

The graph reported below shows a group of 55 random configurations for Milan, for the R 1.b geometry facing south.

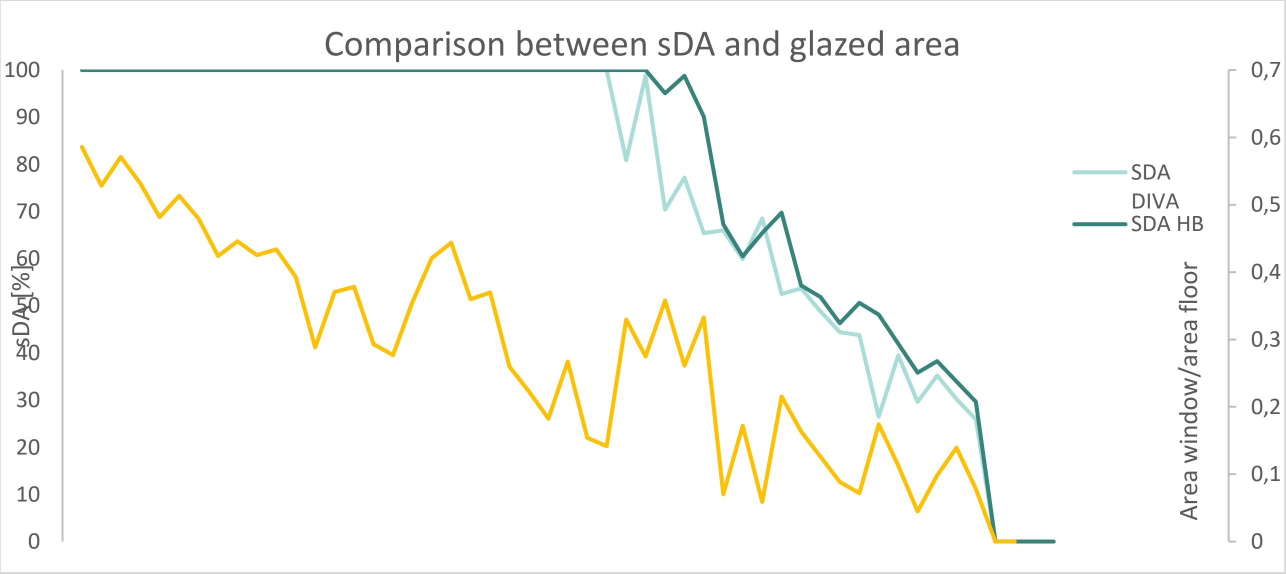


Figure 7-13: Comparison between sDA and transparent area

It is possible to see from Figure 7-13: Comparison between sDA and transparent area that there is a dependence between the dimension of the transparent surface and the spatial daylight autonomy inside the room: bigger transparent areas give higher values of sDA, but this correlation is not linear and is not possible to get an accurate approximation of the sDA considering only this parameter. It can be also seen that only in the last few combinations Honeybee+ and DIVA have similar values of sDA, but for the majority of the cases HB+ has sDA values around 100% even when DIVA has values between 60%-70%. The cases in which the values are the same are the ones obtaining an sDA value really low, lower than 30%. It can be seen also that in the left-hand side of the graph, the trend of the two results is not even paired: sometimes DIVA obtains a peak and in the same case HB+ gets a fall.

7.1.2.1 Sky view factor (SVF)

The second variable considered is the sky view factor, which represents the portion of sky visible from each glazed surface; in fact, the same area of transparent surface gives different contribution to the spatial Daylight Autonomy (sDA) according to its orientation, since the income of illuminance change according to the orientation and the tilting angle of the surface.

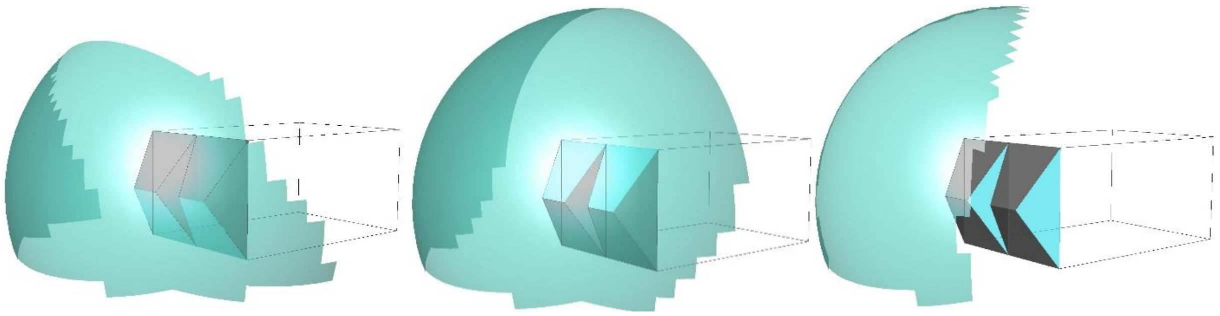


Figure 7-14: Bottom trasp.: SVF=0,36 *Top trasp.: SVF=0,55* *Right trasp.: SVF=0,24*

The calculation procedure for the SVF takes also into account the context since it is calculated starting from a hemisphere centered in the center of the transparent area and this hemisphere is then divided in 300 patches. The sky view factor is calculated considering, using as a starting point of view the center point of the glazing, how many patches are not covered by the context: that number expressed as a percentage on the total number of patches represent the sky view factor.

This parameter is a value between 0 and 1, where 1 is for the case of a horizontal surface facing the sky without obstructions and 0 for a surface that cannot see the sky, due to the context or due to a combination of context and orientation of the surface.

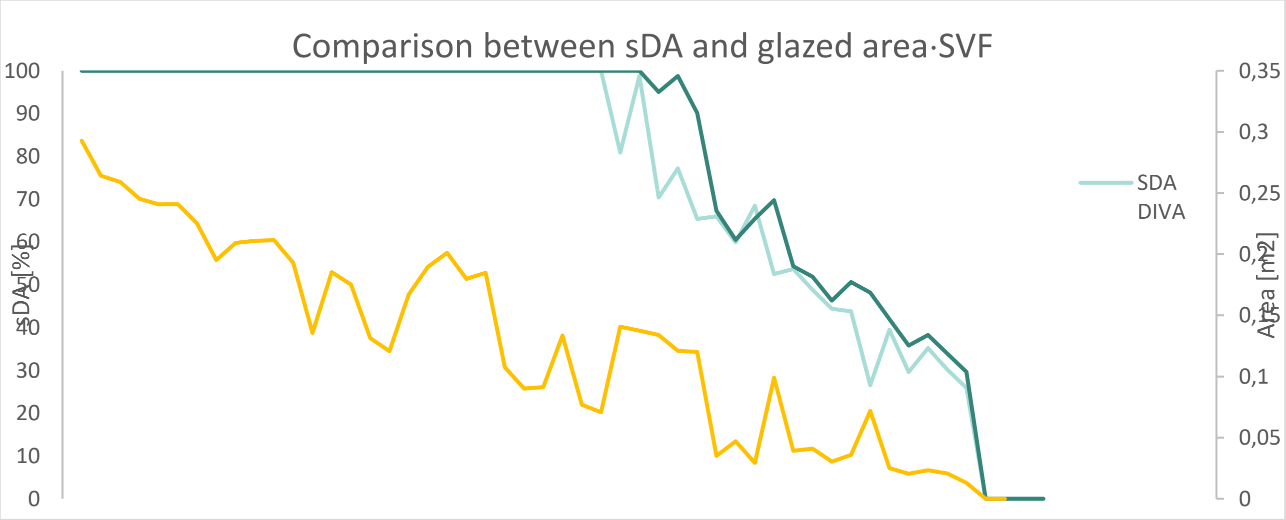


Figure 7-15: Comparison between sDA and weighted transparent area

As it can be seen from the graph, multiplying the transparent surface per the SVF, the result is a smoother curve; the curve gets more linear and the trend is more comparable to the one of Honeybee+ and Diva. This method of calculation takes into account the orientation of the surface and also the context: the same surface gives different contribution at the daylight of the room according to its orientation and to the context; up to now the contribution of the reflection of the context is not considered since tests performed shown that, except from some particular cases, it gives only a marginal contribution to the sDA.

Subsequently, to obtain more reliable results, the weighted area has been multiplied by a factor which considers the height of the window in the room: the same surface with the same SVF placed at different heights from the floor gives different sDA results, since depending from the height the light go deeper in the room; it is important to report that the part of window under the analysis grid placed at 76 cm does not help to increase the sDA values. Starting from this assumption, then the area has been multiplied for a coefficient that gives more importance to the surfaces having a higher barycenter, taking less into account the ones with a lower height from the floor.

The results get even more similar to the ones obtained with HB+ and it is possible to see that for a value having a weighted area bigger than 0.06 transparent m^2 / floor m^2 we obtain values of sDA higher than 100% in Honeybee+ (Figure 7-16).

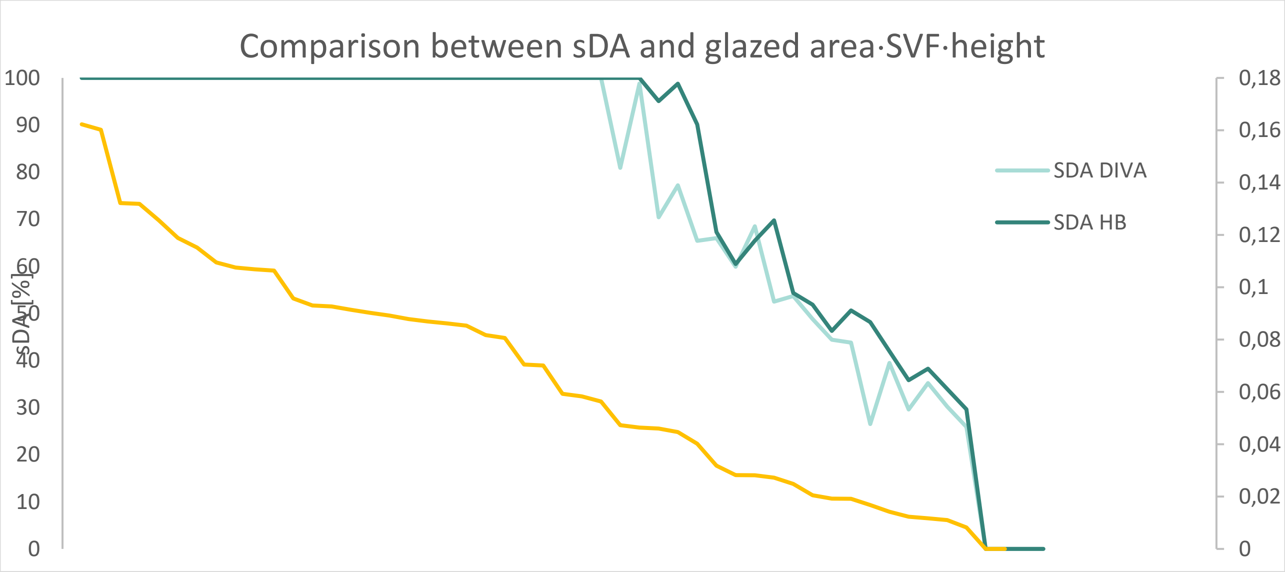


Figure 7-16: Comparison between sDA and transparent weighted area

The following graph shows the values in percentage: all the ones having a weighted area higher than 0.06 report a 100% of sDA as output result, and for the ones below that threshold the value obtained is remapped from the 0-0.06 range to the 0-100% range of the sDA.

As it can be seen from Figure 7-17, the trend is the same between the three methods of calculation, confirming the good quality of the simplified calculation.

Figure 7-17: Comparison between sDA results, simplified method vs other tools

The Simplified Method for the calculation of sDA has been used to evaluate two further climates at different latitudes: Singapore and London. This comparison has been done in order to show that even if the calculation considers mostly a geometrical factor, it is possible to obtain reliable results also changing the climate, considering this calculation somehow climate-based. Nevertheless, it is important to underline that the values are slightly underestimated in tropical/equatorial climates and overestimated in Northern climates. The results are reported in ANNEX I.

The results shown until now have been developed for a south facing façade; in order to take into account the changes in sDA according to the orientation of the façade, a study on the total and diffuse illuminance has been done. The following graph plots the annual illuminance, both total and diffuse along the different directions. To carry out the simulation a surface has been oriented towards the considered direction and the illuminance has been calculated.

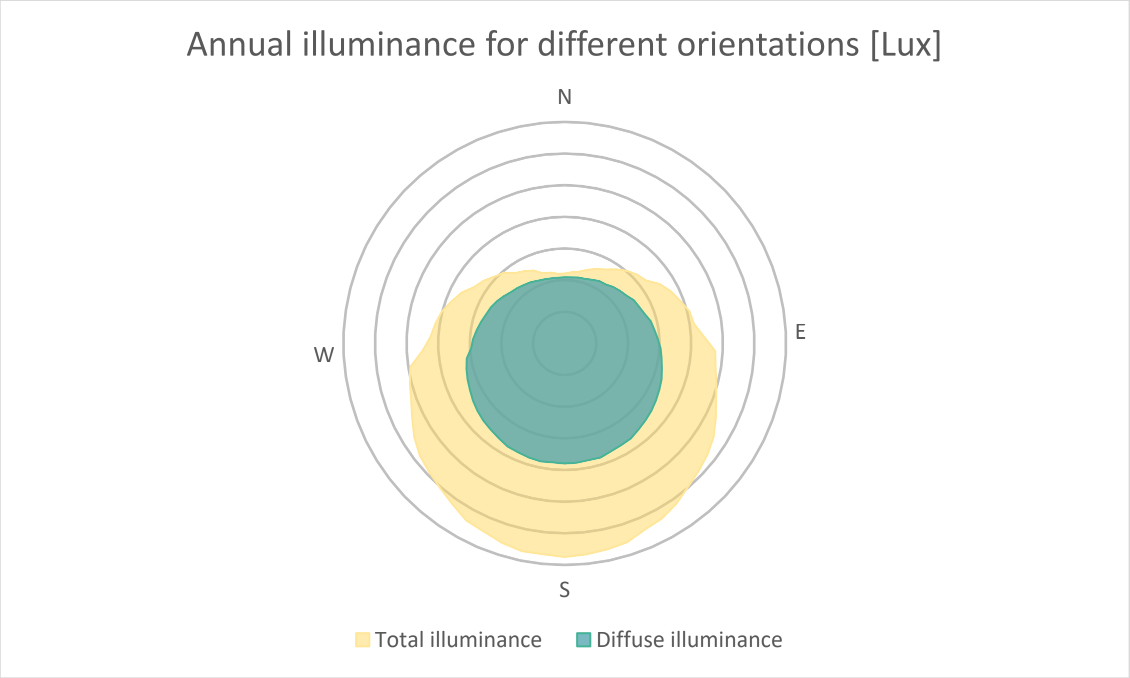


Figure 7-18: Annual illuminance

As is possible to see from Figure 7-18 the diffuse illuminance has a more homogenous behavior changing the orientation of the façade; for example, the value of the north orientation of the annual diffuse illuminance is 55% of the value obtained for the south orientation, while the total illuminance facing north is only the 33% of the maximum value. As a further confirm of the goodness of the results obtained, the analyses performed in the software comparison (see Chapter 3) shown a similar trend with a reduction of the sDA for the same configuration; changing the orientation of the glazed part from south to north, the difference is around 30%.

Consequently, in order to get correct results for sDA, the area obtained following the procedure shown in the previous steps needs to be multiplied by a coefficient related to this reduction.

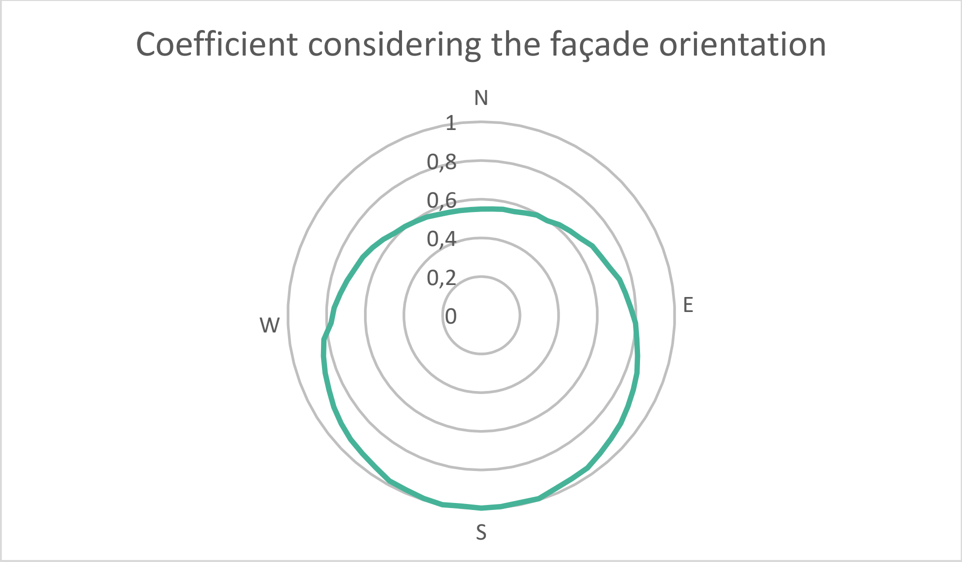


Figure 7-19: Coefficient considering the façade orientation

The coefficient decreases the weighted area, so in order to obtain a sDA value equal to 100% it should start higher than 1 m^2. This coefficient has a value of 0,8 for east and west orientations and 0.6 for north orientation, which implies a higher transparent area towards north in order to reach the sDA minimum threshold.

7.2 ENERGY CALCULATIONS

The main focus of the plug-in is the calculation of the daylight parameters, in order to reach the visual comfort. As said before, more than one configuration can have acceptable results, so in order to not reduce the choice to a mere aesthetic evaluation, it has been thought to perform also some energy calculations, to compare the different geometries. As for the daylight analysis, it has been chosen to not use third parts plug-ins, introducing a property method of calculation: this choice allows to reduce the time needed for the simulation. The plug-in proposes a simplified energy calculation, which does not consider all of the superfluous calculations, computing only the values that can be referred to the geometry and the materials of the panel. In this part of the chapter the calculations and the parameters considered are explained.

7.2.1 ENERGY BALANCE

The determination of the loads for heating and cooling requires the heat balance of every single room. Here below reported the elements of the heat balance, summarized briefly, according to the U.S. Government Publishing Office:

- Conduction heat transfer in buildings constructions such through the solid interior surfaces of ceilings, floors, walls, windows, doors, etc. as affected by temperature changes at their exterior surfaces;
- Radiation heat transfer by emitted and reflected energy among the room surfaces;
- Convection heat transfer between room air and the room surfaces;
- Distribution and magnitude of transmitted solar radiation passing through fenestration areas;
- Heat generation within the room and the resultant convection and radiation heat transfer;
- Heat transfer to room mass such as furniture, furnishings, etc.. This is to be considered with changes in room air temperature only;

- Convection heat and mass transfer from sources and/or forces acting exterior to the room such as infiltration, exfiltration, circulating air and inter and intra-room convective air motion. [24]

The plug-in, among the criteria listed before, only considers the ones that depend only on the heat exchanged through the envelope and on the parameters referred to the incoming light from the solar radiation. This is due to the fact that the panels are compared considering the same indoor conditions: people occupancy, equipment and infiltrations. These values can be considered approximately constant throughout the year; their calculation will be only time consuming and will not affect considerably the final comparison between different panels. Moreover, the purpose of this calculation is the comparison between geometries, so it is also an issue of more interest to understand how the geometry actually effects the energy consumption of the building.

7.2.2 ENERGY CALCULATIONS PERFORMED IN THE PLUG-IN

As explained in the previous paragraph, the calculation of the energy balance will only consider:

- Heat exchanged through the envelope;
- Direct solar gains;
- Lighting gains and consumption due to lighting, which are related to the solar illuminance entering the room through the envelope;
- BIPV production.

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[24] U.S. DEPARTMENT OF COMMERCE, National Bureau of Standards, “Single-Room Heat Balance for Building Heat Transfer”, 1981.

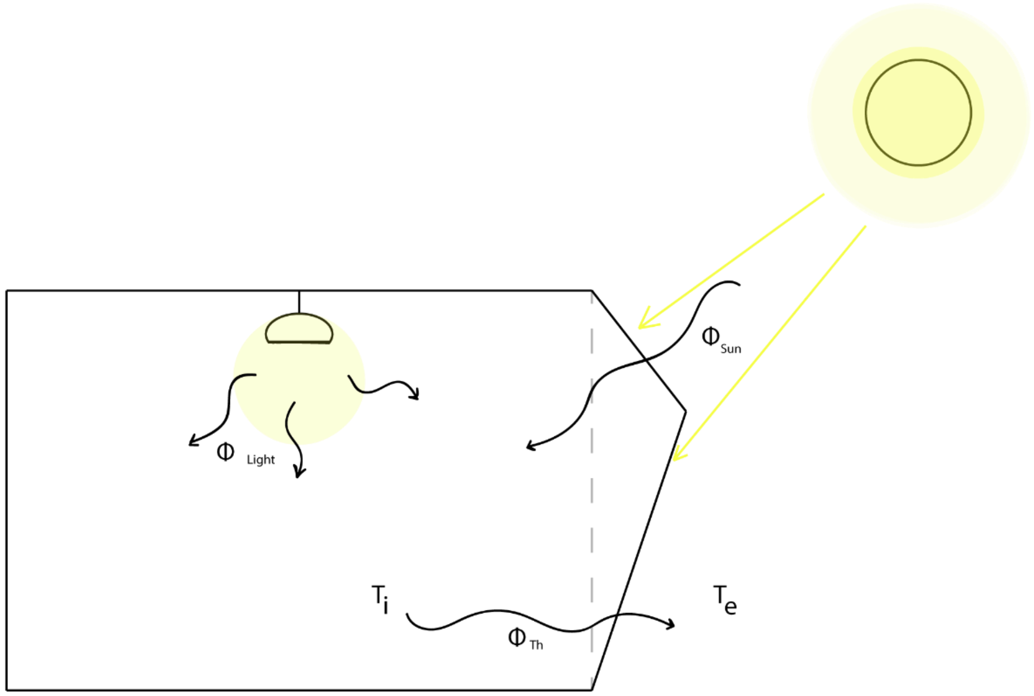

Figure 7-20: Energy balance scheme

7.2.3 Heat exchanged through the envelope

7.2.3.1 Thermal transmittance of the module

According to the UNI EN ISO 10077-1[25], the calculation of the thermal transmittance of the window, in case the module considered is composed both by opaque and transparent panels can be calculated as:

$$U_w = \frac{\Sigma A_g U_g + \Sigma A_p U_p + \Sigma A_f U_f + \Sigma l_g \Psi_g + l_p \Psi_p}{\Sigma A_g + \Sigma A_p + \Sigma A_f}$$

Where:

U_g is the thermal transmittance of the glass;

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[25] UNI EN ISO 10077-1, Marzo 2007

U_f is the thermal transmittance of the frame;

U_p is the thermal transmittance of the opaque panel;

Ψ_g is the linear thermal transmittance due to the combined effects of the glass, the spacer and the frame;

Ψ_p is the linear thermal transmittance of the panel which can be considered equal to 0 if:

- The inner and outer surfaces of the panel are made of material with a thermal conductivity lower than 0,5 $\frac{W}{m^2K}$ and
- The thermal conductivity of all the materials of the thermal bridge on the edge of the panel is lower than 0,5 $\frac{W}{m^2K}$

To evaluate the heat exchanged through the envelope, the areas of the opaque and transparent panels are automatically calculated along with the perimeter of the frame.

For this calculation, the choice of material fell on standard ones, since it is important to underline and focus on the response in terms of energy to the change of geometry; it is crucial that all the configurations are tested under the same conditions, without making distinctions on the savings due to the use of a specific material. The values of the thermal transmittances considered are listed below:

	Thermal transmittance *[W/m^{2}K]*
U_g	1
U_p	0.4
U_f	0.7/1.5

Table 16: Thermal transmittances considered for the energy calculation

The frame has reported two values for the thermal transmittance, which are the one of the internal and external frames; according to the following picture, it is possible to see which part of the frame is considered internal and which external; the U values are respectively 0.7 and 1.5 [W/m^{2}K]

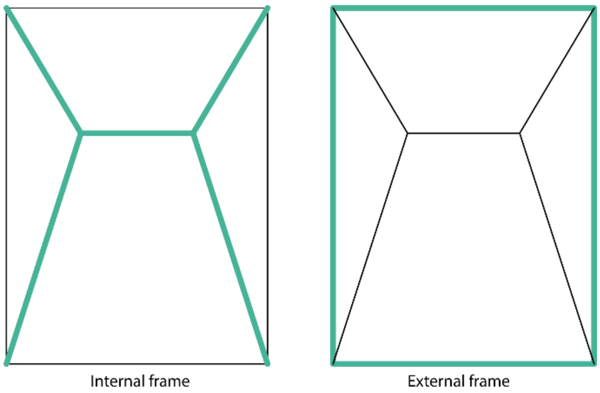
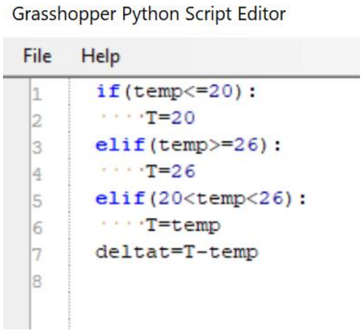


Figure 7-21: Different U-value assignement to the internal/external frame of the panel.

7.2.3.2 *Calculation of the heat flux*

In order to evaluate the heat flow it is necessary to calculate the temperature gradient between the indoor and the outdoor.

The .epw file reports the hourly temperatures along the year; knowing the values it will be possible to calculate the gradient. Since it is not possible to define a prior when the cooling and heating seasons start and end, due to their dependence on the location, a brief script has been made in python;



```
if(temp<=20):
    T=20
elif(temp>=26):
    T=26
elif(20<temp<26):
    T=temp
deltat=T-temp
```

Figure 7-22: Indoor temperature calculation script

if the outdoor temperature falls below 20°C (which has been set as the heating set point), the interior temperature is set equal to 20°C. When the outdoor temperature is higher than 26°C, the indoor temperature is equal to 26°C (cooling set point); finally, if the outdoor temperature is between 20 and 26°C, the indoor one is set equal to the outdoor.

This simplification can be done in order to define a general rule to define the thermal exchanges of heat between the inner and outer spaces. The convention used is that the flow goes from the indoor to the outdoor, as seen in the Figure 7-20.

Knowing the U-value and the temperature gradient it is possible to evaluate the annual hourly exchanged heat:

$$\phi = U \cdot \Delta T \cdot A \quad [W]$$

Obviously, since the convention is from the indoor to the outdoor, when the heat flux is in the opposite direction it will return a negative value.

7.2.3.3 Solar gains

The calculation for the solar gains starts from the basic principles of the ASE calculation procedure, shown in Chapter 7.1.1.

To assess the solar gains, the solar radiation entering the room through the glazing envelope is considered; exactly as for the calculation of ASE it was necessary to calculate the sun vectors and to cull them in function of the obstacles of the context. To obtain the culling list, the hourly sun position is linked with the centre point of the room; if the line “meets” an obstacle, it will return a True Boolean and that vector will not be considered in the calculation. The result will be the one seen in Figure 7-23; as it can be seen, the curve on the solar dome represent the sun position along the year and along the day, and the green lines represent the sun rays which are not obstacled by the context and can reach the centre of the panel.

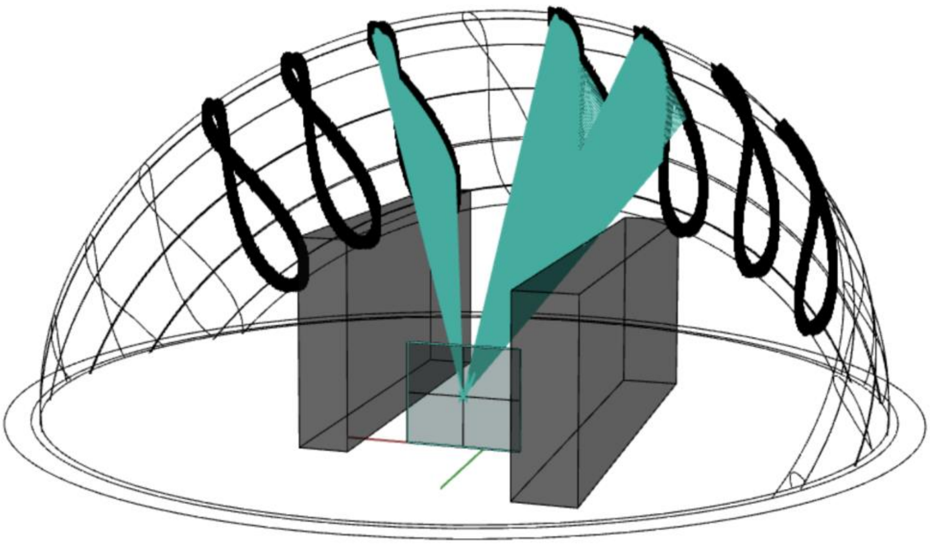


Figure 7-23: Sun vector calculation

Once the vectors are calculated, the transparent area is projected along their perpendiculars.

Then, the calculation of the solar heat gains can be defined as follows:

$$Solar\ Gains = Radiation \cdot Projected\ Area \cdot SHGC \text{ [W]}$$

Where the SHGC represents the Solar Heat Gain Coefficient, considered equal to 0.7.

7.2.3.4 BIPV

The production of energy due to the presence of BIPV can be evaluated with the same procedure explained in the previous paragraph, where the SHGC is substituted by the performance factor of the panel.

The performance factor changes according to the type of panel used, as explained in Chapter 5.3. In particular, the performance coefficient is in a range between 0.15 and 0.22 for a monocrystalline and 0.1 and 0.16 polycrystalline. To consider an intermediate case, a value equal to 0.15 has been considered in the flow, which is a value between the two types of technology. Moreover, the performance coefficient needs to be reduced when the temperature of the panel is higher than the operative temperature, which is usually around 25°C which however is given by the producer; the reduction of the performance coefficient is of 0.4% for each grade over the surface operative temperature.

To calculate the reduction of performance, a coefficient which considers the overheating of the panel is inserted in the flow: at each hour considered it plots the temperature reached by the panel, it makes the difference between that value and 25°C and it calculate the percentage of reduction of performance. This final value will be used to calculate the energy production as follows:

$$Solar\ Gains = Radiation \cdot Projected\ Area \cdot \eta\ [\mathrm{W}]$$

7.2.3.5 Lighting

The lighting is the only contribution of the equipment that has been considered in the energy balance. The main reason for this choice was the strong relationship between the use of lights and the value of sDA; in fact, this parameter represents the percentage of floor which is reached by at least 300 lux for the 55% of the time, as it can be imagined, the higher is the value of the sDA during the occupied hours, the lower will be the need of the artificial light. Daylight control in fact represent an efficient solution to reduce the energy consumption for lighting and studies show that through the control of the artificial lighting according to the daylight availability can allow in electricity savings up to 77%.[26]

Another parameter which is usually used to predict the use of the artificial light is the Daylight Factor, which represents "the amount of illumination available indoors relative to the illumination present outdoors at the same time under overcast skies."[27] It is calculated as: $DF = \frac{Ei}{Eo} \cdot 100$. Generally, for systems which combine the use or artificial and natural light, it is considered well daylit if the DF is higher than 5%, while if the DF falls below 2% it is considered bad daylit, with the need of artificial illumination. In order to assess the lighting in function of the sDA as calculated in the plug-in, a relationship with the value of DF has been investigated. The results, carried out with the use of software for the calculation of daylight, have been compared with the results of sDA, coming from the plug-in. The ratio between the two values shown that the DF can be calculated multiplying the sky view factor used in the sDA calculation for 0,4. In this way, starting from the calculations already

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[26] O.K.Larsen, R.L.Jensen, T. Antonsen, I.Stromberg, "Estimation methodology for the electricity consumption with daylight and occupancy controlled artificial lighting", Lausanne, Science Direct, 2017

[27] http://patternguide.advancedbuildings.net/using-this-guide/analysis-methods/daylight-factor (last visit, 02/08/2018)

performed in the daylight analysis for the definition of the sky view factor, it was possible to evaluate also the lighting.

In particular, the assessment of the lighting consumption is done considering the interior requirement of 300 lux; for each hour, the plug-in computes the difference between the lux required and the one entering due to the solar illuminance.

If the solar illuminance is not enough, the artificial light will cover the difference in terms of lux that will be converted in Watts, using a conversion factor equal to 0.0167 considering a fluorescent light.

8. CHAMELEON DEVELOPMENT

In the previous Chapter all the methods of calculation developed have been explained; at this point, the calculation of ASE, sDA and energy can be done with high reliability and in a shorter time compared to other software.

The challenge at this point has been to define how to use them, in order to obtain the definition of the final flow. Considering the new prescriptions related to the NZEB and the growing importance of the role of energy savings in buildings, the first main aspect that has been considered was to choose and assign a hierarchy to the parameters analyzed for the definition of the flow, in order to design an envelope as much performing as possible. The main priority has been given to the daylight comfort, considering as main parameters the ASE and sDA, as seen before. ASE is directly dependent on the direct solar radiation and the sDA considers also the diffuse radiation: acting on them means also acting on the incoming solar radiation and, as a consequence, on the heating and cooling needs.

Nevertheless, keeping in mind that the final goal is to define a tool for the form-finding during the early stages of the design, the final façade should also take into account the aesthetic aspect; consequently, the flow has been conceived in order to give different opportunities to the user, in order to go to meet also the will of the designer.

This chapter shows the organization of the flows and the combination of the different methods of calculation to obtain the entire process from the definition of the inputs to the achievement of the final façade.

8.1 OUTPUTS OF THE PLUG-IN

Once the calculation procedure for the parameters considered has been well defined as described in Chapter 7, a wide range of possibilities for the outputs were possible. This issue has been evaluated for long time, because it has implications on different aspects of the project. As a matter of fact, the results of the daylight and energy analysis can be used in different ways to allow the design of the façade in different ways. At this point it was important to define firstly which could be the scope of this project. It was then necessary to analyze which are the needs of a designer who uses this plug-in and try to translate these needs in a simplified flow.

On one hand, this tool could be a sketch app for the designers; it means that it gives the possibility to the user to choose among the options that satisfy the comfort parameters, the ones that he wants to apply to the façade and choose how to place them to satisfy also some architectural requirements. On the other hand, it could be a more complex, accurate and time-consuming tool for daylight which involves also energy calculations.

The direction that this plug-in will take is to have an intermediate position: the tools which perform energy analyses are widespread and have a high accuracy, in spite of time-consuming simulations. Obviously, these tools are highly accurate and allow the user to have detailed energy results about the system he is about to choose, but most of the configurations suitable from the point of view of the visual comfort are similar one to the other and the differences in the energy balance are not enough relevant to justify the time spent to run a detailed analysis for the comparison. This appears clear in the case in which most of the acceptable configurations belong to the same family, with only slight changes due to the position of the control points; logically, the energy balance intended as a figure will not change considerably from one to the other, on the other hand, they may have relevant differences compared to a configuration of another family. Then, it will be sufficient to have less precise data, which allow the user to compare configurations, since the experience gained from the simulations run for this project says that the configurations that are acceptable (in terms of visual comfort) at the end of the daylight analyses are more than one and, if it is true that they can be chosen according to their appearance, they may have also differences in terms of energy needs which can be considered as a discriminant for the choice if the configurations present the same results for ASE and sDA.

Anyway, the output of the plug-in is a geometry, that could be easily baked on Rhinoceros 3D or other software to run energy analyses but, as said before, they would be time consuming and this will neutralize the time saved in the daylight one. For this reason, it has been decided to design a flow that will consider also a simplified energy balance of the room, in function of the geometry; as a matter of fact, knowing the type of material, also in a general way (e.g. single pane glass, spandrel etc..) and the area of the transparent and opaque surface, it is possible to calculate the heat flow, the solar gains, the solar illuminance entering the room and considering an energy calculation, considering only the components which are directly affected by the geometry, as it will be explained later on. Obviously, this will be only an approximation of the energy consumption of the building, but it will be helpful in the choice of the final geometry. Anyway, if the user wants to have more precise and accurate results, he can stop at the daylight analysis and evaluate all the possible geometries on another energy calculation software.

As a sketch tool, the output of the process will be a geometry applied to the entire façade; the final output will be generated following different juxtaposing criteria, which can be chosen by the user in different moments of the design analysis.

Another relevant aspect to deal with was how much “freedom” had to be given to the user; the more possibilities are left to be chosen between, the more variables need to be added to the flow. This means that every time the user can choose between different opportunities, parts of the flow may be repeated many times; as a consequence, the procedure may become heavy and time consuming: the risk is that the software has to manage thousands of data with possible crashes. All the possibilities then need to be analyzed and programmed in advance, in order to organize the flow and testing its effectiveness.

Here below in Figure 8-1: Plug-in flow it is shown the plug-in organization with the main steps, starting from the definition of the inputs by the user to the definition of the final façade.

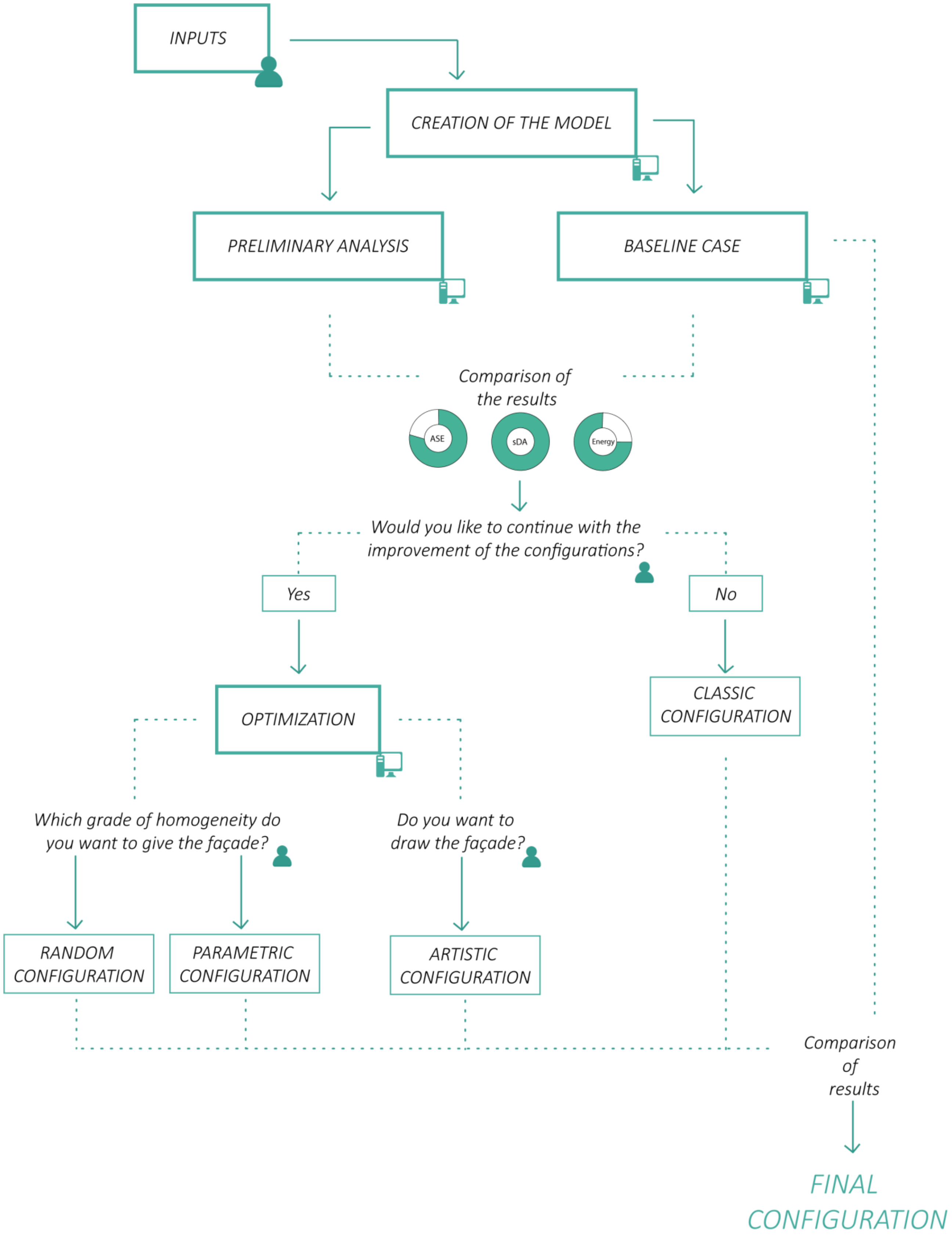


Figure 8-1: Plug-in flow

8.2 INPUTS

The first part of the flow is a common path to all the possibilities that can be further chosen by the user; first of all, Chameleon will ask the inputs of the project. They will be used to create the environment for the simulations and to carry out all the preliminary analysis.

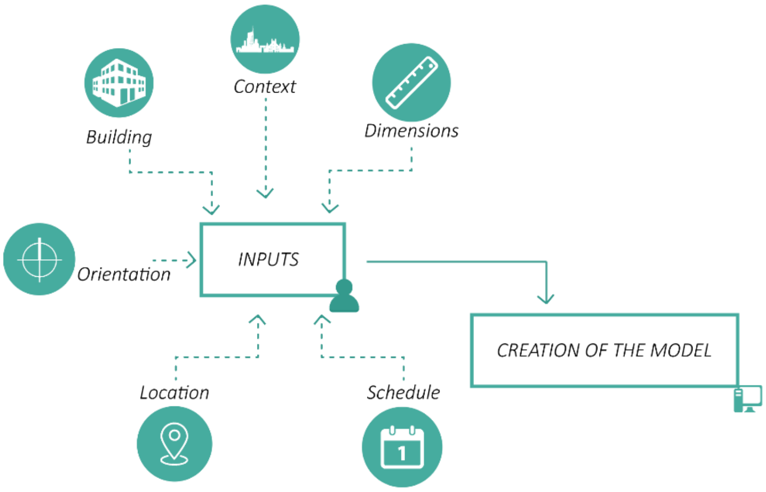


Figure 8-2: Inputs definition

8.2.1 Building and context

The assignment of the input and context is the very first step of the project. They can be drawn in Rhinoceros 3D or imported in the software from other 3D design tools or directly drawn in Grasshopper as parametric objects. They will be treated in Grasshopper as Breps. It is suggested to use context as much as possible simplified, in order to reduce the time needed for the calculation of the vectors shielded by the context.

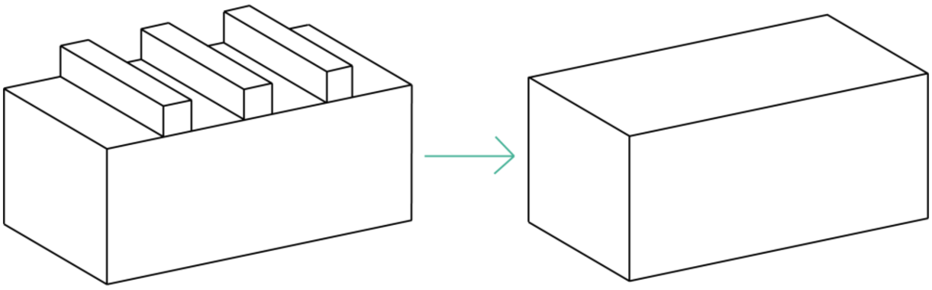
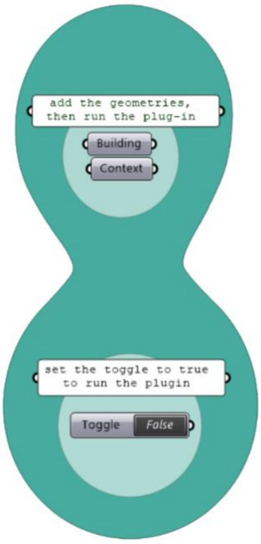


Figure 8-3: Simplification of the context

Finally, the window is composed by a toggle, which needs to be set to True to run the plug-in.



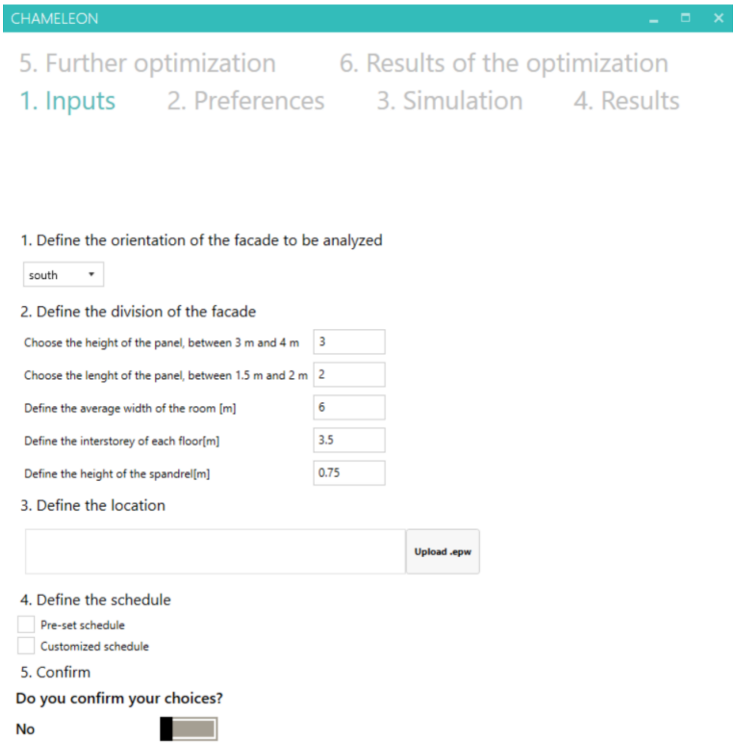
add the geometries, then run the plug-in

set the toggle to true to run the plugin

Figure 8-4: Launch window

8.2.2 Input Tab

When the plug-in is launched, the main window appears, composed by six different tabs. Let's see the first one, the "Model Settings". As it can be seen in Figure 8-5: Input window this part is divided in five points:



1. Define the orientation of the facade to be analyzed

south

2. Define the division of the facade

Choose the height of the panel, between 3 m and 4 m: 3

Choose the lenght of the panel, between 1.5 m and 2 m: 2

Define the average width of the room [m]: 6

Define the interstorey of each floor[m]: 3.5

Define the height of the spandrel[m]: 0.75

3. Define the location

4. Define the schedule

☐ Pre-set schedule

☐ Customized schedule

5. Confirm

Do you confirm your choices?

No

Figure 8-5: Input window

8.2.2.1 Define the orientation

Once the plug-in has recognized the façade and the context, it is possible to choose from a pull-down window which façade has to be analysed, choosing the orientation. The flow has been designed to assign the orientation to the façades independently on how the building is drawn, on the number of façades and on the shape. As a matter of fact, the system explodes the building in the different façades, and each one has been computed analysing the normal vector and its module. Then, all the façades with the vector pointing the same direction are grouped together and all the other façades are added to the context Brep. This is due to the fact that when the plug-in considers only one façade, if the geometry is complex, the other façades may shade the one considered; this method evaluates if the façade is shielded by the others even during few hours a year.

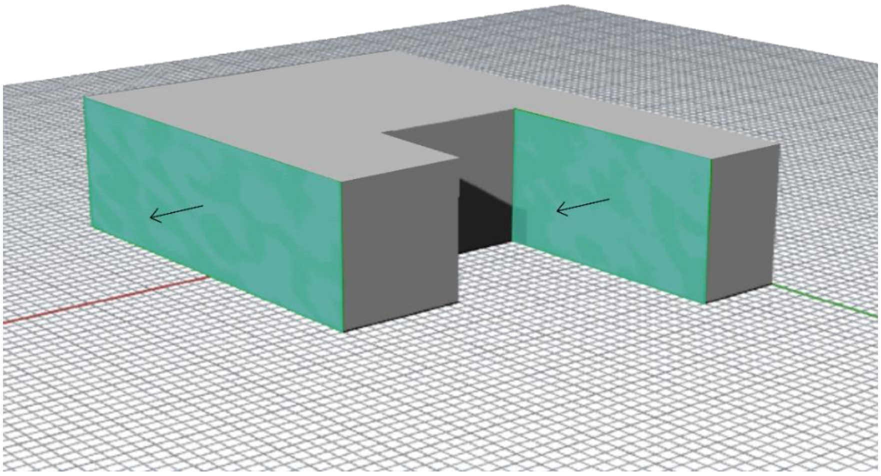


Figure 8-6: Façades direction assignment

8.2.2.2 Define the subdivisions of the façade

The user can choose the width and height of the panels for the façade inside a range, which is specified in the plug-in. The ranges have been established taking into account some limits imposed by the construction of the panels. If the value inserted is out of range a message will appear and the user is invited to define another value. Obviously, the value inserted will not be the final one, but it will be used to divide the façade and the rest of the division will be distributed and added to the value defined by the user.

Moreover, the plug-in asks to define the average width of the room in order to set the grid for the daylight calculation and the interstorey height.

8.2.2.3 *Define the location*

The user can set the location of the building by uploading the .epw file. It can be downloaded from the Energy+ website. The .epw file has hourly information about different aspects of the climate (e.g. temperature, solar radiation, illuminance etc..).

The .epw file is organized in rows and columns and each information belongs to one column; it can be then analyzed in Grasshopper without using any third part plug-in but only reading the column containing the information needed.

In the preliminary analysis many are the variables used, which are taken from the weather data file:

- Sunpath;
- Latitude and longitude;
- Temperature;
- Solar direct radiation;
- Solar direct illuminance.

8.2.2.4 *Define the schedule*

The user is asked to select the intended use of the building, he can choose between preset schedules or customized ones. Up to now the choice of a preset intended use can be done between:

- Office;
- Residential;
- School;
- Commercial.

Further implementation of the software may comprehend a higher number of preset schedules.

These intended uses will lead to a proper schedule which has been designed inside the flow; the values are taken from ASHRAE standards. The values provided by the prescription are daily ones, with distinction between weekly days and week-end days; they are hourly values, starting from 0 (midnight) to 24. Each value given is between 0 to 1 and it is a fractional multiplier.

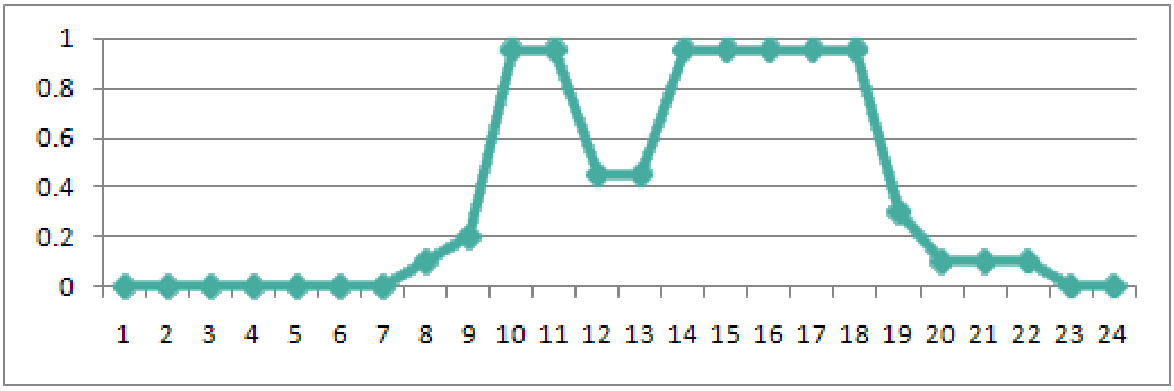
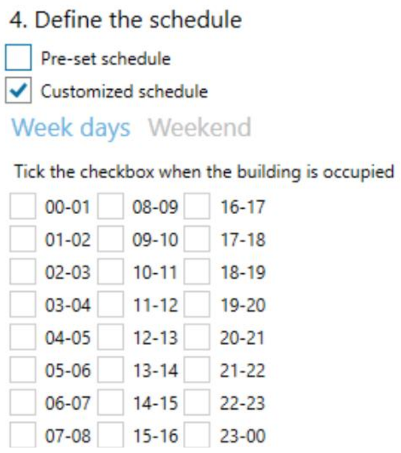


Figure 8-7: Example of schedule as given by ASHRAE

It means that if a building has an occupancy density of 100 people:

- A schedule value of 1 means that 100 people are assumed to be in the building during that hour;
- A schedule value of 0 means that no people are assumed to be in the building during that hour;
- A value of 0.1 means that 100 * 0.1 = 10 people are assumed to be in the building during that hour.

If the user chooses a customized schedule, a panel with checkboxes appears and the user will tick the boxes of the hours of occupation of the building, creating a schedule for week days and one for the weekend.



4. Define the schedule

☐ Pre-set schedule
☑ Customized schedule

Tick the checkbox when the building is occupied

☐ 00-01
☐ 01-02
☐ 02-03
☐ 03-04
☐ 04-05
☐ 05-06
☐ 06-07
☐ 07-08
☐ 08-09
☐ 09-10
☐ 10-11
☐ 11-12
☐ 12-13
☐ 13-14
☐ 14-15
☐ 15-16
☐ 16-17
☐ 17-18
☐ 18-19
☐ 19-20
☐ 20-21
☐ 21-22
☐ 22-23
☐ 23-00

Figure 8-8: Customized schedule settings

Both systems will be then translated into a list of True/False; this list will be used as a cull pattern for the solar rays, in order to run the analysis considering only the hours in which the building is actually occupied.

8.2.2.5 Confirm

By moving the toggle to “Yes”, the plug-in suggests the user to move to a new tab, where the user can express the preferences on the materials.

Done!
Move to panel 2!

If you want to change your choices, press the button

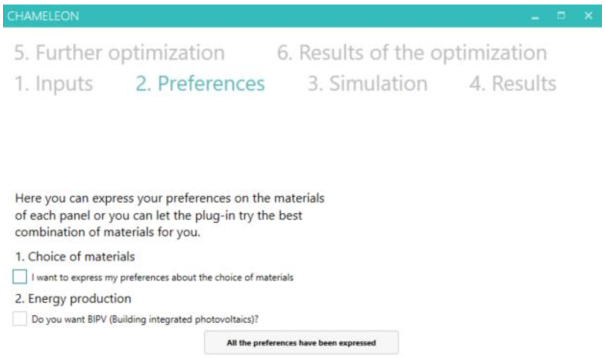
Figure 8-9:"Move to new panel" message

Moreover, it suddenly appears a new button to refresh the choices to change the inputs defined.

8.2.3 Preferences Tab

This part of the plug-in is used to express preferences on materials, since the geometries that will be tested by the plug-in will have opaque or transparent panels. This may seem a countersense, since Chameleon should be used in order to find the best configuration according to the boundary conditions; it is true also that it may happen that the user *h*as preferences on the disposition of materials: some intended use of buildings may prefer to have light coming from the top and do not need the view from the outside, the user in this case should express his preferences in order to test only geometries with a combination of materials suitable for that specific needs and to not waste attempts with for example a complete transparent module, which is not appropriate for the scope. The default option is to not express any choice on the materials, for the reason explained before; however, the user can click on the tick-box and express his preferences.

In addition, in this tab there is another tick-box, which is related to the use if BIPV (Building Integrated Photovoltaics), which can be ticked simultaneously with the other one. It is used to indicate if the system will have the BIPV; choosing this checkbox means that the energy production will be considered in the energy calculation and the system will evaluate in which panel (or panels) place the photovoltaic cells, to make the most of the energy production.



Here you can express your preferences on the materials of each panel or you can let the plug-in try the best combination of materials for you.

1. Choice of materials

☐ I want to express my preferences about the choice of materials

2. Energy production

☐ Do you want BIPV (Building integrated photovoltaics)?

Figure 8-10: Preferences tab

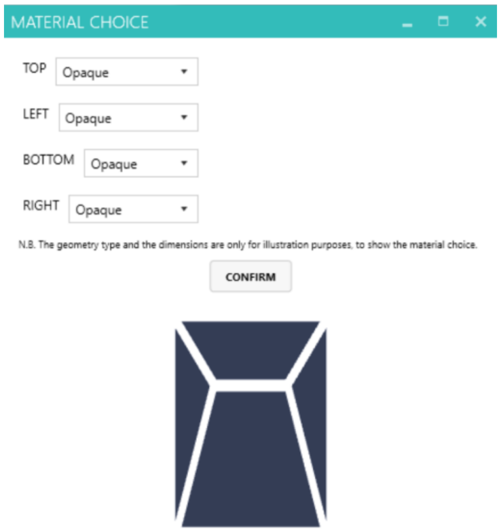
If the first checkbox is ticked, there will be automatically opened a new child window.

8.2.3.1 Material Choice Window

The preferences window can be used to express the choices on the materials for each panel. Visually, the preference can be expressed from a pull-down menu, where the possibilities are:

- Transparent;
- Opaque;
- No preference;

and it is shown on a reference panel using different colors. The panel shown is just for illustration purposes, only to represent the four panels, but it is not indicative of the subfamily or of the dimensions.

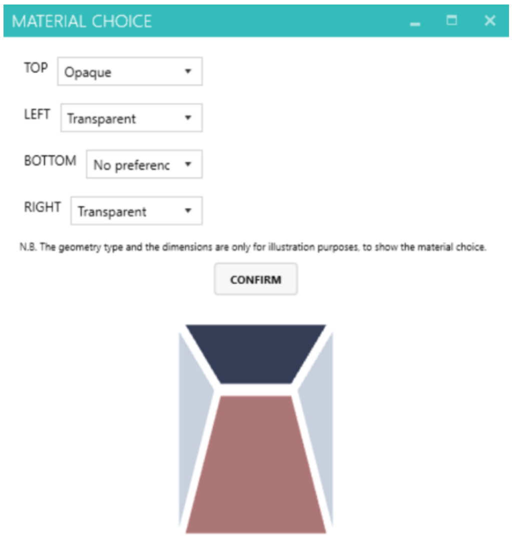


TOP Opaque
LEFT Opaque
BOTTOM Opaque
RIGHT Opaque

N.B. The geometry type and the dimensions are only for illustration purposes, to show the material choice.

Figure 8-11: Preferences window

The dark blue is used to represent an opaque panel; the light blue for a transparent panel; the red for a preference not expressed.



TOP Opaque
LEFT Transparent
BOTTOM No preferenc
RIGHT Transparent

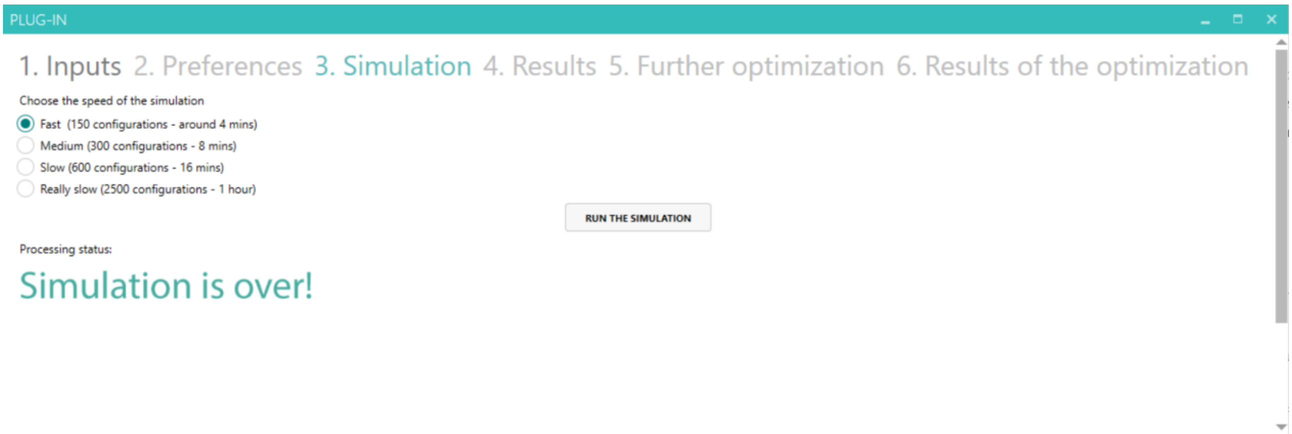
N.B. The geometry type and the dimensions are only for illustration purposes, to show the material choice.

Figure 8-12: Example of the choice of materials

By choosing “no preference”, the system will arbitrarily assign to each configuration generation to that panel a transparent or opaque material; in the case of Figure 8-2, the bottom panel will be used in the different combinations as transparent or opaque.

8.2.4 Simulation Tab

The simulation window gives the possibility of choosing how many configurations the software will analyze, in terms of time spent for the simulations.



Choose the speed of the simulation

● Fast (150 configurations - around 4 mins)
○ Medium (300 configurations - 8 mins)
○ Slow (600 configurations - 16 mins)
○ Really slow (2500 configurations - 1 hour)

Processing status:

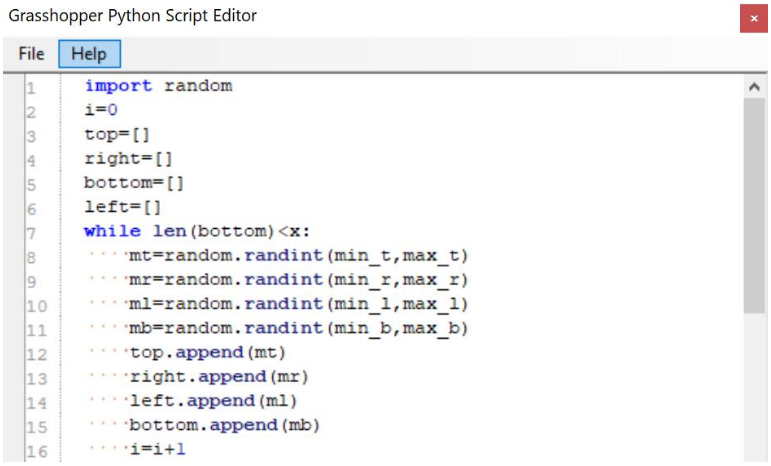
Simulation is over!

Figure 8-13: Simulation tab

After the simulations are completed, a message will appear in the window and the user will be able to move to the visualization panel to choose the configurations.

8.2.4.1 Configurations

The configurations are automatically generated inside a Python component. It will receive the inputs from the user interface for the materials, that are converted from string to numbers. Once all the parameters are all defined as numbers, it is possible to create random configurations for the geometries and materials, as seen below.



```python
import random
i=0
top=[]
right=[]
bottom=[]
left=[]
while len(bottom)<x:
    mt=random.randint(min_t,max_t)
    mr=random.randint(min_r,max_r)
    ml=random.randint(min_l,max_l)
    mb=random.randint(min_b,max_b)
    top.append(mt)
    right.append(mr)
    left.append(ml)
    bottom.append(mb)
    i=i+1
```

Figure 8-14: Python script for the generation of configurations

It can be argued that this method culls many solutions and options, indeed this solution came up after many different solutions have been evaluated. As the reader can remember from par. 6.1.3, the first group of solutions has been done with the use of solvers, but due to the high number of geometries that come from the combination of parameters (19200 configurations, 6200 per each family), the solver slowly learns from the results it obtains and this would imply a forsooth long time needed to start obtaining good and accurate results.

Thinking about another way to obtain geometries, there was not any mathematic rule which allowed to explore configurations picking examples from the entire domain, since having to test hundreds of geometries on 19thousands, it will imply that only the "first" part of the domain will be considered. The random function, which is one of the libraries of python, allow to pick configurations on the entire field; simulations run considering at least 150 cases showed that the geometries generated were quite representative of the different general cases and combination of materials possible for each family; consequently, the choice fell on the use of the random generation.

8.3 FLAT FAÇADE CASE

The geometries used in Chameleon are articulated and composed by panels not necessarily equal in shape; this leads to higher costs, which need to be evaluated at the beginning, in order to understand if the initial costs are amortized with the savings due to the lower energy consumption for lighting and HVAC system.

In order to evaluate the benefits that the system considered can bring, a baseline case is analysed at the beginning of the entire process, in order to allow comparisons after the preliminary analysis is carried out. The analysis is done considering a model with the divisions defined in the "Model Settings" tab, using a flat glazed façade, with a window/wall ratio equal to 0.6 and the simulations carried out are the ASE, sDA and energy calculations on each room of the building.

The presentation of the results has been a controversial issue; the final choice expects to show only the values of ASE and sDA, while the energy output will be only stored in the flow, to make further comparisons, tracking the improvements achieved with the further optimizations. This choice has been influenced by the fact that the energy calculation cannot be considered complete: as said before, it comprehends only the components which are affected by the geometry. Consequently, giving a numerical value would be misleading, so the energy consumption of the baseline case will be considered as the 100%, and all the other values coming from the analyses will be referred to this value as a reduction percentage.

The output of the daylight values will follow the scheme of Figure 8-16: the tab is divided in two expanders with the same structure, one for the ASE statistics and the other for the sDA ones. A preview of the façade will be shown coloured with a gradient of colours (Figure 8-15):

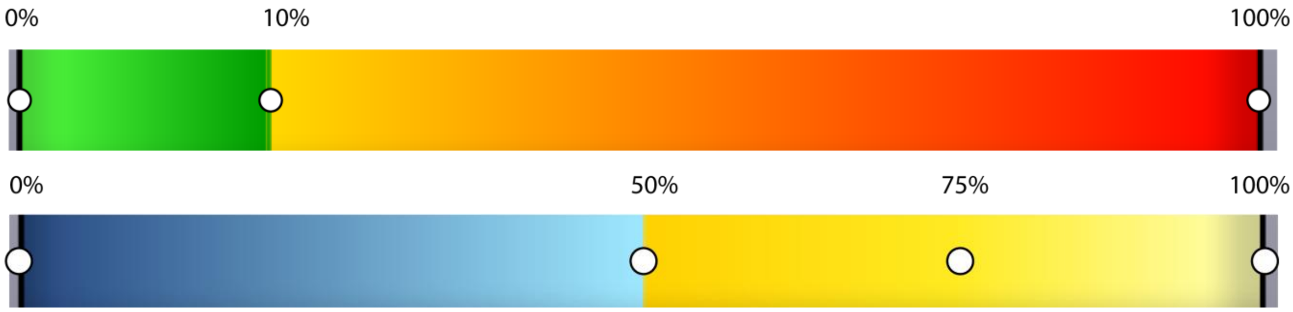


Figure 8-15: ASE and sDA colour gradient scale

alongside the façade preview, two doughnut charts will show the minimum and maximum values for the two parameters considered.

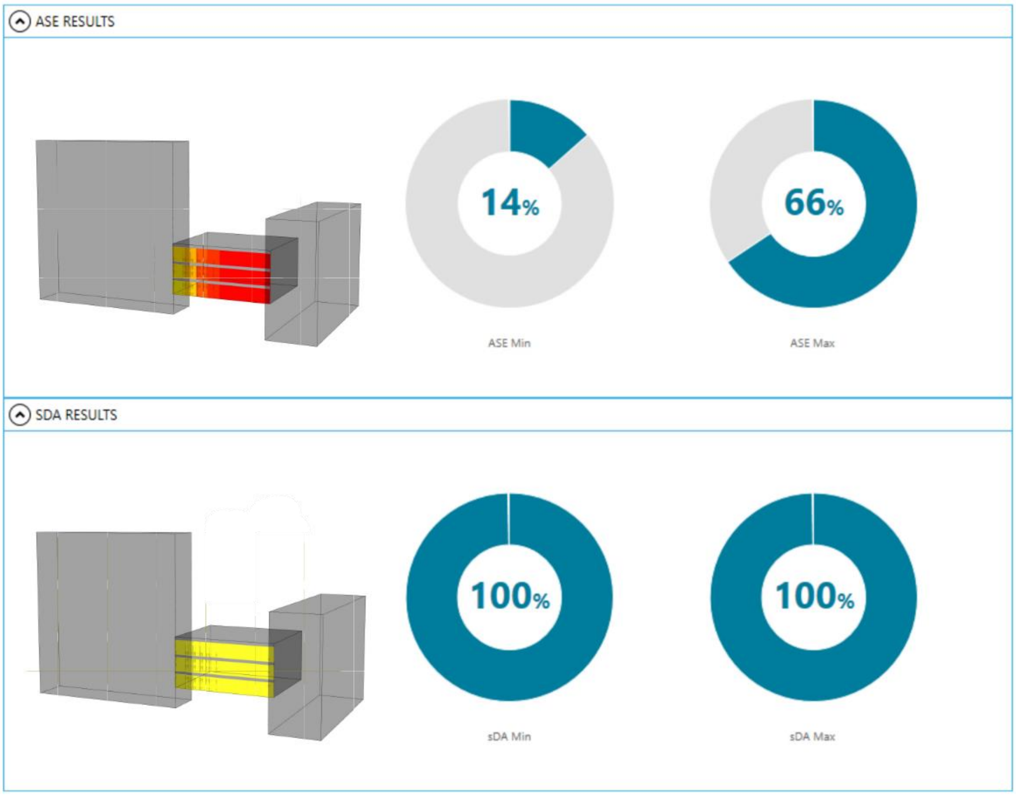


Figure 8-16: Flat façade results

The analysis carried out on the baseline model is crucial for the correct progress of the subsequent simulations: the rooms with the highest ASE and the lowest sDA will be considered as testing room for the different configurations since their closeness to the unacceptable range of values; the average room will be considered too.

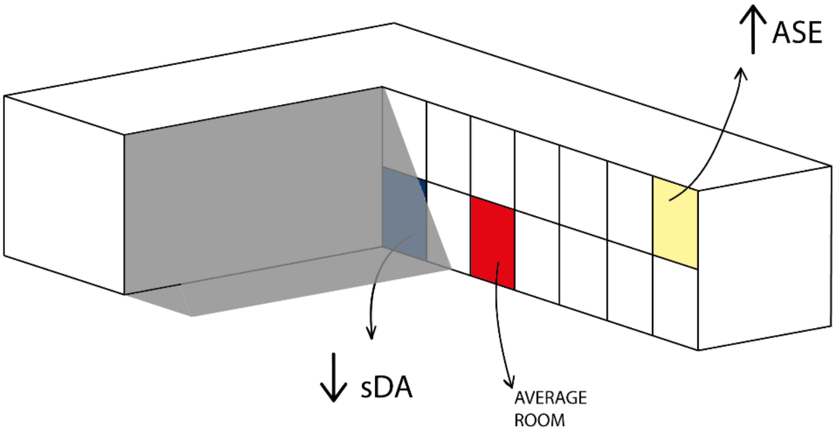


Figure 8-17: Example of rooms considered according to the values of ASE and sDA

For example, in Figure 8-17 the two rooms considered are the ones at the corners: the blue room will have the lowest value of sDA, since it is shielded by the other part of the building and the yellow room with the highest ASE in at the opposite corner on the top; it is not shaded by the building and it receives the highest amount of solar radiation. The red room, on the other hand, represents the average room of the façade.

The identification of these three rooms is a sensitive aspect of the process, especially considering their use in the following steps. In fact, the subsequent step is to test different geometries on a reference room. The choice of each room as the testing one has its own pros e cons, especially considering which optimization path the user wants to undertake; in the next paragraph, this issue will be explained.

8.4 PRELIMINARY ANALYSIS

Once the inputs are defined and the baseline case has been studied, it is possible to run the preliminary analysis. The first analysis is carried out considering only one room, which is evaluated by the plug-in after the outcome of the results of the baseline case; it is important to define which room has to be analyzed after this step, since it allows to understand the indoor conditions due only to the outdoor conditions and context and to not consider any shading. The process will continue with the form-finding process on the chosen room, in order to define the geometries allowing to have visual comfort and reduce the energy consumption according to the boundary conditions.

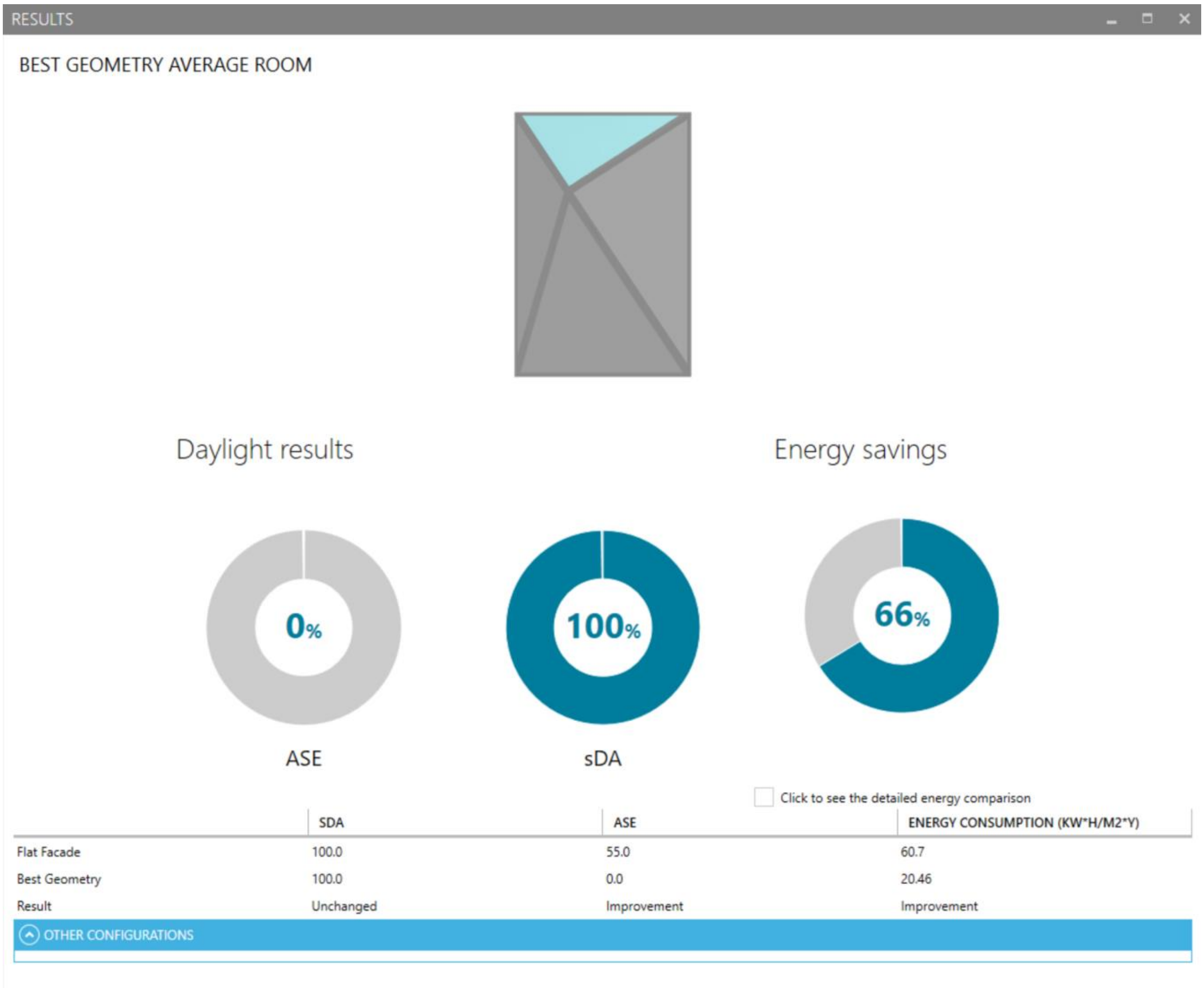
Between the suitable configurations the user will choose his favorite, which will be tested spreading it along the entire façade or with some slight variations, keeping constant the distribution of the materials and the geometry. During the first approach to this topic, the room chosen has been the one receiving the highest direct solar radiation, which is the one that in the baseline case has the highest value of ASE: it will be the room with more issues related to the satisfaction of the ASE requirements, so it will be harder to find a satisfactory configuration. The form-finding process through the testing of the different configurations has been done on that room, in order to analyze the worst condition and to obtain more conservative results. As a matter of fact, the analysis carried out to understand the behavior of the calculation procedure show that the ASE requirement is the hardest to be satisfied, since it is more restrictive; on the other hand, the value of sDA has a higher probability to be within the acceptable range. For these reasons, analyzing the one with the highest ASE will cull more configurations from the field of possibilities; once a configuration is suitable for that room, there is a higher possibility that the it will get acceptable results also for the other ones. On the other hand, if the chosen geometry will be then spread along the façade, in the rooms having lower ASE values (in the flat façade case) that configuration will probably get unacceptable sDA values. Due to this assumption, the choice later moved towards performing the preliminary analysis of the average room, which in most of cases has an ASE between the highest ones, due to higher number of rooms not shaded by the context compared to the one shielded.

Once the preliminary analysis is run on the average room, the best configurations are found between hundreds of different possible combinations and they will be shown to the user who will be then able to choose the one (or ones) he prefers.

8.4.1 Results tab

Once the simulation is completed, the plug-in will analyze the configurations and automatically cull the ones which are not satisfactory in terms of ASE and sDA. As said before, the simulations up to this stage are tested only in a single room and so the results will then be related to this room.

The tab will show firstly the best configuration among the ones tested, giving results in terms of ASE, sDA and energy; the energy is expressed in terms of energy saved, compared to the baseline case and it comprehend both the energy consumption and the energy production (if present); by clicking on the checkbox it is possible to see a comparative bar chart, which compares the differences between the flat façade and the best geometry considering all the components of the energy balance.



☐ Click to see the detailed energy comparison

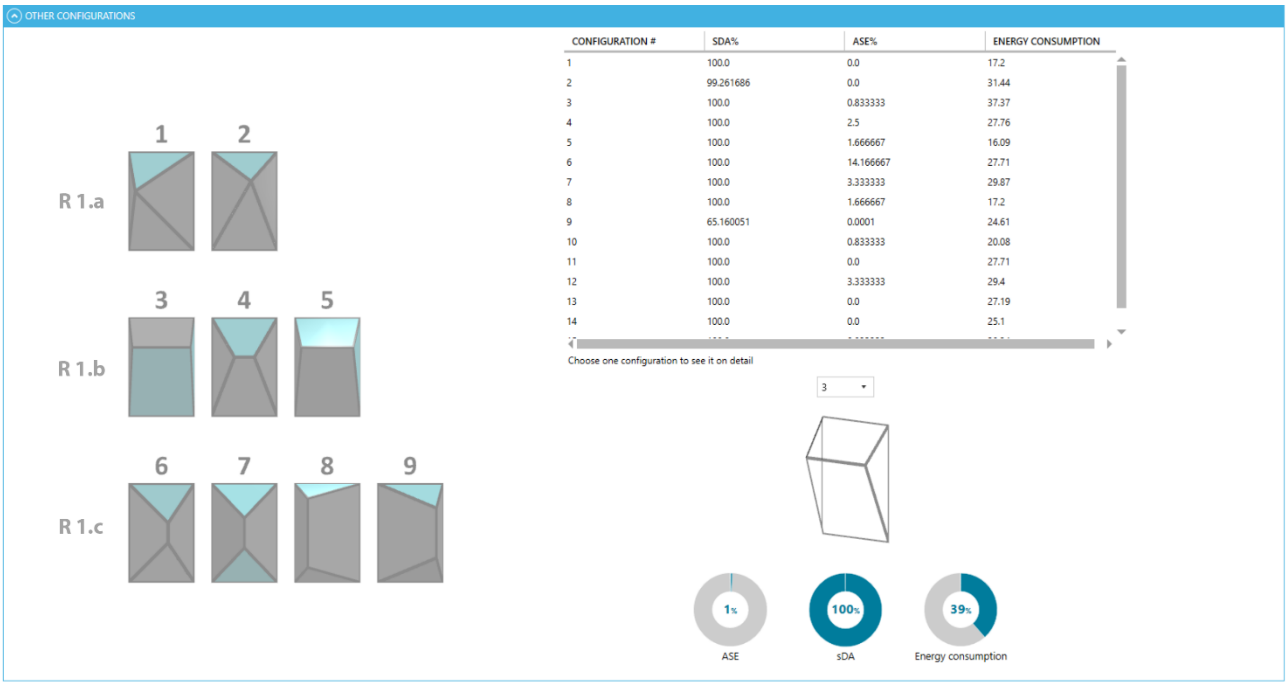
	SDA	ASE	ENERGY CONSUMPTION (KW*H/M2*Y)
Flat Facade	100.0	55.0	60.7
Best Geometry	100.0	0.0	20.46
Result	Unchanged	Improvement	Improvement

Figure 8-18: Results tab

The comparison between the best case and the flat façade in terms of the three parameters considered is shown in the table, highlighting if the result obtained is an improvement or a worsening. By clicking on the expander “Other configurations”, the user can see all the other suitable geometries and their statistics.

The geometries are shown sorted by family in the left-hand side of the screen, while on the right part the user will have a table reporting all the results of the configurations and a drop menu to select the number of configuration, to have a preview of the panel and the doughnut charts with its statistics. Moreover, the table gives the possibility to sort the values according to one of the three parameters:

this can be a useful tool if the user wants to choose a configuration giving more priority to one of the criteria.



CONFIGURATION #	SDA%	ASE%	ENERGY CONSUMPTION
1	100.0	0.0	17.2
2	99.261686	0.0	31.44
3	100.0	0.833333	37.37
4	100.0	2.5	27.76
5	100.0	1.666667	16.09
6	100.0	14.166667	27.71
7	100.0	3.333333	29.87
8	100.0	1.666667	17.2
9	65.160051	0.0001	24.61
10	100.0	0.833333	20.08
11	100.0	0.0	27.71
12	100.0	3.333333	29.4
13	100.0	0.0	27.19
14	100.0	0.0	25.1

Choose one configuration to see it on detail

3

Figure 8-19: Results tab for preliminary analysis

With the comparative table and all the other tools, the user has all the data to make a more conscious choice, regarding which panel should be used in the further steps along the façade.

8.4.1.1 Optimization failed

What if the optimization fails? It is possible that the simulation is not able to find an acceptable solution. This may be due to the preferences expressed as boundary conditions. First of all, it can be related to the preferences of the materials; let’s think to a façade exposed towards south, with a building in front of it shading it from south-west. As it can be imagined, if the user wants to have a left panel transparent and a right one opaque, this solution will not be an effective shading. The opaque panel on the right is not useful, since from that side the building is shielded by the context; on the other hand, the transparent panel on the right side, will leave the solar radiation pass, which is not blocked by any other building.

Another cause will be the number of simulations performed, which in some cases (very extreme) may be not enough to find a good configuration.

Once the optimization fails, a message appears at the end of the simulation process. Then the user can choose to not express preferences on the materials or at least to change them, making them less restrictive.

8.4.2 Pursuance of the optimization

At this point of the flow, the user has four opportunities given by the plug in. As the reader can imagine, once the calculation of parameters is done, the designer may have the freedom of creating and composing the façade as he prefers; this solution will imply the introduction of several variables to be considered in the flow, making the combinations thousands more. Moreover, each path the user wants to undertake needs a specific flow or at least a proper combination of the already existing sub-flows, which turns out to be a not passable path. For the reason explained, it was necessary to establish some preset paths, from the scripting point of view with the main con of limiting the power of choice of the user. Each flow has been designed specifically, disabling the other ones and trying to avoid not useful calculations which cause delay in the simulation process. The preset flows try to combine different aspects that can be interest of the designer beside the visual comfort: costs and aesthetics.

Here below the four options are explained:

8.4.2.1 Option A – Classic

The output of the preliminary analysis is a geometry optimized for a single room; nevertheless, the user can choose to apply that configuration to all the panels of the façade.

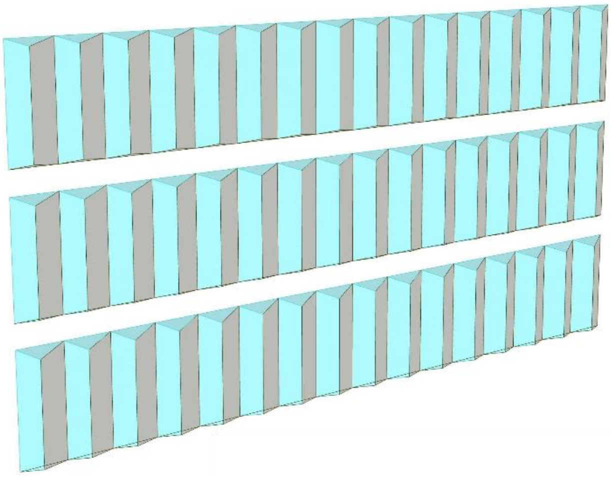


Figure 8-20: Generation of façade – Classic Option

This choice can turn up to be a good compromise under certain conditions: first of all, the application of a single panel may allow to economize from the production point of view. The configuration chosen has been tested on the average room, which means that for the most of the configurations, it will have both good values for ASE and sDA; on the other hand, there will be other rooms, which are the ones having a higher ASE in the flat façade analysis, that probably will be out of range, while the sDA should obtain good values on the entire façade.

As said in the previous paragraph, at the beginning the preliminary design was done on the room with the highest ASE, considering that if the configuration chosen guarantees an acceptable value of ASE in the most exposed room, the same configuration in other rooms would obtain a lower value of ASE, increasing the comfort. This implies that as opposed to what happens with the average room, the ASE is always satisfied; the opposite may happen to the sDA, which can have more rooms out of range, compared to the ones obtained with the average room analysis. Whichever of the two solutions implies that it is possible that Chameleon will not reach completely the optimization of the façade, so the decision was mainly between giving more importance to ASE, penalizing the sDA or giving the same importance to the two parameters, reaching only a partial optimization for both. The decision fell on the analysis on the average room.

From the aesthetic point of view, the user can have a preview of the façade right after the preliminary analysis, to choose among the best cases the ones that presents a good balance between the daylight comfort, the energy consumption improvement and the match with the aesthetic requirements of the designer. The preview shown at the end of the preliminary analysis is only referred to the aspect of the façade, since a simulation of the building with the same panel has not been carried yet. The analysis will be done in the optimization process. If the results on the overall building are not satisfactory, the user can go back to the choice of the panel, try other solutions and compare them.

At the end of the optimization analysis, in order to make the choice more immediate for the user, the plug in has the possibility of showing the façade with a gradient of colors, to represent which rooms satisfy more the comfort requirements: from green to red for the ASE and from blue to yellow for the sDA. This tool will help the choice adding a visual interpretation of the results.

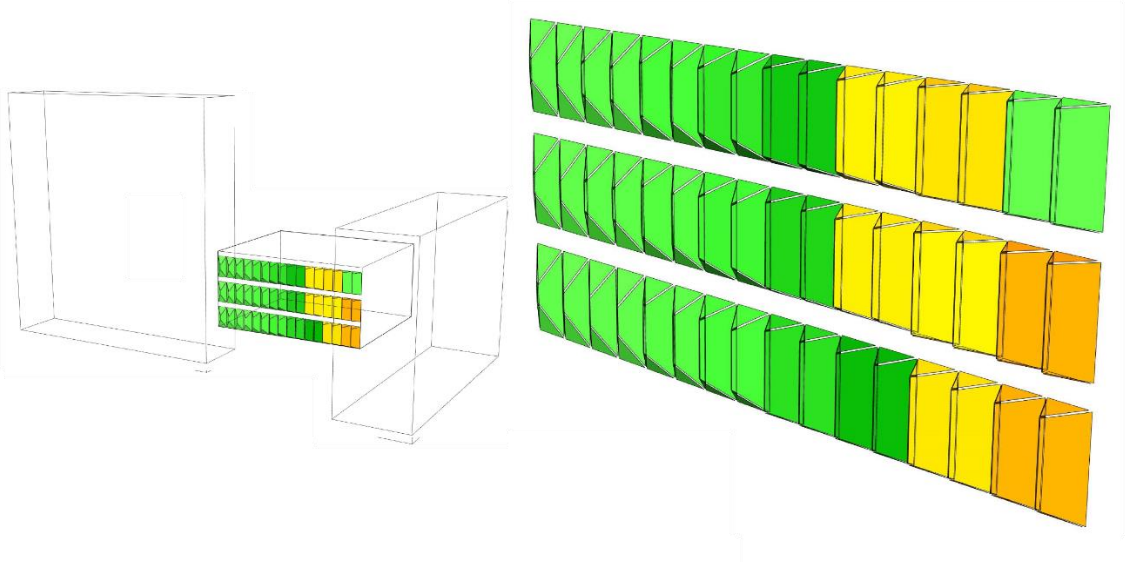


Figure 8-21: Preview of results – Classic Option

The choice of applying the same panel can be interpreted as a counter sense, since the tool has been designed to optimize the façade and the application of a panel that has been designed for only one room can seem going to the expense of a complete optimization. Nevertheless, this solution can have benefits especially in case the context is homogeneous and the income of solar radiation is comparable in each point of the façade considered and the same panel can be satisfactory in all the rooms, guaranteeing economical savings in production too.

On the other hand, the choice of this solution can be done most on the base of aesthetic aspect of the façade, meeting the requirements of the architect. In this case, the plug-in will show the critical issues (if any) and the designer will know that in that room the comfort is not guaranteed only by means of the envelope, but other solutions have to be considered.

8.4.2.2 Option B – Parametric

This solution has been developed starting from the option A, thinking about an improvement of the solution which sees the application of the same panel to the entire façade. As said before, this option can be preferred to limit the costs of production and to have a homogeneous architecture, despite a not complete optimization for each room of the building.

Once the user has chosen the panel (according to the daylight comfort, energy savings or visual preference), he can choose to optimize the façade using only panels having small and slight differences from the one chosen. The configurations in an initial approach to this solution were obtained with a script in Python which generates random combinations starting from the known values of the chosen one:

```python
import random
min_l=2
max_l=9
min_e=1
max_e=10
min_a=1
max_a=5
if(min_l<larghezza<max_l):
    largh = random.randint((larghezza-1),(larghezza+1))
elif(min_l==larghezza):
    largh = random.randint((min_l),(min_l+2))
elif(max_l==larghezza):
    largh = random.randint((max_l-2),(max_l))
if(min_e<estrusione<max_e):
    extr = random.randint((estrusione-1),(estrusione+1))
elif(min_e==estrusione):
    extr = random.randint((min_e),(min_e+2))
elif(max_e==estrusione):
    extr = random.randint((max_e-2),(max_e))
if(min_a<altezza<max_a):
    alt = random.randint((alt-1),(alt+1))
elif(min_a==altezza):
    alt = random.randint((min_a),(min_a+2))
elif(max_a==altezza):
    alt = random.randint((max_a-2),(max_a))
print largh, alt, extr
```

Figure 8-22: Python script for geometry generation

The chosen values of width, height and extrusion are recorded inside Python and the dimensions of the configurations to be tested are calculated in a range +1/-1 starting from the value. As seen previously, each geometrical dimension can vary inside a range: length between 2 and 9, extrusion between 1 and 10 and height between 1 and 5. If the starting value is equal to the maximum or minimum, the value of the geometry can assume a value equal respectively to the maximum -2 or the minimum +2.

For example, width can vary between 2 and 9; if the chosen geometry has a width equal to 2, the new value can assume values between 2 and 4.

Further analysis on the baseline case, paired with the considerations made in par. 6.3 allowed us to bypass the creation of geometries in Python, but directly obtain them from the outputs of the baseline analysis. In fact, the results of the radiation analysis carried out in par. 6.3 showed that it was possible to establish a relationship between the solar radiation, the daylight values and the geometrical morphology of the module; as a matter of fact, a certain combination of extrusion, height and width and relative materials can lead to a shielding or transit of the solar radiation, which implies a change in the values. As a consequence, if the plug-in optimizes the room with the highest ASE and lowest sDA according to the baseline case analysis, since the radiation on the façade vary smoothly, all the suitable geometries can be obtained with smooth changes starting from the configuration of one room to the one of the other. The procedure expects that the user selects a configuration in the preliminary analysis results tab; this selection (keeping family and distribution of materials fixed) will be optimized for the two rooms, in order to evaluate the changes in geometry to meet the visual comfort requirements. The two results will be used as extremes of the domain for the generation of the geometries of the façade. Moreover, since the preliminary analysis studies the average room, knowing exactly its position along the façade, there will be a third known geometry to be added, which gives many more information about the smooth change and its distribution in the different rooms.

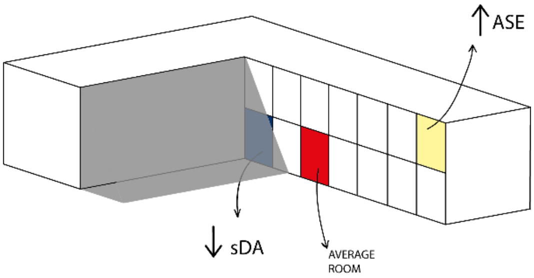


Figure 8-23: Example of the building

Let's considered the example of the picture: the rooms which will be optimized are the ones on the two corners. Let's assume that the best configuration for the "blue room" has a height equal to 5, in order to have a higher amount of solar illuminance passing through the envelope, the "yellow room" has a height equal to 1 to block the direct illuminance, while the "red one", which is the average room has an height of 2; since the radiation is homogeneously distributed along the façade, the height will be spread according the change in ASE of the reference case, considering as fixed points the three heights. The same will be done with the other geometrical parameters obtaining a smooth change in the façade shape.

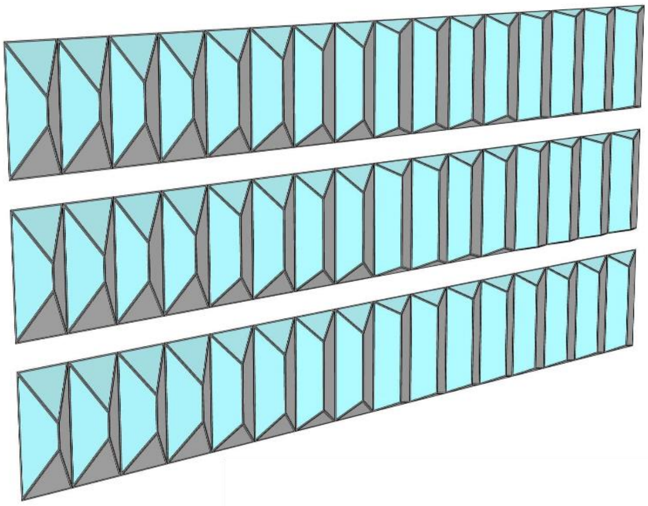


Figure 8-24: Generation of façade – Parametric Option

Obviously, after the generation of the geometries for all the rooms, they need to be tested to verify if the geometry that has been created actually reaches acceptable values of ASE and sDA.

This solution has been developed to obtain a higher visual comfort, with a final façade which will have a sort of homogeneity, avoiding panels with relevant differences one from each other.

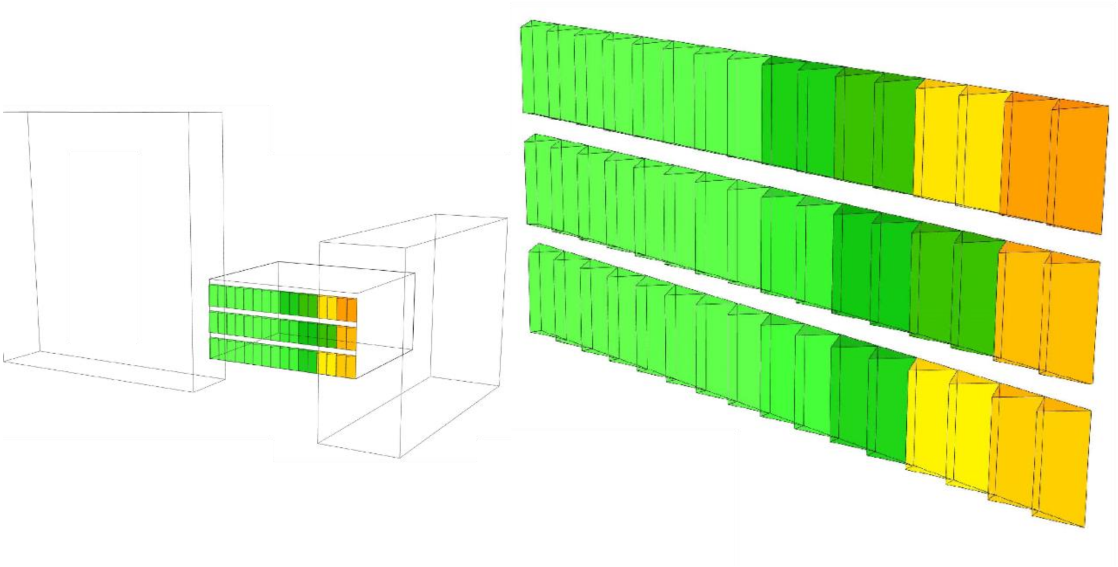


Figure 8-25: Preview of results - Parametric option

8.4.2.3 Option C – Random Generation

The third option is the one which theoretically may guarantee the best optimization for each room. Each room is analyzed and at the end of the optimization the output will be the best configuration for the façade; as it can be imagined, since the optimization is done trying all the rectangular sub-families, the output will be probably composed by panels of different families, with no necessarily visible trends from the point of view of the different geometrical parameters. For this reason, this option is the one which allows less freedom for the user and less homogeneity in tiling.

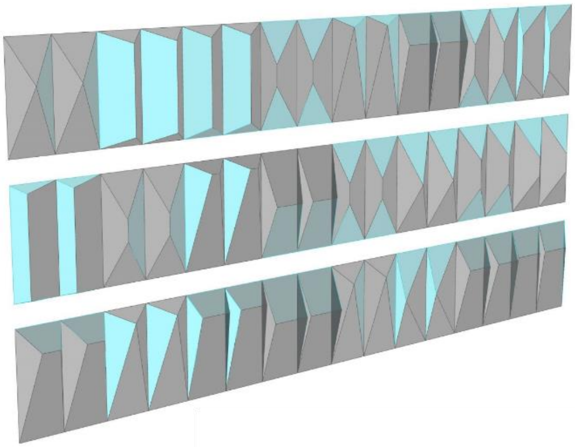


Figure 8-26: Generation of façade - Random option

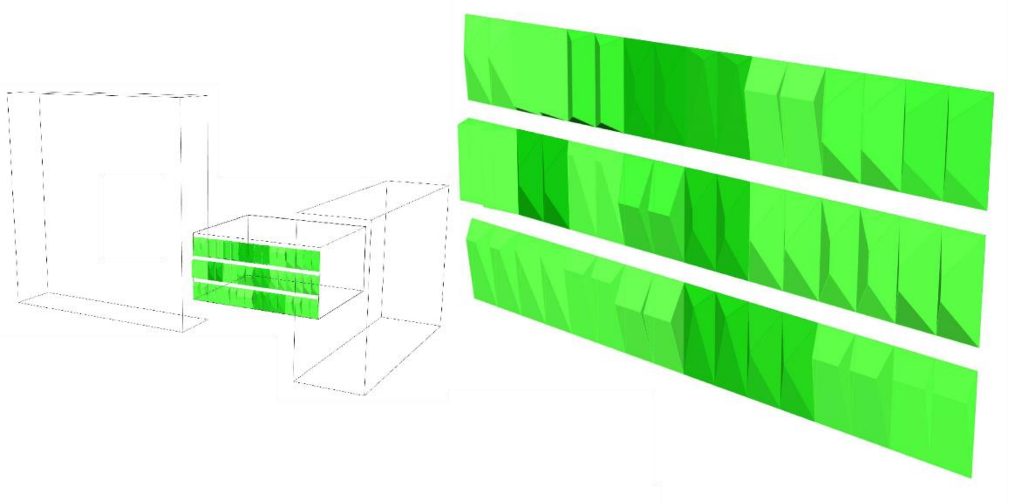


Figure 8-27: Preview of the results - Random Option

Nevertheless, it is possible to create a uniformity between the different panels, expressing some preferences on the materials; the plug in will test only configurations composed by materials as expressed in the preferences.

For example, if the preferences are top=opaque, left, right and bottom=transparent, the outcome of the simulation will be a façade composed by different geometries, but with the previous distribution of materials. The opaque panels may be also customized with some oriented patterns, colors and so on, trying to make the geometry as homogeneous as possible.

8.4.2.4 Option D – Artistic

This option is the one that allows the user to express his will the most. All the families of geometry considered have a different number of control points that can move along the three axes. As it can be imagined, the geometries can be also ordered along the façade with increasing\decreasing values for each of the parameters considered. The result will be a regular movement of the façade, obtained considering a variation of only one parameter or the combination of variation of more parameters together (e.g. increasing height, decreasing width).

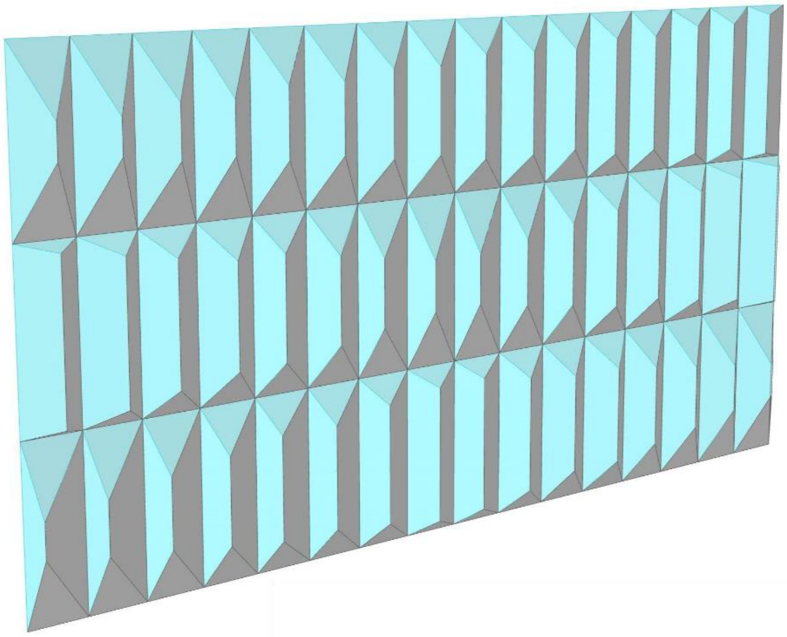


Figure 8-28: Generation of façade – Artistic Option

The generation of the geometries has been done with a script in Python. This process up to now allow the user to choose the trend along one floor (in horizontal) or along the floors (in vertical); further implementation of this method will obtain the combination of the two processes, allowing the user to choose the trend both in horizontal and in vertical. To explain the method, the horizontal trend will be considered. The façade is divided in columns, one for each panel of a row; in this way it is possible to recognize the "control column", which is the room in the middle or the two central ones according if the number of rooms is odd or pair. This action is required because the system lets the user choose two trends for each floor, one on the right-hand side of the control room and the other one on the left-hand side, as seen in the following picture:

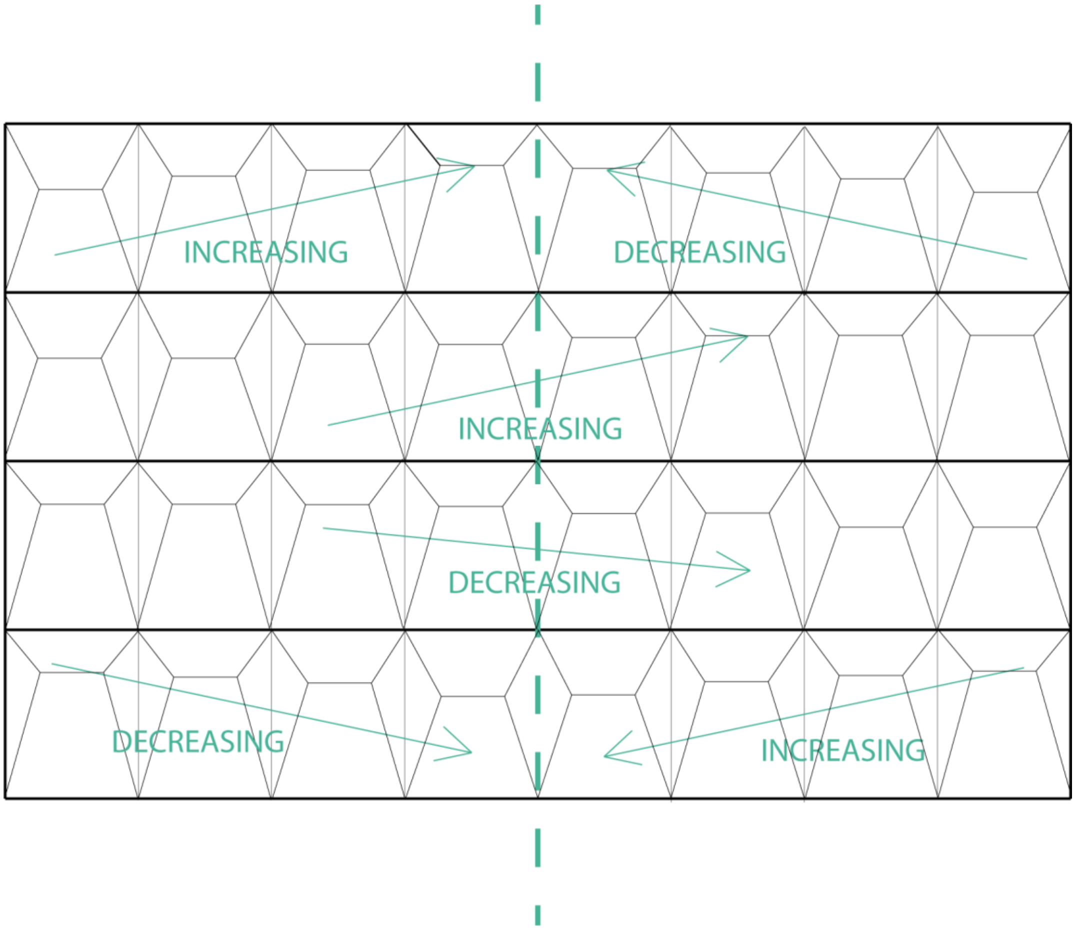


Figure 8-29: Possible trend choices for each floor

As it can be seen, if the number of rooms is pair and along the floor there are two different trends, the maximum (or the minimum) value will be in the rooms adjacent to the control line; on the other hand, it will be in the control room.

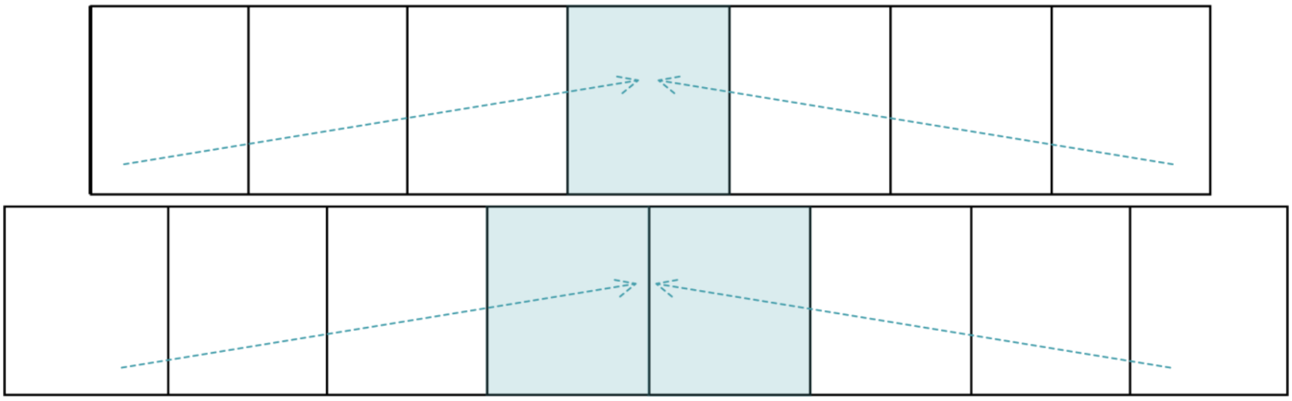


Figure 8-30: Control room according to the number of rooms

The user can choose the trend of each floor, using pull-down menus, two for each floor of the building, representing the two trends that can be chosen, obviously if the user wants only one trend, he will be choose on both menus the same trend and the script in Python will automatically recognize it:

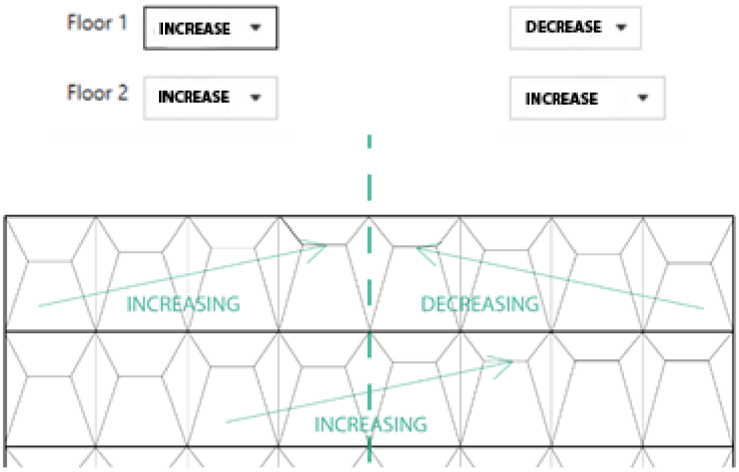
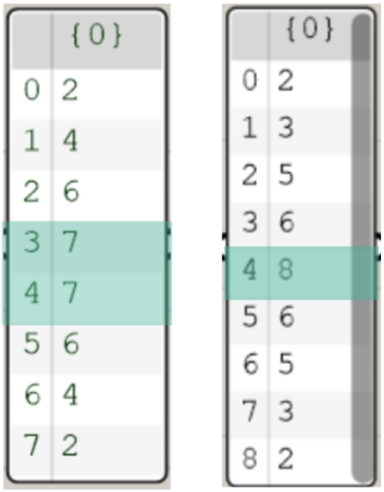


Figure 8-31: Choice of trend for each floor

What the plug-in asks to the user is to choose two on three geometrical parameters, that will be the ones that he can choose the trend for, while the other is left free to vary inside its range. From the interface, the python script will receive a list of increase/decrease that will be used to organize the trend and generate the geometries.

To make the reader understand the process, we can make the example reported in the Figure 8-31, where the trend is increasing before the control line and it decreases after the control line. If the parameter chosen is the extrusion, the range of values of the extrusion is from 2 to 9, the delta between them is then divided in four (one for each room) and rounded after this process; each half floor has the values of the geometrical dimension stored in one temporary string, which will be reverted to create the other half; each time a floor is completed, the values are stored in a permanent string which will be the output of the python component and will be used to create the geometry.

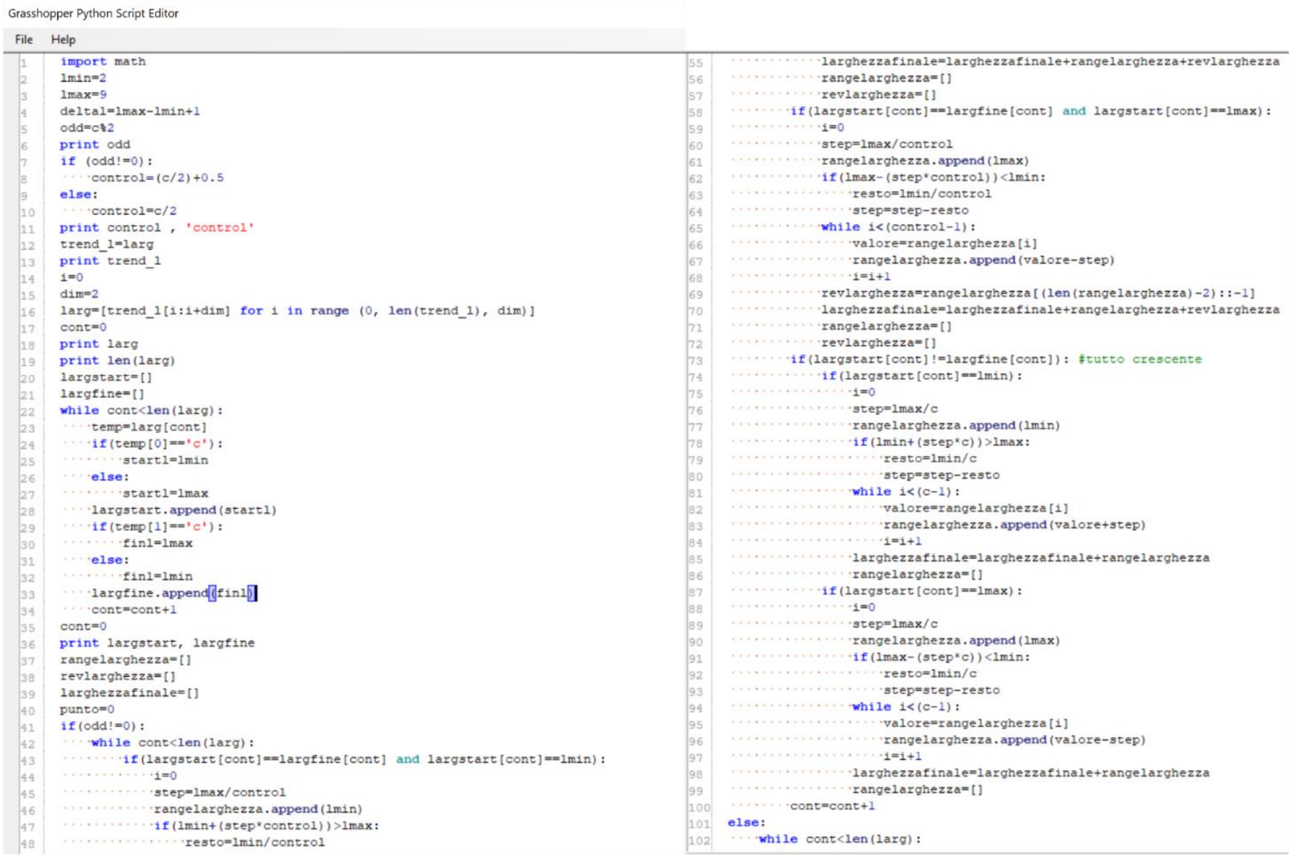


	{0}
0	2
1	4
2	6
3	7
4	7
5	6
6	4
7	2

	{0}
0	2
1	3
2	5
3	6
4	8
5	6
6	5
7	3
8	2

Figure 8-32: Range for pair and odd number of rooms

On the other hand, if the trend is the same along the façade, the range of numbers will be divided in eight parts and then rounded, without the need of using the reverse list.



```
import math
lmin=2
lmax=9
deltal=lmax-lmin+1
odd=c%2
print odd
if (odd!=0):
    control=(c/2)+0.5
else:
    control=c/2
print control , 'control'
trend_l=larg
print trend_l
i=0
dim=2
larg=[trend_l[i:i+dim] for i in range (0, len(trend_l), dim)]
cont=0
print larg
print len(larg)
largstart=[]
largfine=[]
while cont<len(larg):
    temp=larg[cont]
    if(temp[0]=='c'):
        startl=lmin
    else:
        startl=lmax
    largstart.append(startl)
    if(temp[1]=='c'):
        finl=lmax
    else:
        finl=lmin
    largfine.append(finl)
    cont=cont+1
cont=0
print largstart, largfine
rangelarghezza=[]
revlarghezza=[]
larghezzafinale=[]
punto=0
if(odd!=0):
    while cont<len(larg):
        if(largstart[cont]==largfine[cont] and largstart[cont]==lmin):
            i=0
            step=lmax/control
            rangelarghezza.append(lmin)
            if(lmin+(step*control))>lmax:
                resto=lmin/control
```

```
            larghezzafinale=larghezzafinale+rangelarghezza+revlarghezza
            rangelarghezza=[]
            revlarghezza=[]
        if(largstart[cont]==largfine[cont] and largstart[cont]==lmax):
            i=0
            step=lmax/control
            rangelarghezza.append(lmax)
            if(lmax-(step*control))<lmin:
                resto=lmin/control
                step=step-resto
            while i<(control-1):
                valore=rangelarghezza[i]
                rangelarghezza.append(valore-step)
                i=i+1
            revlarghezza=rangelarghezza[(len(rangelarghezza)-2)::-1]
            larghezzafinale=larghezzafinale+rangelarghezza+revlarghezza
            rangelarghezza=[]
            revlarghezza=[]
        if(largstart[cont]!=largfine[cont]): #tutto crescente
            if(largstart[cont]==lmin):
                i=0
                step=lmax/c
                rangelarghezza.append(lmin)
                if(lmin+(step*c))>lmax:
                    resto=lmin/c
                    step=step-resto
                while i<(c-1):
                    valore=rangelarghezza[i]
                    rangelarghezza.append(valore+step)
                    i=i+1
                larghezzafinale=larghezzafinale+rangelarghezza
                rangelarghezza=[]
            if(largstart[cont]==lmax):
                i=0
                step=lmax/c
                rangelarghezza.append(lmax)
                if(lmax-(step*c))<lmin:
                    resto=lmin/c
                    step=step-resto
                while i<(c-1):
                    valore=rangelarghezza[i]
                    rangelarghezza.append(valore-step)
                    i=i+1
                larghezzafinale=larghezzafinale+rangelarghezza
                rangelarghezza=[]
        cont=cont+1
else:
    while cont<len(larg):
```

Figure 8-33: Python script for the generation of the configurations

Obviously, this method mainly aims to achieve an aesthetic effect, following the trend designed by the architect, but it may happen that the trend chosen by the user is not satisfactory in terms of comfort, since the optimization is mainly architectonic rather than targeting the visual comfort. The final visualization will be the optimized façade with the gradient from green to red, in order to understand how many rooms are filling or not the prescriptions for the comfort.

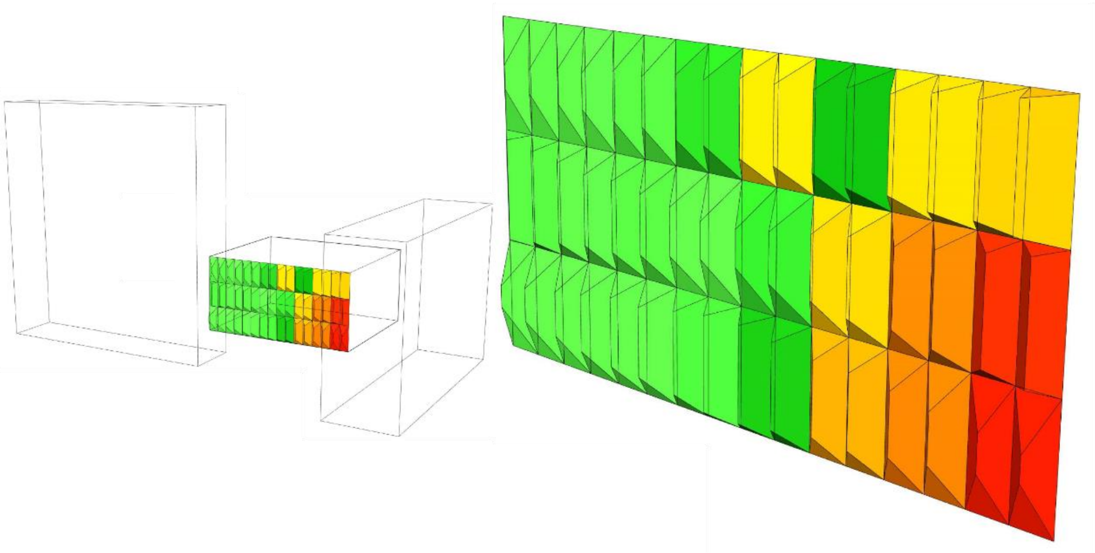


Figure 8-34: Preview of the results – Artistic Option

8.4.2.5 RESULTS

All the optimization processes have the same layout for the results window. First of all, the tab is divided as for the baseline case into two expanders, one for the ASE results and one for the sDA. Opening each of them, the façade will be shown both in a realistic visualization mode and with a range of colours to describe the goodness of the results obtained for the value in each room. Besides the doughnut charts will report maximum and minimum values for ASE and sDA, according to the following thresholds:

	ASE	*sDA*
IN	<10%	>75% (3 Leed pts.)
ACCEPTABLE	10%<ASE<15%	55%<sDA<75% (2 Leed pts.)
OUT	>15%	<55%

Figure 8-35: Threshold for ASE and sDA

Two gauge-charts will show how many rooms fit the requirements and are inside the comfort range, how many will be acceptable or out of the range compared to the flat façade case. Lastly, the energy consumption will be shown expressing it as a reduction percentage from the flat façade case.

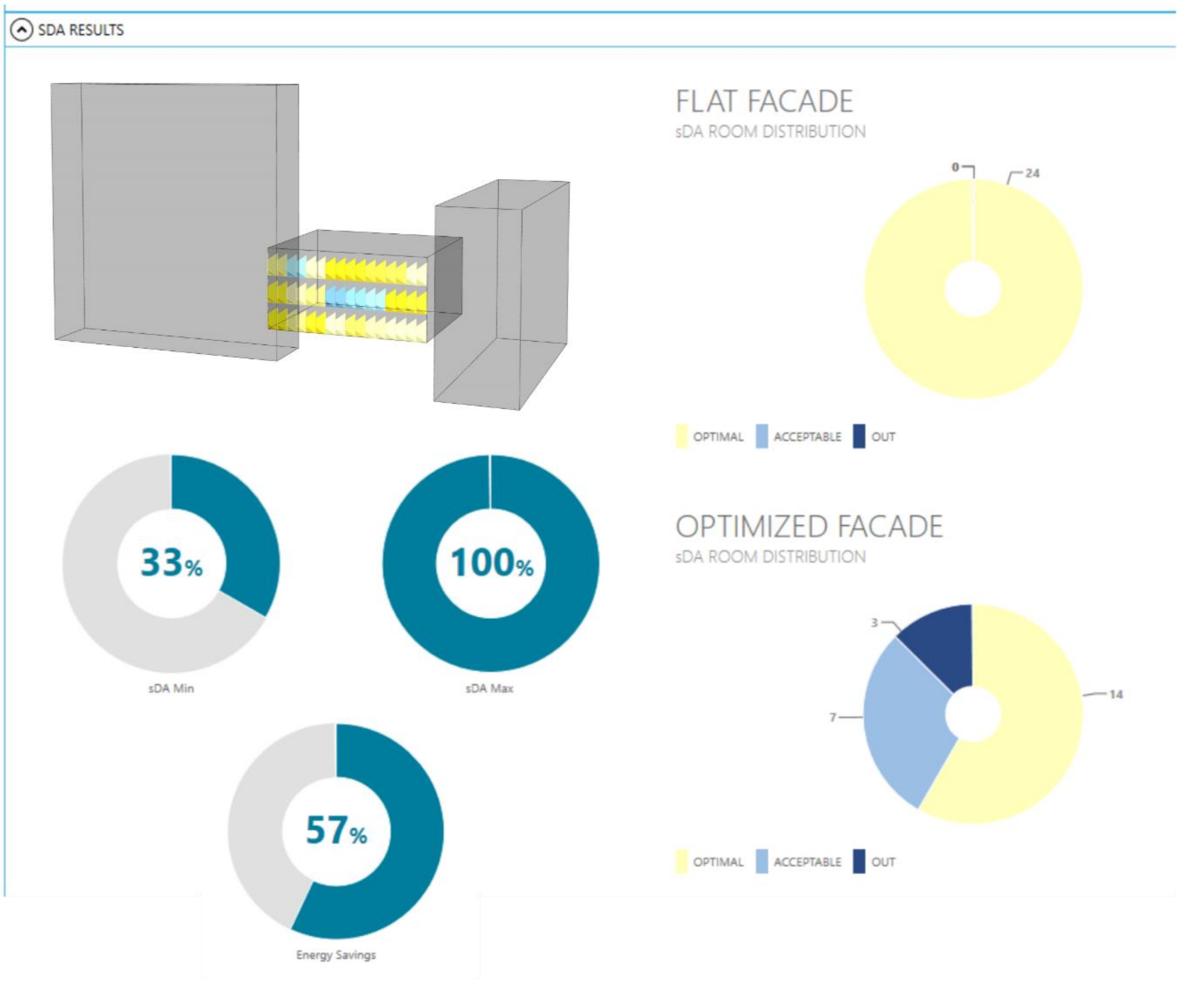


Figure 8-36: sDA Results panel

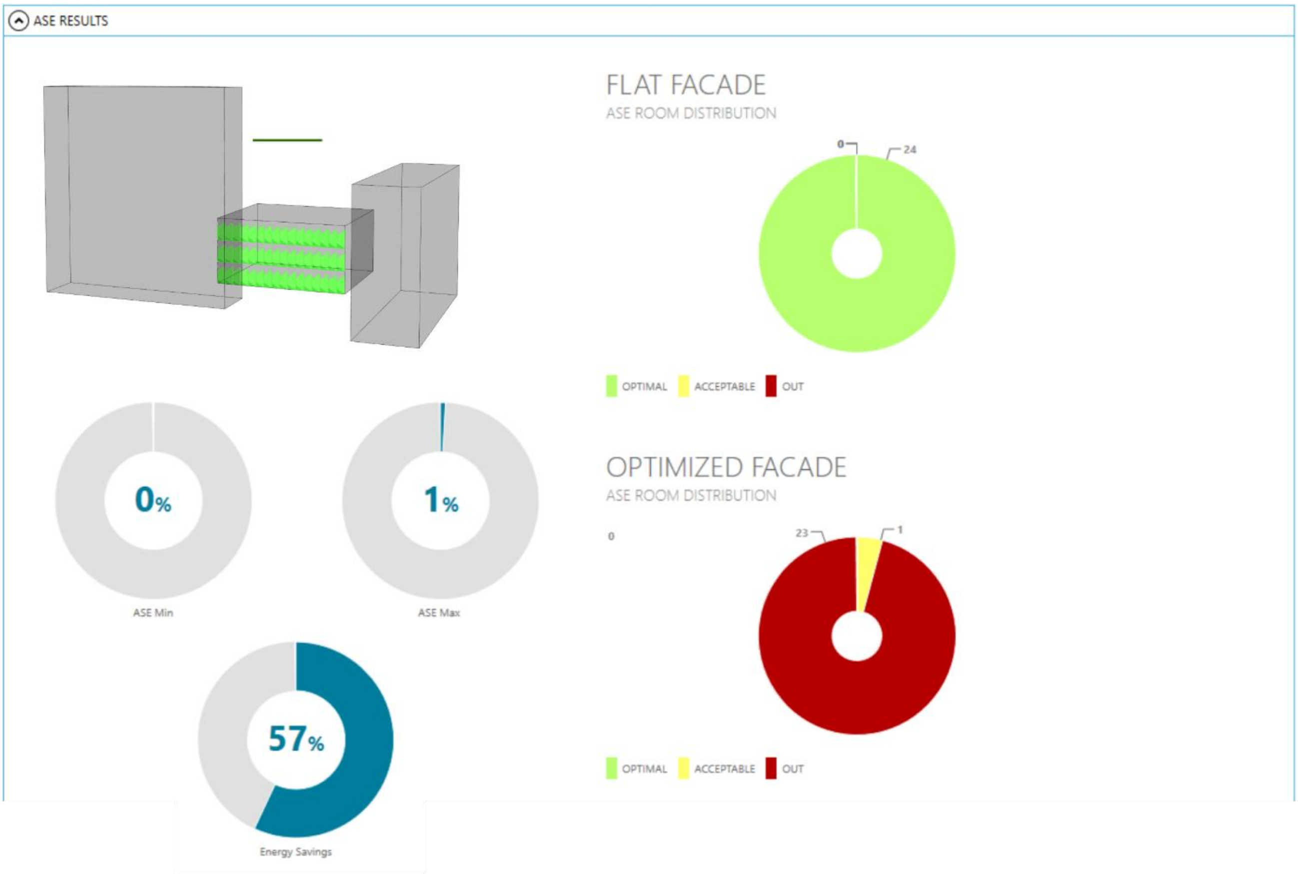


Figure 8-37: ASE Results panel

8.4.3 End of optimization

Once the optimization is completed and the user decides the final configuration, which suits better the set requirements for the project, he will be able to Bake the geometry on Rhinoceros 3D directly from Chameleon's interface, getting a 3D model which can be used from other tools. Along with the geometry the user will receive a table reporting all the data required for the production of the panels: each panel will be numbered and it will report the list of materials and the values for height, width and extrusion.

9. CASE STUDY: “NAVE” BUILDING, POLITECNICO DI MILANO

Once Chameleon has been defined completely, both in terms of flow, choice options and interface, it has been decided to test it considering a real building, in order to enhance the work done and the results which can be obtained with the plug-in.

The choice of the building fell on one of the buildings of Leonardo Campus of Politecnico di Milano, mainly to use a building which is well known. In particular, the building chosen is the Building 14. This choice is due to the geometry of the building and the context: to show effectively the potential of the plug-in, it was necessary to study a building with many floors (in order to show in a more effective way the changes in the trend along the façade, for optimization options B and D) and with a non-homogeneous context, to have different results in the different rooms. Considering all the previous requirements, the “Nave” building was the best option.

The chapter will show the results of the optimization, describing the reasonings which guided the process and the choices, underlining which solutions and optimization options are good and describing the potential problems. On the other hand, in the final part of the chapter the same building will be hypothetically placed in other cities, at different latitudes to see the change in shape, combination of materials to obtain in all of them the visual comfort and the reduction of energy consumption.

9.1 PRELIMINARY ANALYSIS

The 3D model of the building has been imported in Rhino with its surrounding context. In order to reduce the time needed for the simulations, the context has been slightly simplified (e.g. the different AHUs on the roofs have been compacted in only one rectangular box and other particularities of the geometry have been schematized as rectangular boxes).

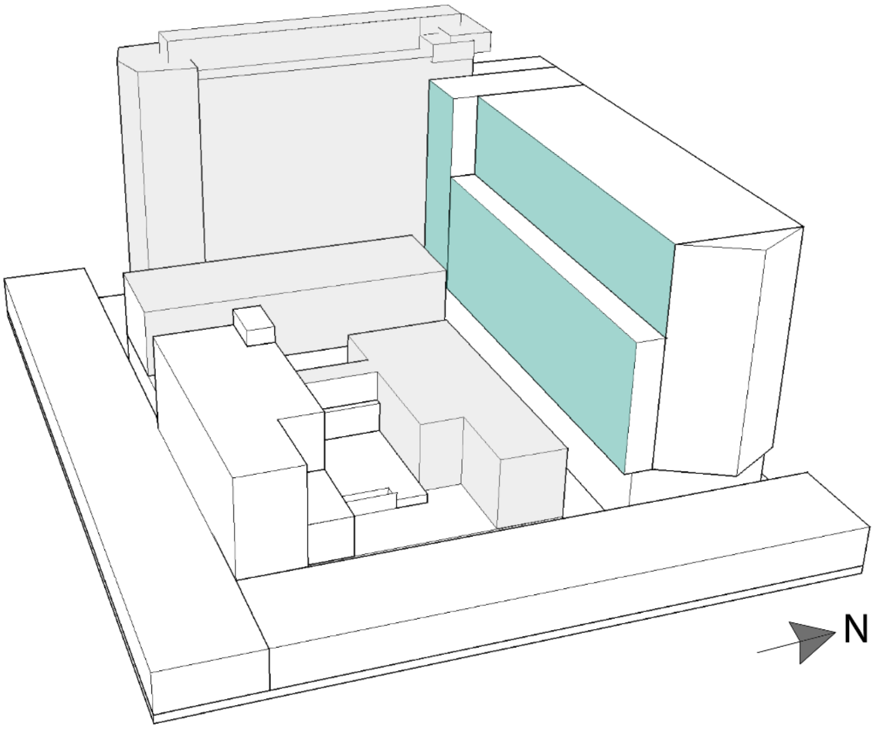


Figure 9-1: Building 14 and context

The façade considered is the coloured one, chosen for its southern exposition and the building which are creating a shade on it are the grey ones.

In particular, the sun path around the building has been analysed too:

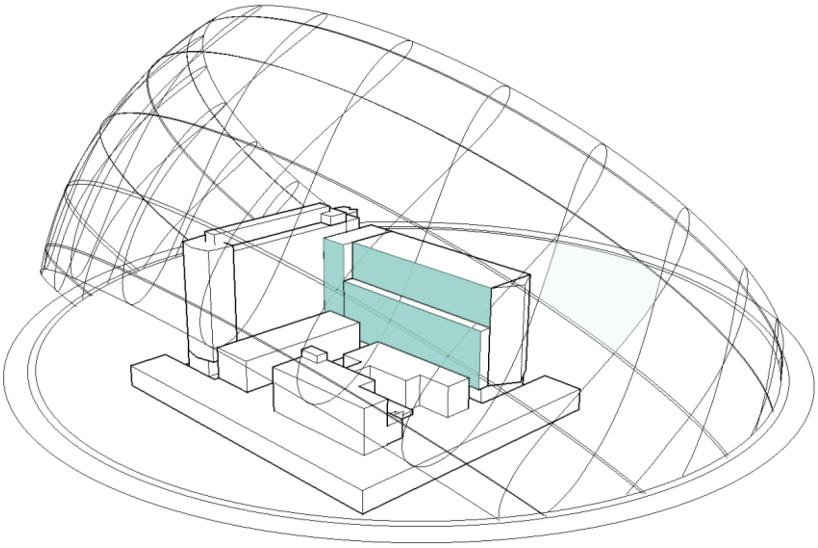


Figure 9-2: Sunpath for Building 14

The sun path has been used mainly to consider which buildings had an influence on the façade studied; the ones not producing a shade on the façade were automatically cut to simplify the calculation and to reduce the time needed for the simulation. It is also possible to make previsions on the probable configurations that will be generated with this context.

9.1.1 Study of the baseline case

Once the model has been set and the buildings assigned in Grasshopper in a correct way, dividing them between building and context, Chameleon defines the baseline case and runs the simulation for that. As seen in Chapter 8.3, the baseline case is designed starting from the number of divisions of the room chosen by the user, assigning a glazed area equal to the 60% of the total. Since the inter-storey height is around 6 meters, it has been chosen to apply a spandrel in order to reduce the dimension of the panels. The baseline case runs sDA, ASE and energy consumption analyses and the results are shown below:

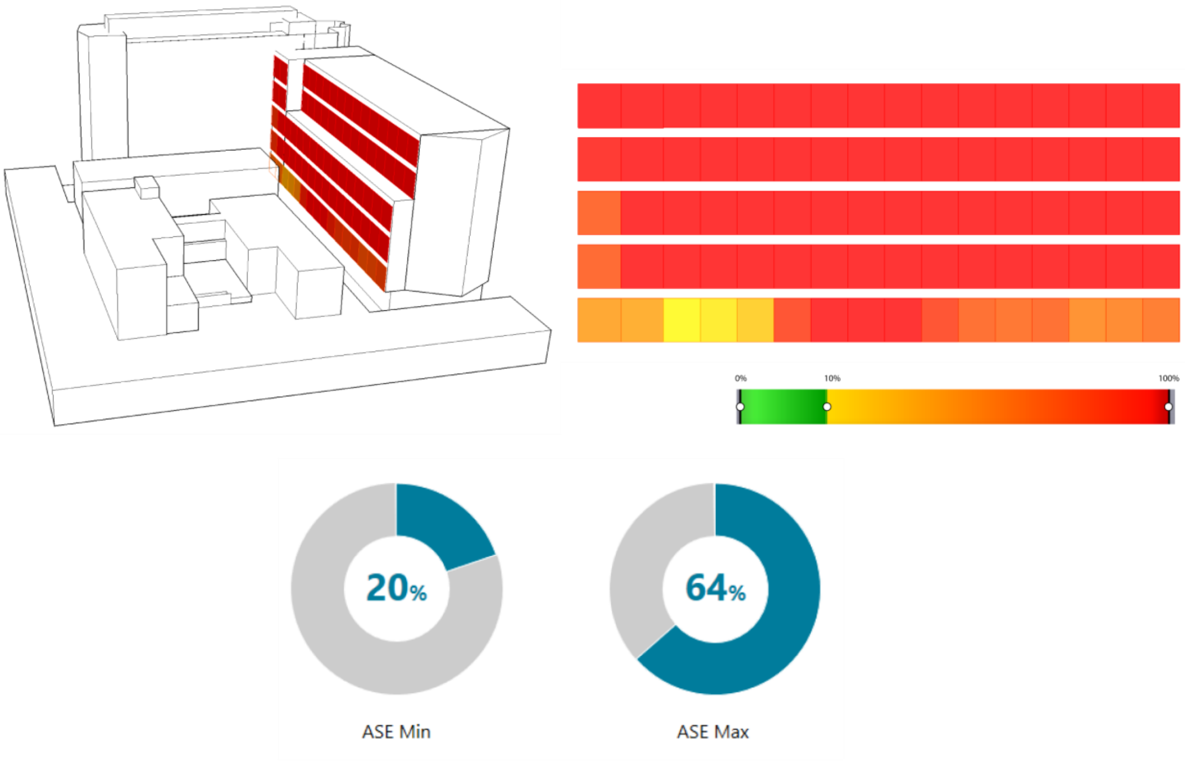


Figure 9-3: ASE Results - Baseline Case

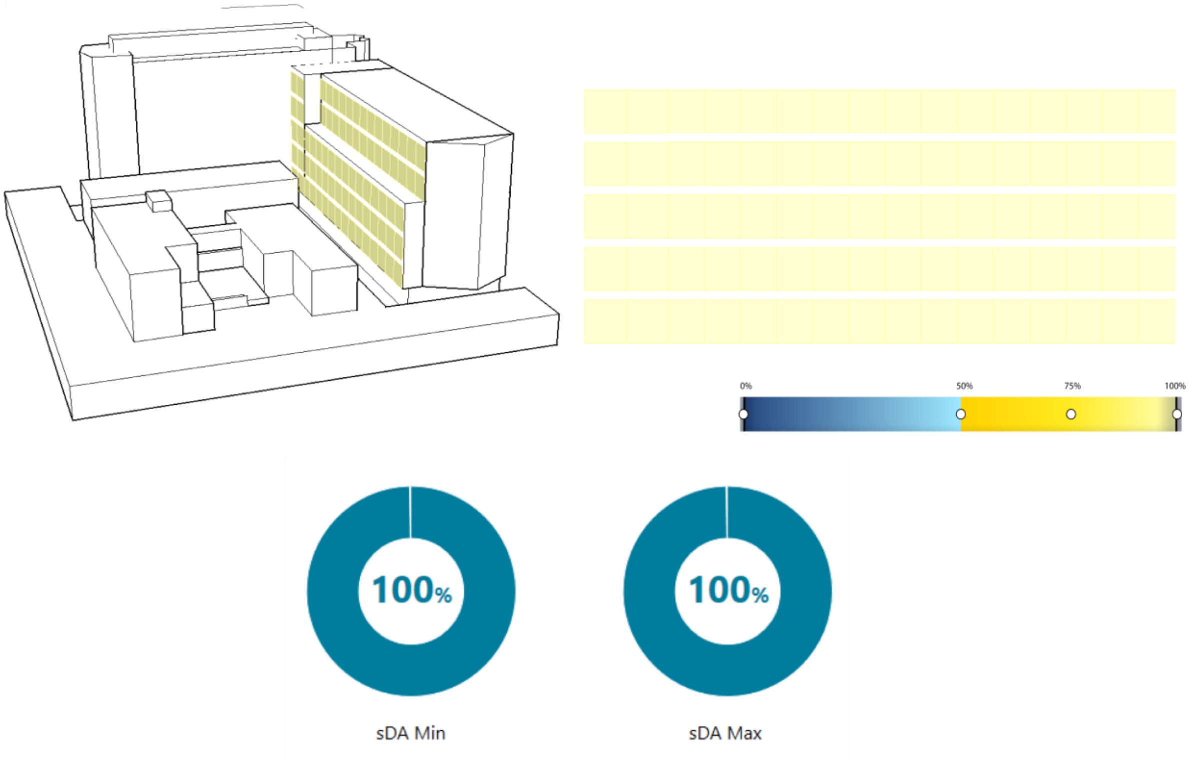


Figure 9-4: sDA Results – Flat façade case

As it can be seen, the Annual Sunlight Exposure is out of range in all the rooms of the building, its minimum value, which is 10% higher than the acceptable threshold is only reached in two rooms on 79. As it can be seen from the gradient coloured façade, the lowest values are only reached in the bottom part of the building, where the rooms are more shielded by the context. On the other hand, the spatial Daylight Autonomy reaches 100% in all the rooms considered. As the reader can imagine, the further optimization will have to work especially towards the reduction of the ASE, which may probably bring to a reduction of the value of the sDA too.

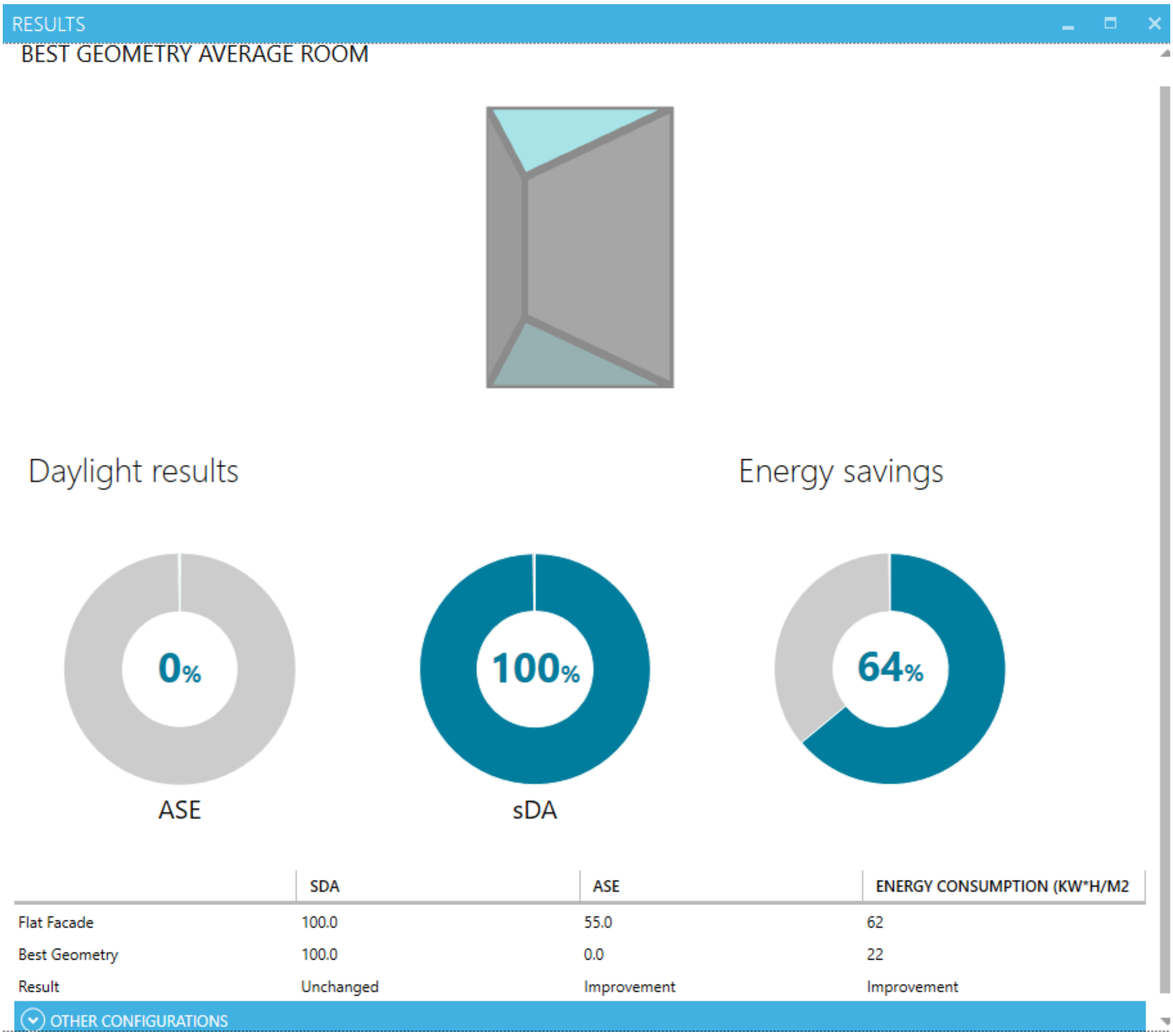
The energy consumption has been calculated, but for the reasons explained in the previous chapter, they are not shown at this stage, but only in the subsequent ones, in order to make comparisons.

9.1.2 Preliminary analysis

Once the baseline case is studied, it is possible to define which is the room to be analyzed in the preliminary analysis, to test the different geometries, which is according to the assumptions made in Chapter 8.4 is the average one. To carry out this simulation no preferences on materials have been expressed, but it has been kept the default option, to let the tool explore more possibilities and options.

9.1.2.1 Results

The result of the preliminary simulation is a geometry belonging to R3 family, as shown in the following picture; along with the values of ASE and sDA, a stack bar chart shows the changes referred to the baseline case of all the components considered in the energy balance.



	SDA	ASE	ENERGY CONSUMPTION (KW*H/M2
Flat Facade	100.0	55.0	62
Best Geometry	100.0	0.0	22
Result	Unchanged	Improvement	Improvement

Figure 9-5: Preliminary analysis results - Building 14

As it can be seen, it is a configuration composed by two panels opaque (right and left) and the top and bottom ones transparent. It has been used for the option A of the optimization.

9.1.3 Optimization

According to the optimization process carried out, a different geometry has been chosen for each optimization process, in order to show different outputs and final shapes. In this part of the chapter the starting conditions and the results of each optimization have been reported.

9.1.3.1 Option A – Classic

Since the output result of the preliminary analysis is the best configuration on the average room, it was the best geometry to be tested in this kind of optimization.

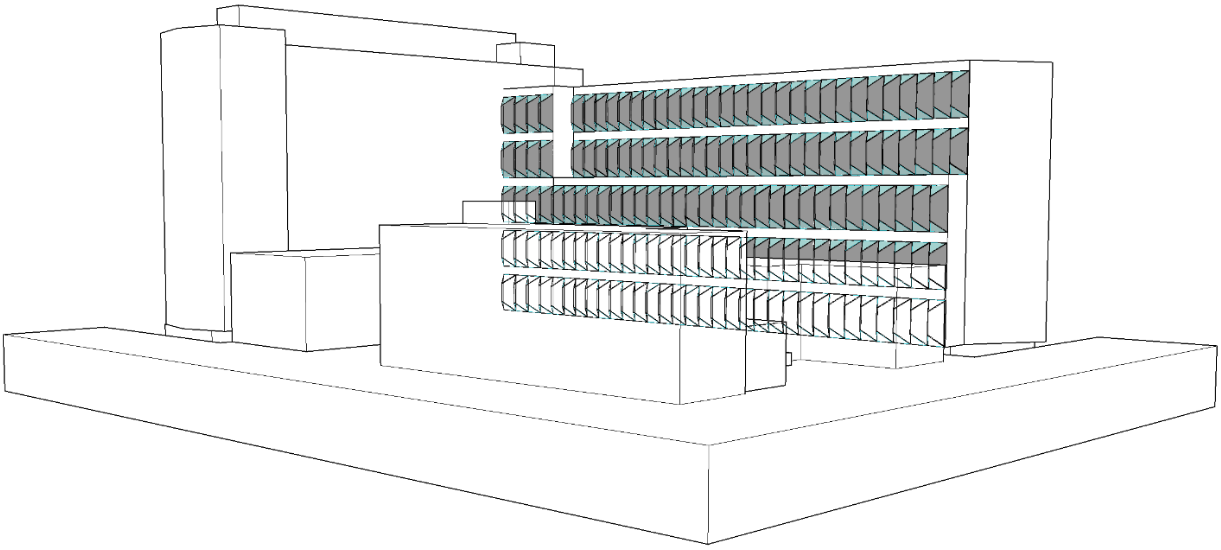


Figure 9-6: Option A – Preview of the façade

Results

As it can be seen in the following picture, reporting the results of the ASE for Classic optimization option, the chosen configuration allows to obtain that all the rooms satisfy the requirement. This result validates the goodness of the choice explained in the previous chapter to consider as testing room the average one.

This configuration having the top panel transparent can obtain good ASE values since the high position of the glazing avoids the concentration of the direct radiation in a small portion of the floor increasing the hours of exposure.

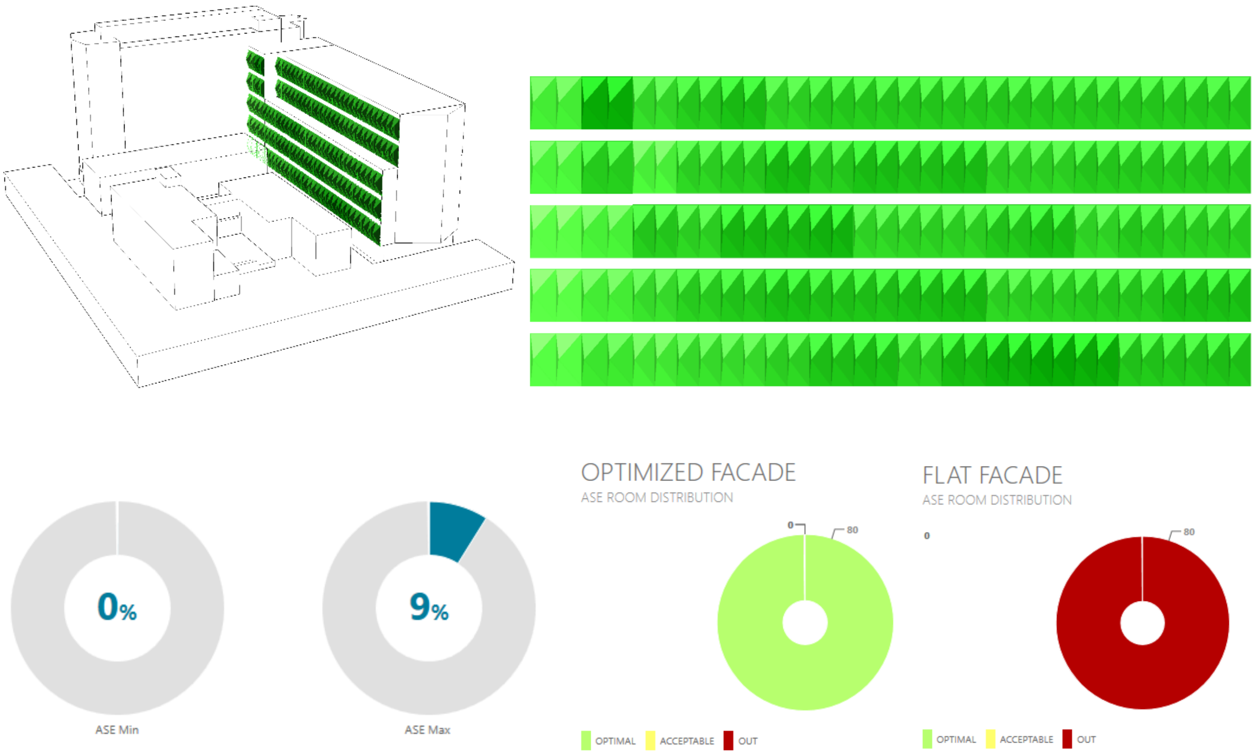


Figure 9-7: ASE Results – Classic optimization

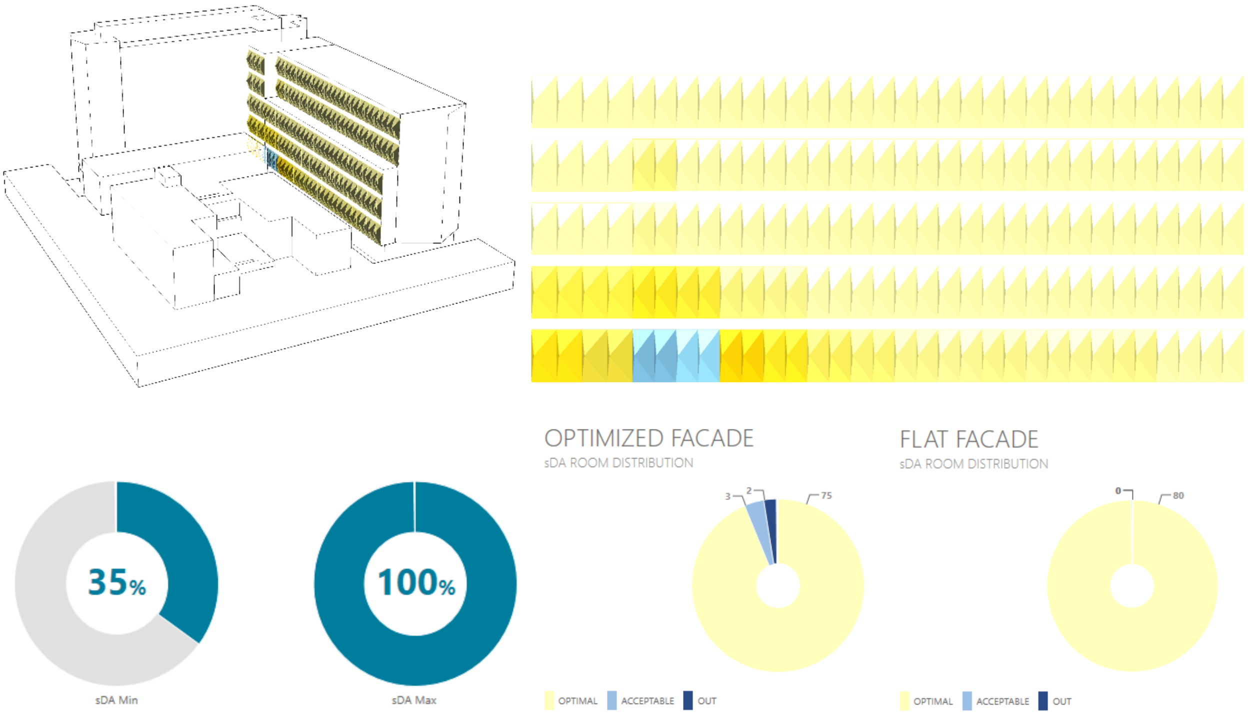
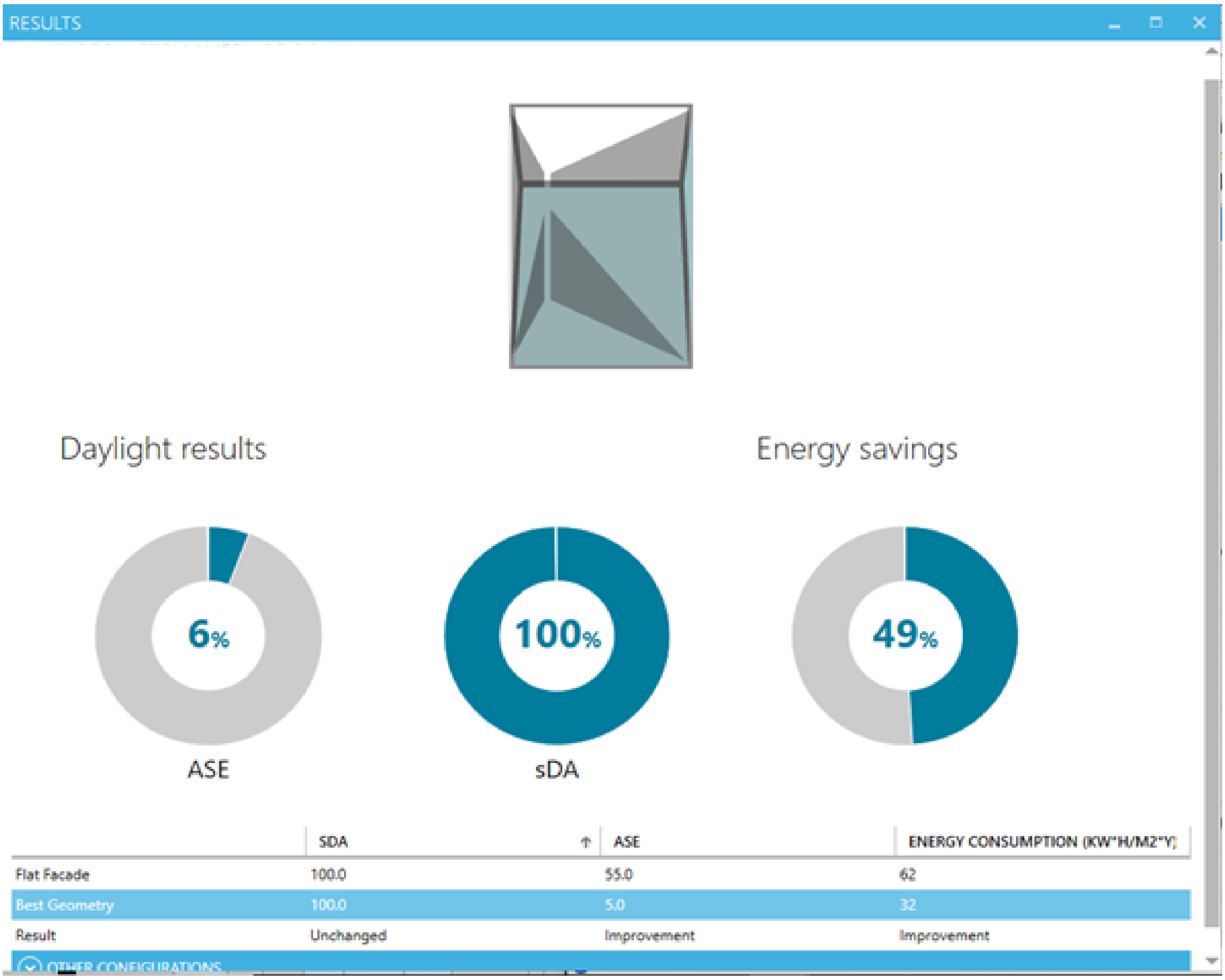


Figure 9-8: sDA Results – Classic optimization

The results obtained for the sDA are acceptable, since only two rooms get a value which is under the threshold of 55%; considering the context, it is conceivable that those parts of the building are the ones which may probably have issues with the satisfaction of the sDA requirement.

9.1.3.2 Option B – Parametric

Once the Option A has been carried out and the results are always good both in terms of ASE and sDA, the parametric option carried out with the same configuration will probably not return interesting effects on the façade. Then the decision fell on the choice of another family, in order to obtain a bigger variation of the module due to the context. Moreover, the panel considered in the classic option does not allow to have a view on the outside, so a panel belonging to R.1.b family having the bottom panel transparent has been chosen, in order to test a configuration allowing also the view of the outside landscape.



	SDA	ASE	ENERGY CONSUMPTION (KW*H/M2*Y)
Flat Facade	100.0	55.0	62
Best Geometry	100.0	5.0	32
Result	Unchanged	Improvement	Improvement

Figure 9-9: Panel chosen for Parametric Option

The panel chosen among the possible configurations for the average room is a panel from the R.1.b family with a higher sDA value and less energy consumption compared to the best one, which is the one used in the Classic option. On the other hand, this panel has a bigger glazed surface and it has a higher value of ASE compared to the best option.

In order to proceed with the remap it was necessary to test the configuration in the rooms with the highest ASE and lowest sDA of the reference case, keeping constant the geometry and the materials in terms of opaque and transparent panels. This analysis is important to find the optimized configuration for the two rooms and use the value of extrusion, height and width in relation to the results of ASE obtained in the reference case to proportionally generate the configurations for each room of the façade.

Results

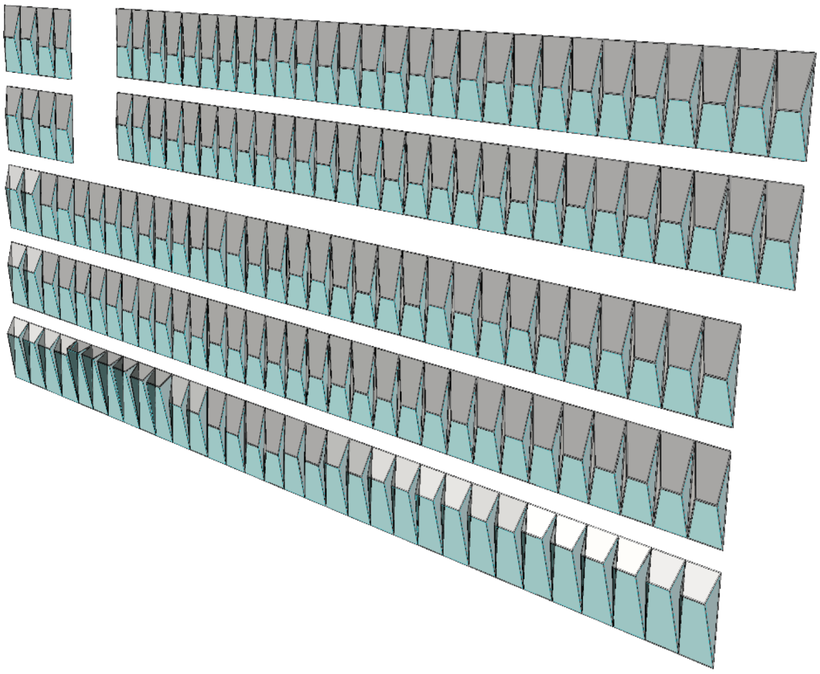


Figure 9-10: Option B – Preview of the façade

The result of this optimization is useful, since it is possible to recognize from the output geometries which are the rooms receiving more or less solar radiation; in particular, the effect of this optimization is well noticeable in the lower floors and on the left-hand side of the façade, which are the parts of the façade which interact the most with the context.

Even if all the configurations are generated considering optimized geometries, it is necessary to test each single room in order to verify if all the rooms achieve the visual comfort.

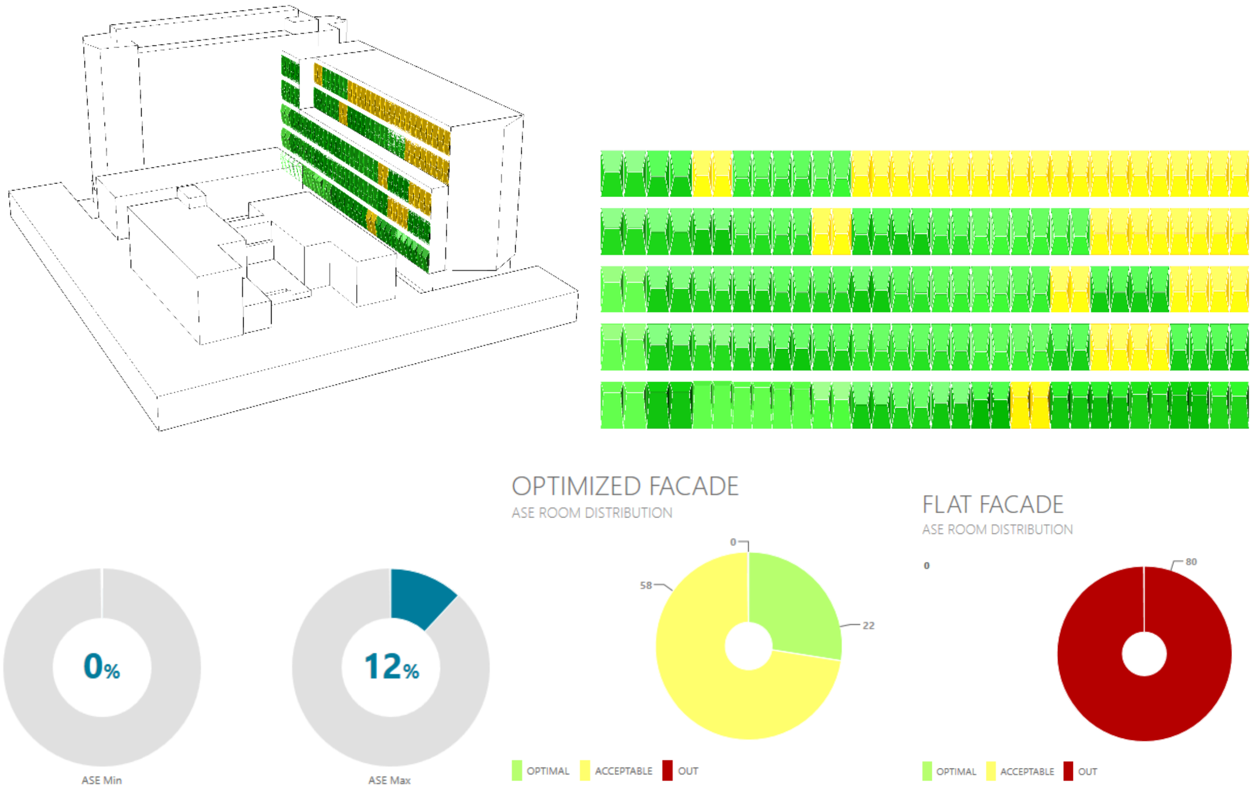


Figure 9-11: ASE Results – Parametric configuration

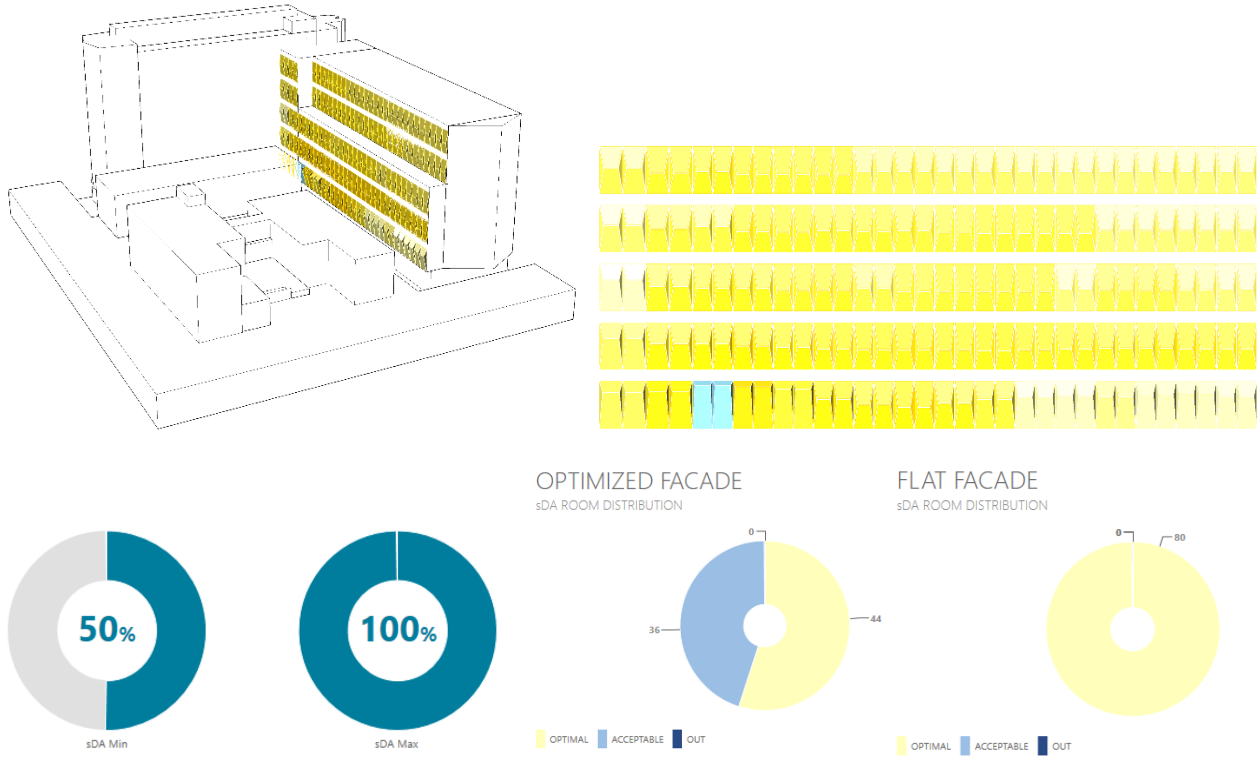


Figure 9-12: sDA Results – Parametric configuration

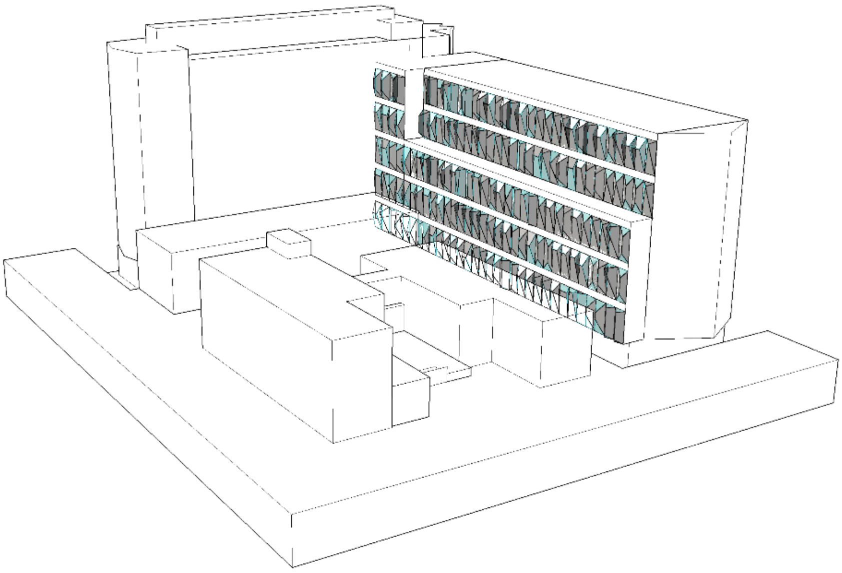
The parametric optimization, changing the configuration according to the context can reach values of ASE which are not as good as in the previous case, but they are still in the acceptable range. The values of sDA are all in the acceptable range too.

This solution can be considered equally good as the output of the classic option, even if the results for the ASE are slightly worse; on the other hand, this configuration allows the view of the outside, which is an aspect that should be taken into account also for the satisfaction of the occupants of the building.

9.1.3.3 Option C – Random

The random optimization tests a defined number of configurations, (the number can be chosen by the user) for each panel of the façade, searching the best optimized solution for each point.

It is possible to set preferences on the distribution of materials, but for this façade, which has a difficult context due to its large exposure not shielded, it has been preferred not to cull options on the solution by adding some preferences.



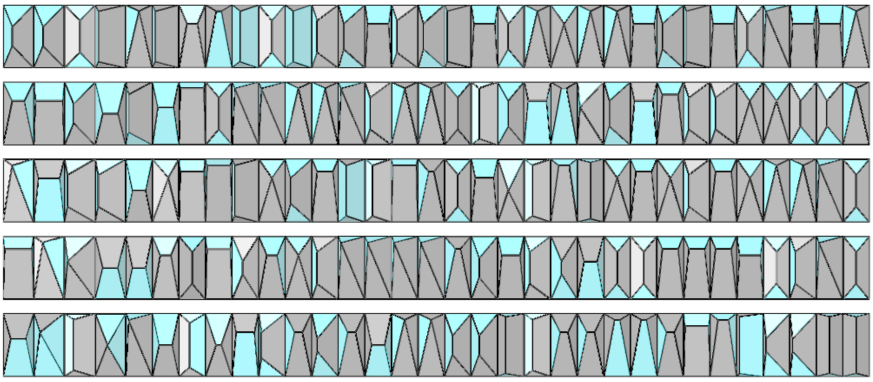


Figure 9-13: Preview of the façade – Random optimization

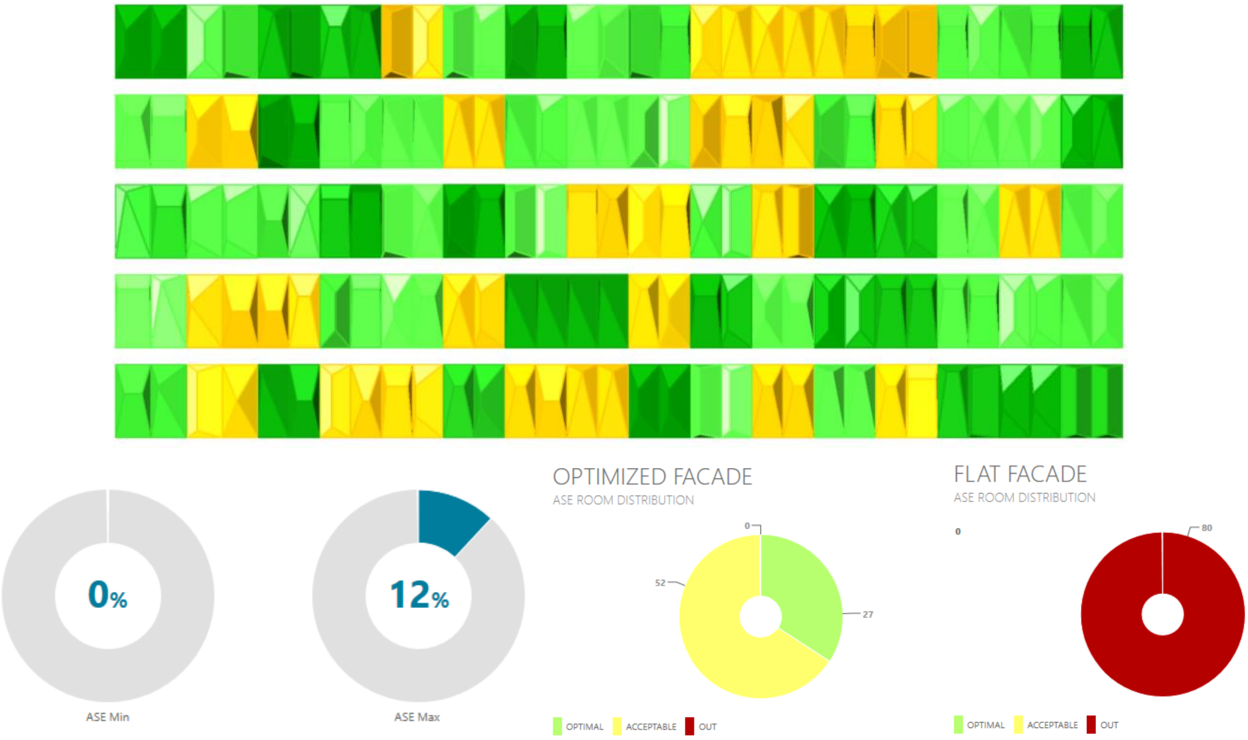


Figure 9-14: ASE Results - Random optimization

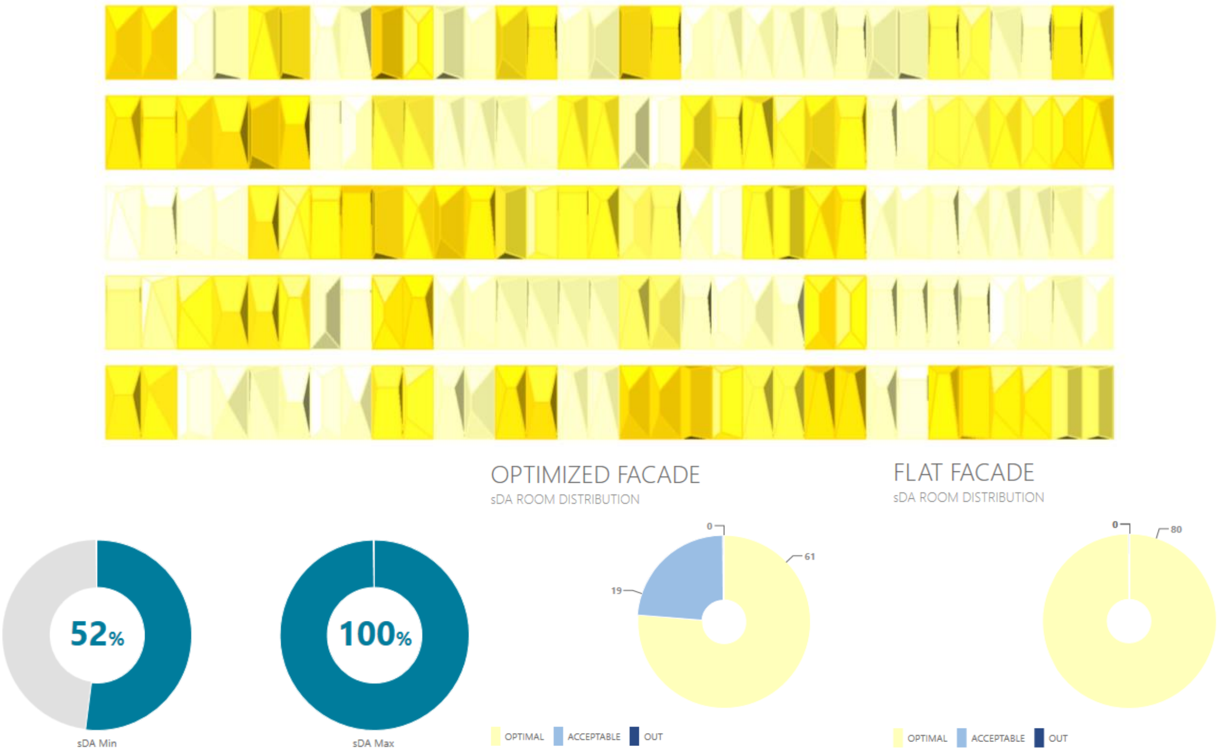


Figure 9-15: sDA results – Random optimization

With the random optimization it is possible to understand the range of variety of the geometrical combinations that can fit the requirements; as expected, the results are good in all the rooms considered. Moreover, as it can be seen, the larger glazed panels are towards the left-hand side of the façade, due to the effect of the context on that part.

9.1.3.4 Option D – Artistic

With the artistic configuration the user can "draw" the trend of the façade, setting the trend of two on the three geometrical parameters which define each geometry; in this way Chameleon can work only changing the third parameter, in order to get the best possible result within the constraints decided by the user.

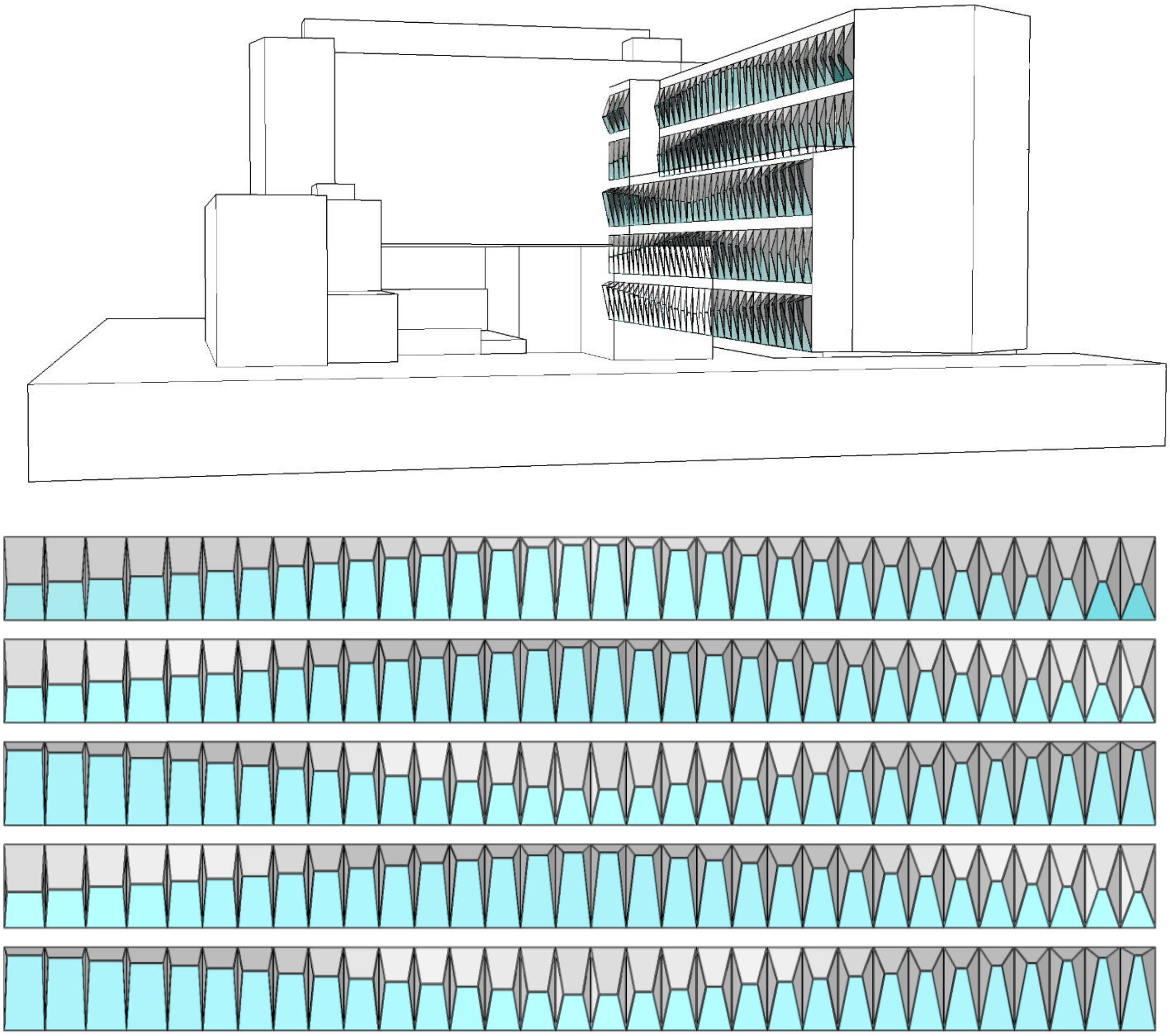


Figure 9-16: Preview of the façade - Artistic optimization

As it can be seen, this option is the one which allows to get a trend along the façade and a smooth dynamism.

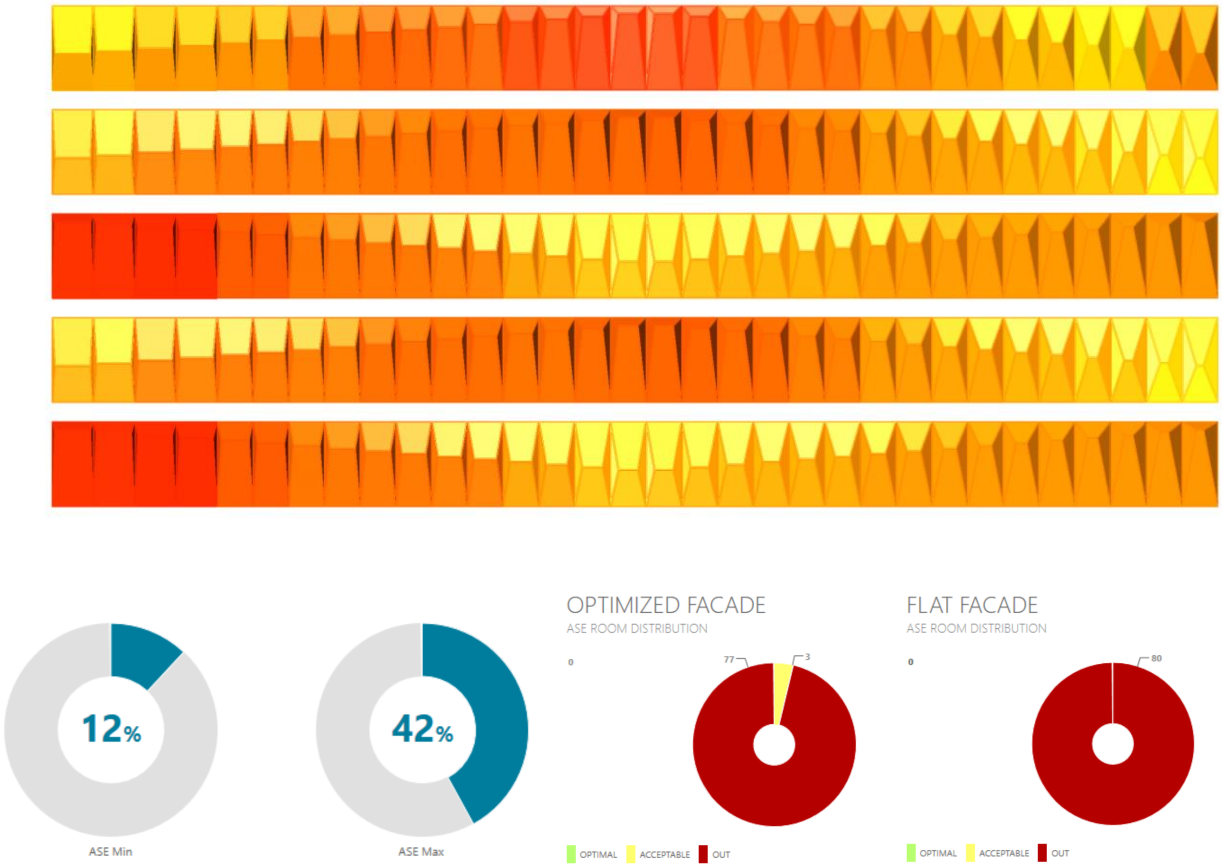


Figure 9-17: ASE Results - Artistic optimization

As it is possible to see from Figure 9-17 in most of the rooms the value of Annual Sunlight Exposure exceeds the set threshold. This is due to the fact that the geometry tested, even if it is acceptable from the preliminary analysis output, is complicated to be applied to the entire façade, due to its large glazed façade on the bottom panel. Moreover, also the results of the Random optimization rarely obtained a configuration belonging to R1.b family. Nevertheless, it was important to show also a failure in the results, at this point the user can choose another geometry to be tested (in this case a geometry belonging to R1.c family would be better) and try again this option.

It is important to underline the fact that Chameleon is a tool which forecast a certain intervention of the user: it is important for a good outcome of the optimization that the user is aware of the constraints given by the context and understands why some path are not practicable.

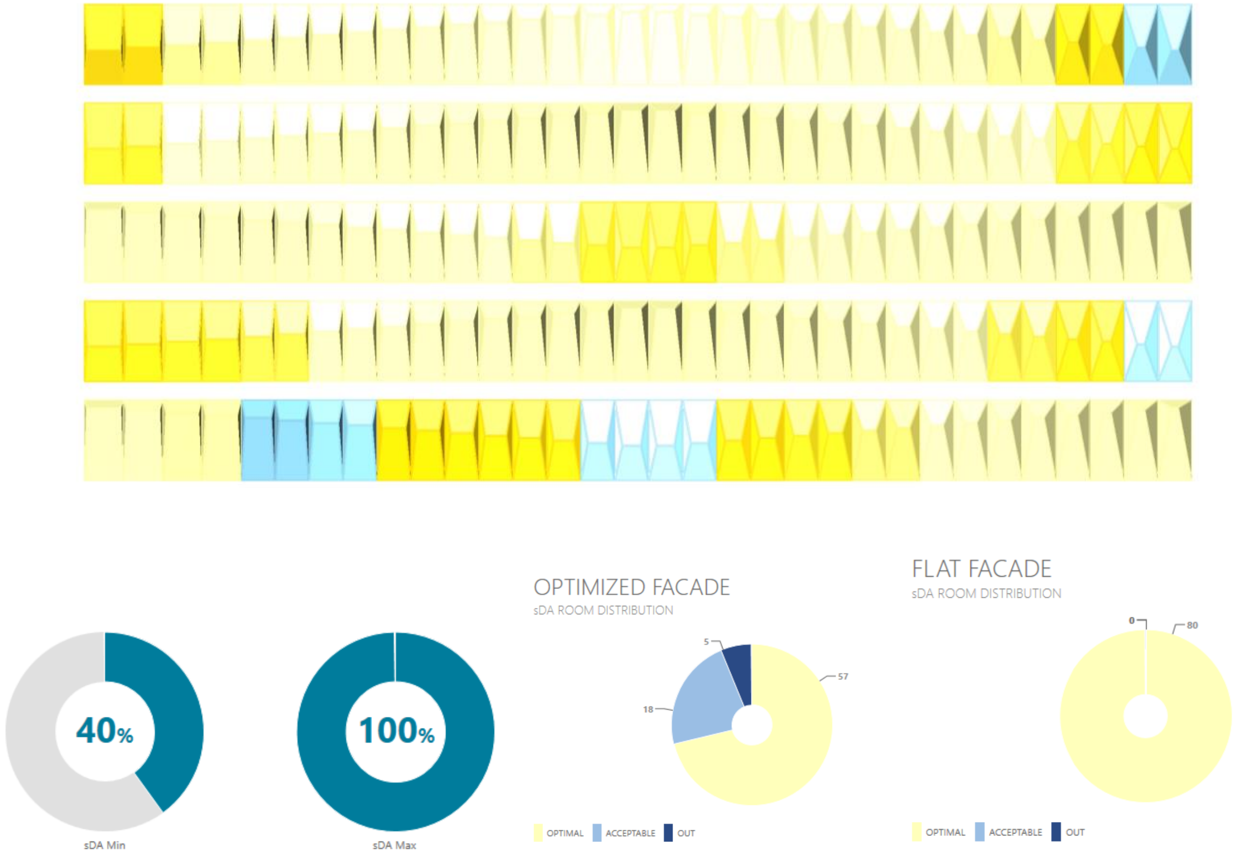


Figure 9-18: sDA Results - Artistic optimization

9.2 OPTIMIZATION PROCESS IN OTHER CLIMATES

Once the model has been correctly set and the results for the different optimization process in Milano have been obtained, the same model has been considered in another climate, in order to show how the final result change, due to a change in latitude, to validate Chameleon as a climate-based tool.

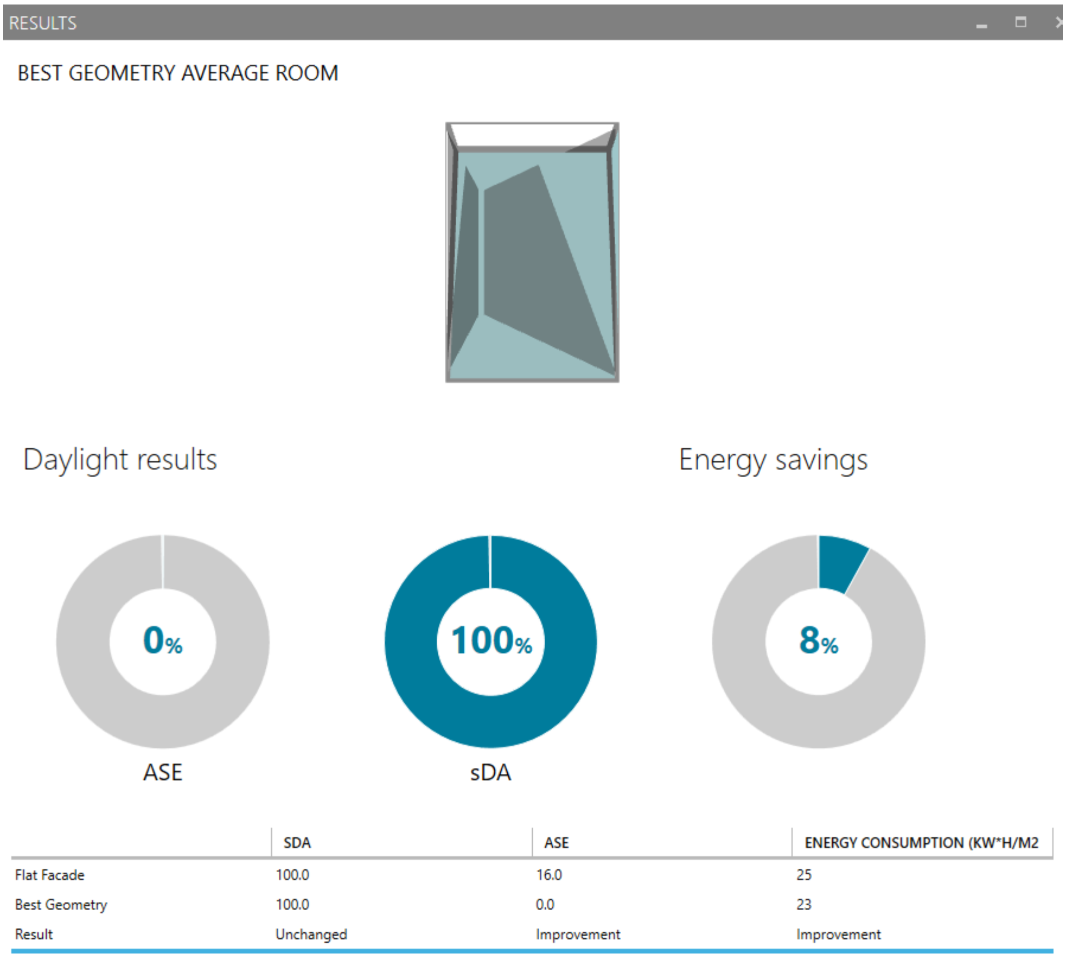
The city chosen is one considered also in the other validation processes: Singapore; London has not been considered, due to a small change in sun height compared to Milan, the results turned out to be really similar.

Moreover, Singapore has been chosen as an extreme climate, due to the height of the sun along the year; as a matter of fact, during summer, the sun is so high in the sky that the façade is not reached by direct solar radiation. Considering this aspect, it is clear that also the values of ASE will be easily satisfied: the sun reaches the glazing panels from a really low angle, hitting only the points of the grid closer to the façade, reducing the value of the ASE.

Here below, the results of the different optimization processes are reported.

9.2.1.1 Option A – Classic

As configuration for the classic facade it has been chosen an extreme configuration which is not the best one due the small energy savings, but the one with the higher glass surface in order to highlight the dependence of the climate on the geometry.



	SDA	ASE	ENERGY CONSUMPTION (KW*H/M2
Flat Facade	100.0	16.0	25
Best Geometry	100.0	0.0	23
Result	Unchanged	Improvement	Improvement

Figure 9-19: Configuration for Classic option

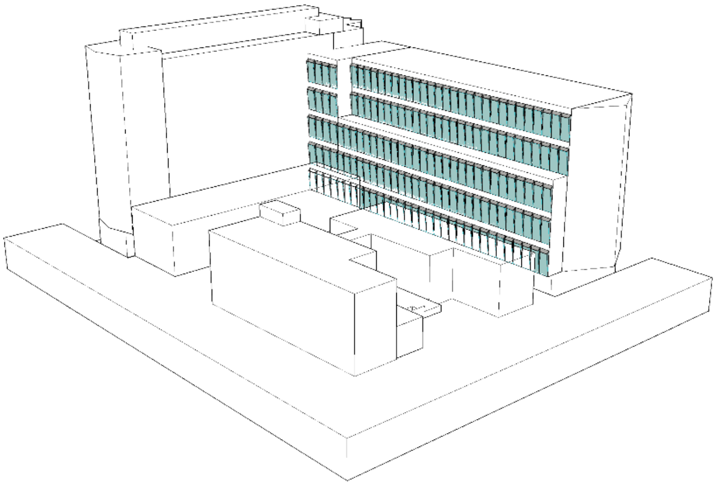


Figure 9-20: Classic configuration

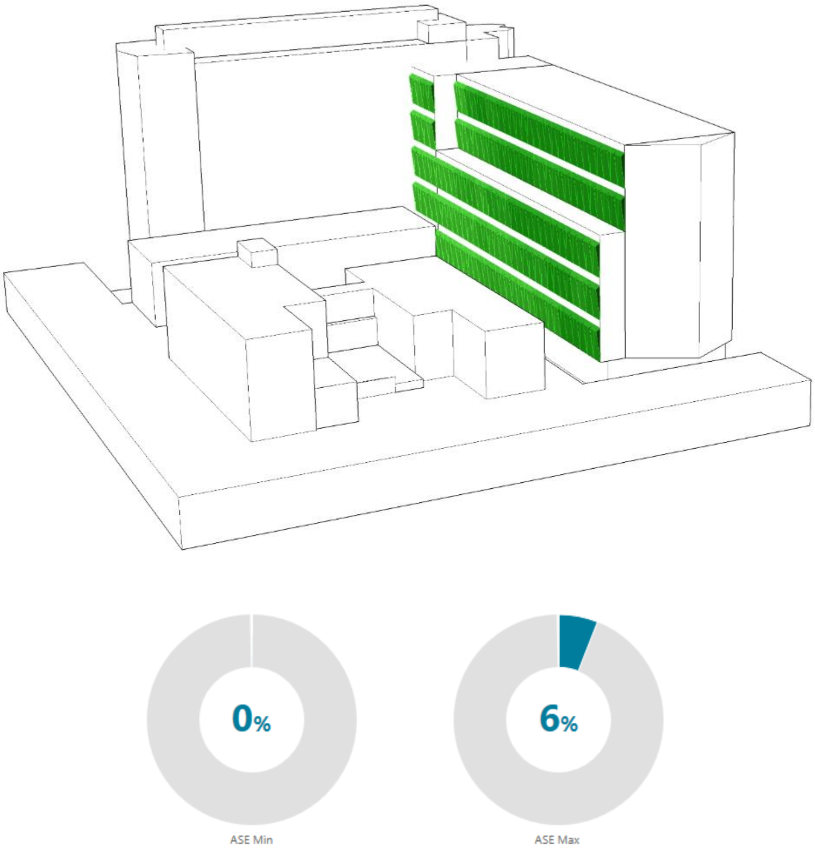


Figure 9-21: ASE classic configuration

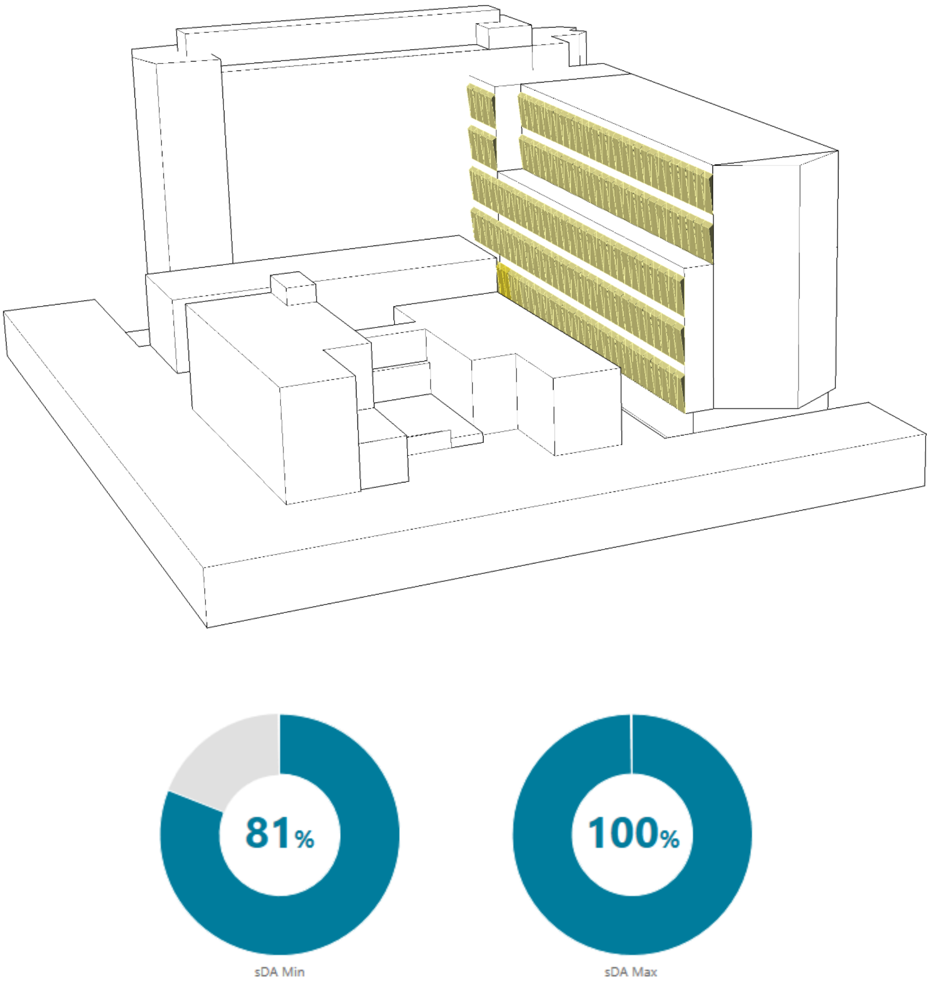


Figure 9-22: sDA classic configuration

For the classic configuration, with the panel with the high glazing percentage the results come out inside the threshold for both ASE and sDA.

9.2.1.2 Option D – Artistic optimization

As a further comparison, the artistic configuration has been tried in Singapore, using the same settings as for the simulation in Milan and the results are really different. As the reader can remember, that configuration was the worst among the ones tested, while for this climate it obtains good results, especially considering ASE.

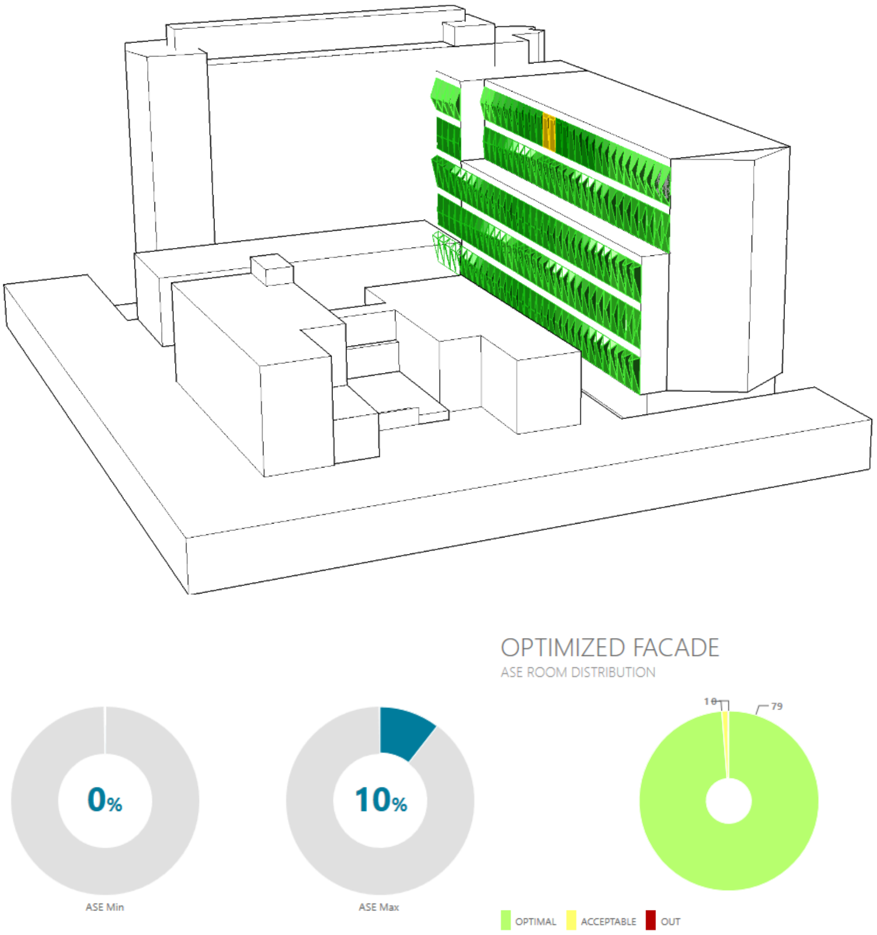
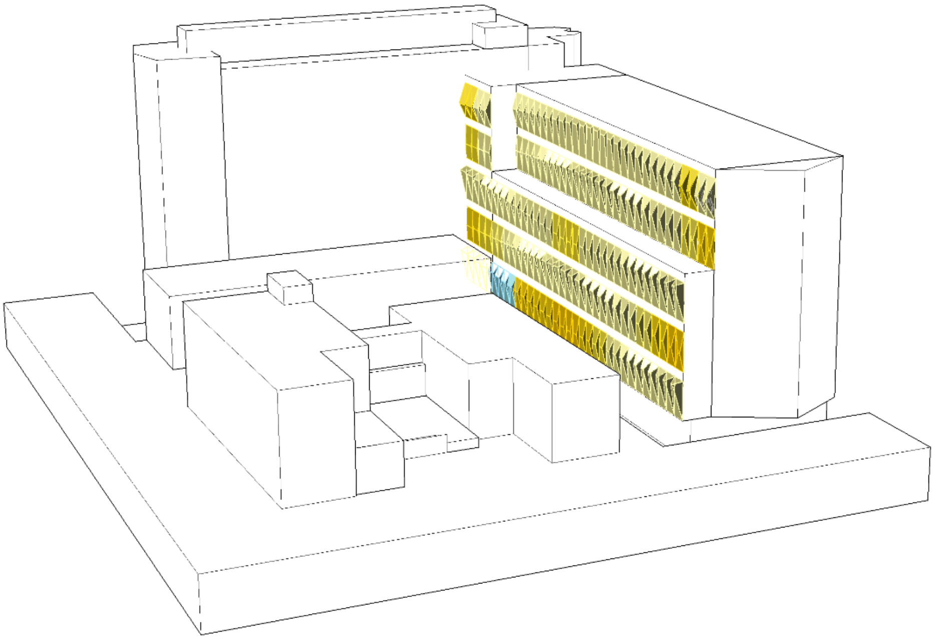


Figure 9-23: ASE artistic Singapore



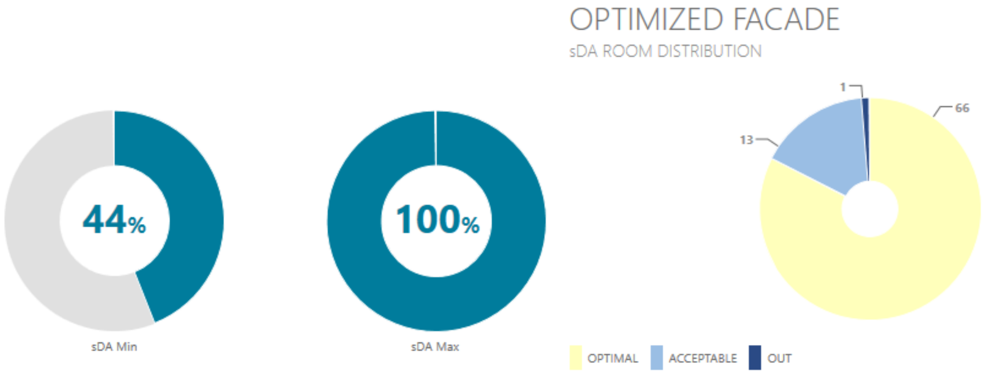


Figure 9-24: sDA artistic configuration

The output of this simulation is important since it shows how results are affected by the site and the location: geometries, distribution of materials and best optimizing options change. Chameleon can be then considered as a climate-based tool, obtaining reliable results.

It is important to underline that all the results reported in this chapter have been compared with the ones obtained with HB+, assessing their goodness.

10. USE OF CHAMELEON WITH OTHER GEOMETRIES

The plug-in has been studied specifically for the type of geometries considered; sliders, geometries and the interface are defined starting from this specific kind of geometry, then declined in the different families. Nevertheless, the procedure established for the calculation of ASE, sDA and energy consumption is general, so they can be used for different geometries and types of shading; as a matter of fact, the calculations are performed considering geometrical formulas which can be applied to whatever geometry.

To validate this statement, the final part of this thesis work has been the application of the procedure studied to other cases, shading types and geometries, through a change of few components in the flow, making Chameleon truly suitable and usable with generic shading devices.

This chapter shows the changes applied and the results obtained, with the application on a reference room of a lamellae shading; moreover, the changes in the interface will be shown too.

10.1 CALCULATION METHODS

The calculation method developed for sDA and ASE is not related to a specific type of façade but, except for some changes that needs to be done on the generation of geometry, which of course is different, it then can work with any type of geometry.

10.1.1 ASE calculation

As far as the ASE is concerned, the main difference from the façade panels studied previously is that for a general case the projection of transparent part of the façade is not enough to evaluate the part of grid hit by direct illuminance and define the value of ASE; In fact, the area considered should be defined by the difference of projection of the transparent part and the one of the shading. This change is necessary and in terms of time difference it does not affect the efficiency of the plug-in. As a matter of fact, with the “default” geometries it is always clear in the plug-in which are the areas transparent or opaque and it is possible to only project the glazing part, not considering the influence of the opaque one. On the other hand, if we consider a system for example composed by external shadings it is not possible to define a prior the projected area, since the shading is in front of transparent part and they need to be projected together.

The changes applied to Chameleon obtained a satisfactory result: the value of ASE is comparable to the one obtained from other softwares, which are studied and used to define whatever combination of glazed geometry and shading.

10.1.2 sDA Calculation

As far as the calculation of sDA is concerned, it needs some more considerations and effort. In fact, the calculation method for the default geometry provides the calculation of the sDA through the definition of the sky view factor for each different transparent part of the panel, as described in par.7.1.2). In that type of geometry, it is possible to say that the view towards the outside through a specific transparent panel is the same in each point and as a consequence only one sky view factor can be considered for each panel. On the other hand, for an external shading system it is not possible to define the façade considering only one point because the conditions of exposure and sky view factor change from each point: there is the need to define the behaviour of the transparent part in more than one point.

Consequently, the façade panel is divided in parts with maximum length of the edge of 55 cm and in the centre of each sub-part the sky view factor is calculated in order to obtain an average sky view factor of the entire panel. This type of procedure implies an addition of calculations in each iteration and the process become a little slower; nevertheless, it is still faster than the other software.

10.1.3 Energy consumption

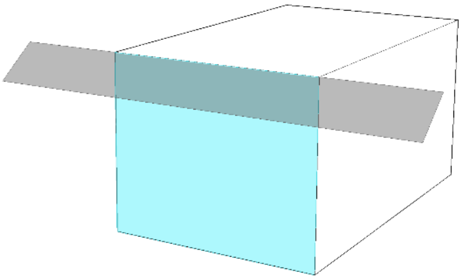
As seen in the previous chapters, the energy consumption is a parameter that has been evaluated as a choice discriminant in the flow. As considered in this project, the energy calculation comprehends only those aspects of the energy balance which can be affected by the geometry; the most of the calculations are derived from the paths of ASE and sDA, as a consequence, once their flows are defined, the energy consumption calculations is directly derivable by that.

10.1.3.1 Case considered: external shading with lamellae

In order to test the calculation methods a room with an external shading device has been analysed; the shading device is obtained through a parametric flow, where the variables are:

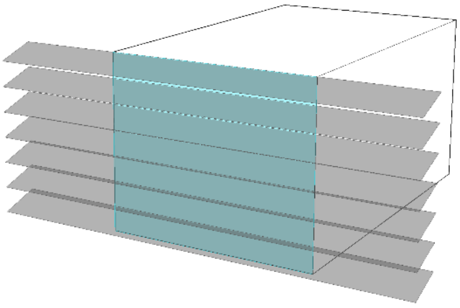
- The number of lamellae;
- The length of the lamellae;
- Lamellae inclination;
- Lamellae width.

As for the analyses carried out in Chapter 6.2, the room has been tested with different orientations in order to compare the results and analyse how the method deals with different amounts of direct and diffuse radiation according to the direction considered. Here below the results of the different attempts are reported; the results are given not only as a comparison of the values with DIVA and Honeybee+, but also in time spent for the simulation.



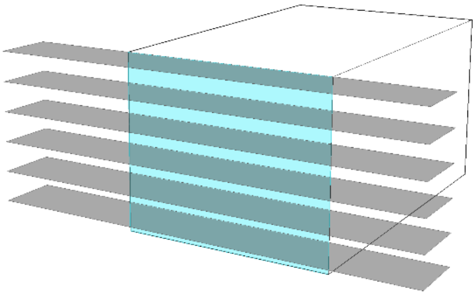
	ASE	sDA	Time of calcultaion
Diva	29%	100%	Low quality 25 sec
		100%	Medium quality 5 min
Honeybee +	27%	100%	55 sec
Chameleon	30%	100%	6 sec

Figure 10-1:Lamella South orientation, Milan



	ASE	sDA	Time of calcultaion
Diva	0%	0%	Low quality 55 sec
		41%	Medium quality 8.4 min
Honeybee +	0%	55%	55 sec
Chameleon	0%	25%	20 sec

Figure 10-2: Lamellae south orientation, Milan



	ASE	sDA	Time of calcultaion
Diva	0%	55%	Low quality 46 sec
		100%	Medium quality 6 min
Honeybee +	0%	100%	55 sec
Chameleon	0%	64%	11 sec

Figure 10-3: Lamellae south orientation, Milan

	ASE	sDA	Time of calculation
Diva	0%	16%	Low quality 51 sec
		59%	Medium quality 7.4 min
Honeybee +	0%	69%	55 sec
Chameleon	0%	48%	7 sec

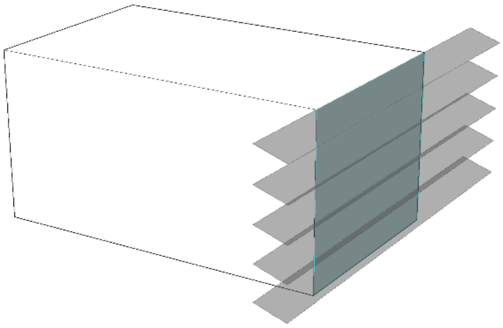
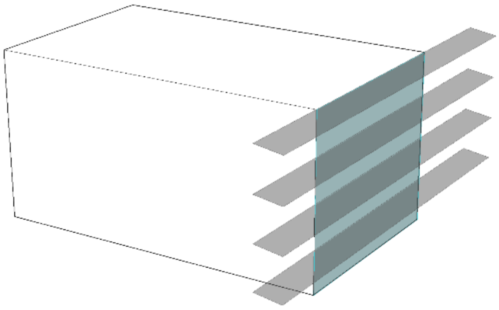
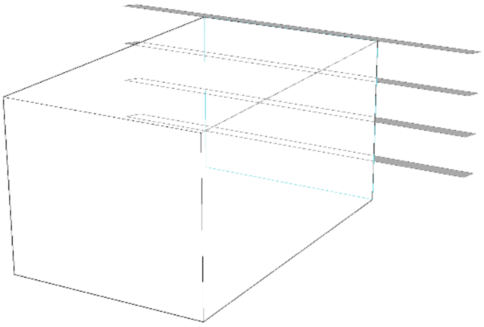


Figure 10-4: Lamellae East orientation, Milan



	ASE	*sDA*	*Time of calcultaion*
Diva	9.5%	67%	Low quality 51 sec
		100%	Medium quality 6.2 min
Honeybee +	0%	100%	1 min
Chameleon	0%	100%	7 sec

Figure 10-5: Lamellae East orientation, Milan



	ASE	*sDA*	*Time of calcultaion*
Diva	0%	67%	Low quality 33 sec
		100%	Medium quality 5.9 min
Honeybee +	0%	96%	47 sec
Chameleon	0%	97%	7 sec

Figure 10-6:Lamellae North orientation, Milan

The flow has been tested for different lamellae configurations and orientations and the results are comparable to the ones obtained in the previous chapters in most of the cases.

Important to report is also the time needed for the simulations: Chameleon gets a maximum of 20 seconds of simulation, in the case denser of lamellae; Honeybee+ requires 55 seconds, while DIVA more than a minute to obtain reliable results. It can be seen that in all of the cases Chameleon is the briefer method of calculation, with small variations according to the shading complexity. Honeybee+ has a time needed which is quite always the same in all the simulations performed. On the other hand, when the configuration becomes complex DIVA in low quality is not satisfactory since the results are out of an acceptable range of reliability; as a consequence, the DIVA simulation needs to be carried out in medium quality, implying a time for a simple simulation longer than 5 minutes. It can be deduced that, comparing the results accuracy and the time needed, Chameleon obtains reliable results in the lowest time.

This analysis focused also a possible problem in the calculation of the sDA. The calculation up to now, it is based only on geometrical parameters and calculations, which in the “default geometries” turned out to be a reliable approximation. On the other hand, it does not calculate in any way the properties of materials in terms of reflectance: in shading systems like the one considered, where part of the sDA is given also by reflected light, this component cannot be calculated in Chameleon.

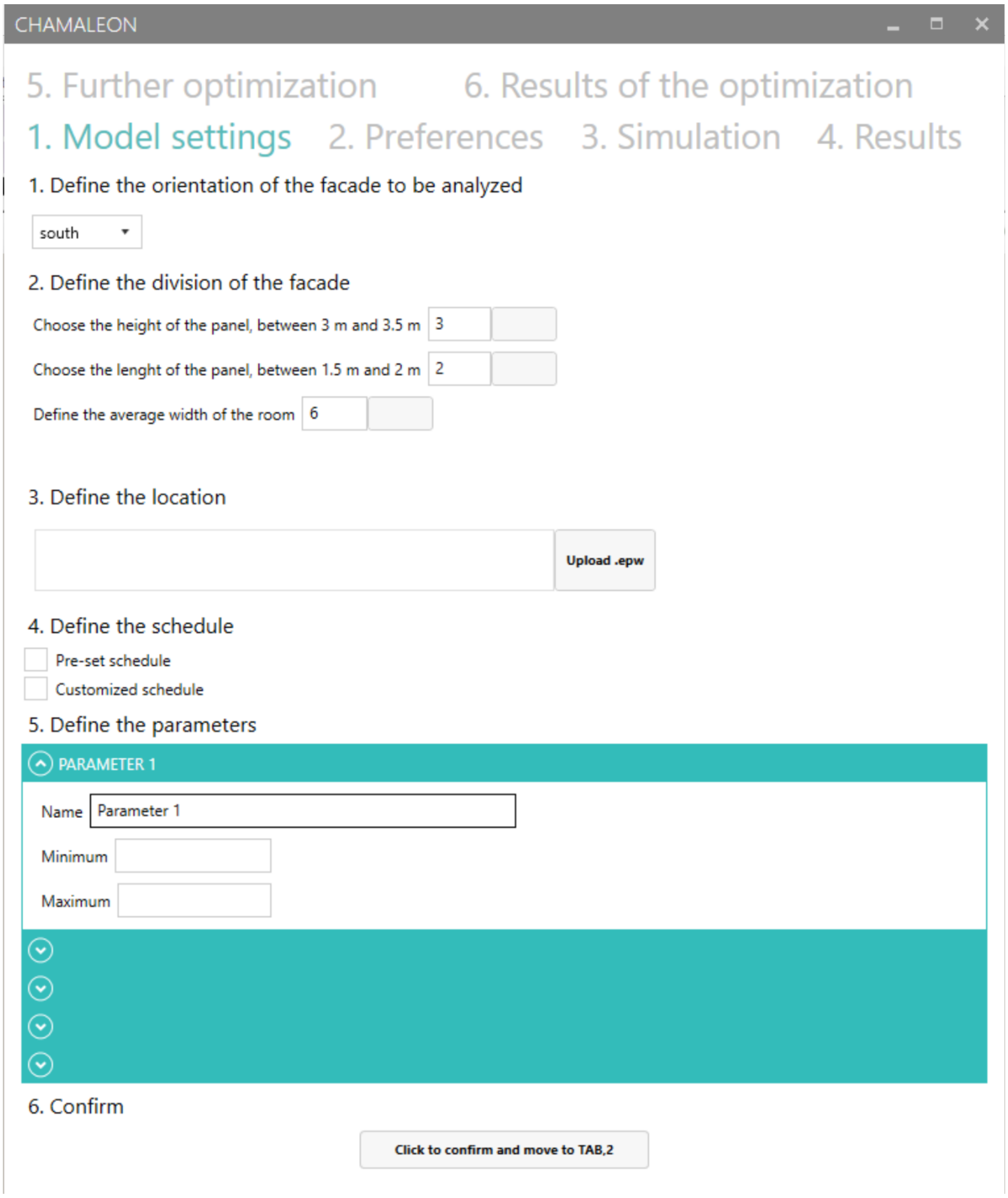
As a matter of fact, in terms of sDA the tool presents differences in the results decreasing the space between the lamellae: this implies a higher amount of reflected light. Further optimization of this calculation would be the introduction of a calculation for the reflected light in the sDA, in order to evaluate in a more reliable way the systems were the illuminance inside the room is highly guaranteed by the reflected component.

10.2 CHAMELEON INTERFACE FOR GENERAL USE

As seen in the previous chapters, the flow as it has been intended does not allow the user to have a complete freedom, since the number of variables that could derive from this choice could not be managed by the plug-in: it needs to be designed and scripted forecasting all the different options and their implications.

Even in this case, the user is not completely free to design a parametric shading device, but he has a limit to the number of variables that parametrize the system. This number has been set to 5, thinking about the three dimensions, the possible inclination of the system and the number of repetitions of the element.

These five variables will be asked to the user in the interface, in the very first panel which is the “Model definition” one.



1. Define the orientation of the facade to be analyzed

south

2. Define the division of the facade

Choose the height of the panel, between 3 m and 3.5 m: 3

Choose the lenght of the panel, between 1.5 m and 2 m: 2

Define the average width of the room: 6

3. Define the location

4. Define the schedule

☐ Pre-set schedule

☐ Customized schedule

5. Define the parameters

Name: Parameter 1

Minimum:

Maximum:

6. Confirm

Figure 10-7: Main window for custom shading system

In order to not create confusion, the interface has been kept as more similar as possible to the one for the default geometry. As a consequence, with all of the differences due to the type of shading, the steps for the optimization will be the same. In the interface what changes is the new panel 5 of the “Model settings” where the user can define the different parameters: Chameleon gives the possibility to define the name of the parameter which will be in real time assigned as a name of the expander menu and the minimum and maximum value which will become the domain of that parameter. These values will be introduced in the flow as 2D domains and will be used as the parametric definition of the geometry.

Considering the example of a shading system composed by lamellae, after the evaluation of the best dimension, the needed number of lamellae and their inclination, the user can choose to apply the same combination to all the rooms in the building (option A, par. 8.4.2.1), remapping it according to the analyses carried out in the baseline case(option B, par.8.4.2.2), try a random configuration (option C, par.8.4.2.3) or define the trend of the lamellae along the façade (option D, par.8.4.2.4).

11. USER SHELL

Once the methods of calculation are defined and a flow in Grasshopper is set, it is not possible to consider this process completed, since generally the flows in Grasshopper are complex structures and usually it is difficult for an extraneous to start working with a flow not defined and designed by himself. In fact, Grasshopper is a parametric software which has hundreds of native components and hundreds of plug-ins from third developers; this means that even a simple action can be done in many different ways: with a group of Grasshopper components put together in a flow or with a component from a specific plug-in which groups many components and calculations in only one component, allowing to obtain easily and rapidly a complex action. Both have pros and cons: a flow of Grasshopper's native components can be not intuitive if it has been done by someone else also because the majority of geometrical transformations can be reached in different ways and thought differently. On the other hand, a Grasshopper's file with components from different plug-ins requires that the user downloads the plug-ins and installs them, which can be a waste of time and space in the computer and requires a constant attention to updates; in fact, plug-ins are constantly updated and if the user has to use a file with no updated components, it will not work, requiring a manual update.

As a consequence, it has been decided to introduce a user interface, in order to make the interaction between the user and the flow more intuitive and to reduce the probability of errors due to a wrong way of defining inputs. All the pictures seen from Chapter 8 are screenshots of the interface of the plug-in; this final chapter explains which tools has been used to design the user shell and describes briefly its characteristics and options.

11.1 GRASSHOPPER’S FLEXIBILITY

As an example of the number of ways that can be used to obtain a simple geometrical transformation, the following pictures will show the definition of a grid 4x3 starting from a rectangular surface; the methods shown have different level of complexity and imply also the use of components of a third part plug-in.

Method 1 – Subdivision of the domain

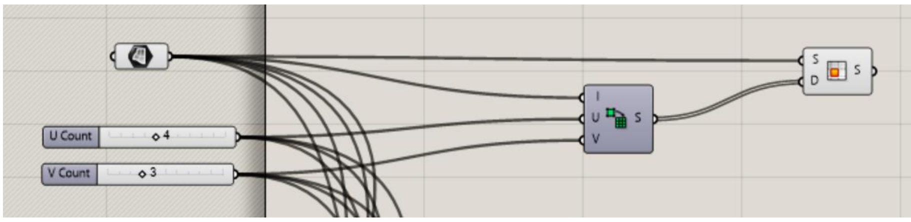


Figure 11-1: Method 1 - Grasshopper flow

This method uses two components: subdivision of the domain and isotrim; once the number of divisions in x and y directions has been chosen, the isotrim component splits the mother surface into 12 sub-surfaces.

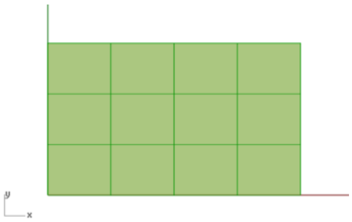


Figure 11-2: Method 1 - Rhinoceros output

Method 2 – Surface division

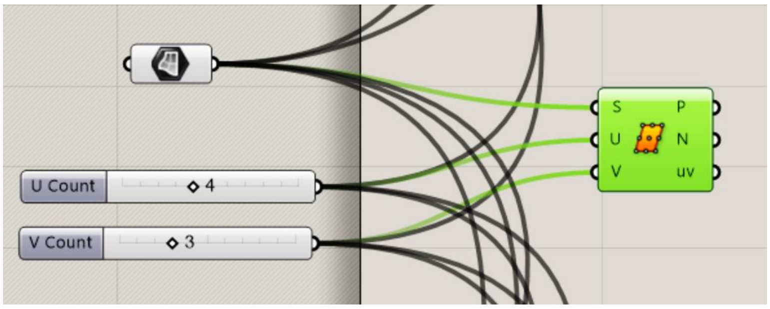


Figure 11-3: Method 2 - Grasshopper flow

This method uses a single component native of Grasshopper: surface division. Once the surface and the number of divisions in the two directions are given, it creates automatically a grid of points that can be used to divide the surface in sub-surfaces.

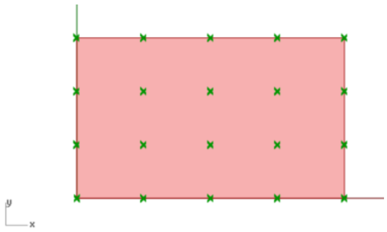


Figure 11-4: Method 2 - Rhinoceros output

Method 3

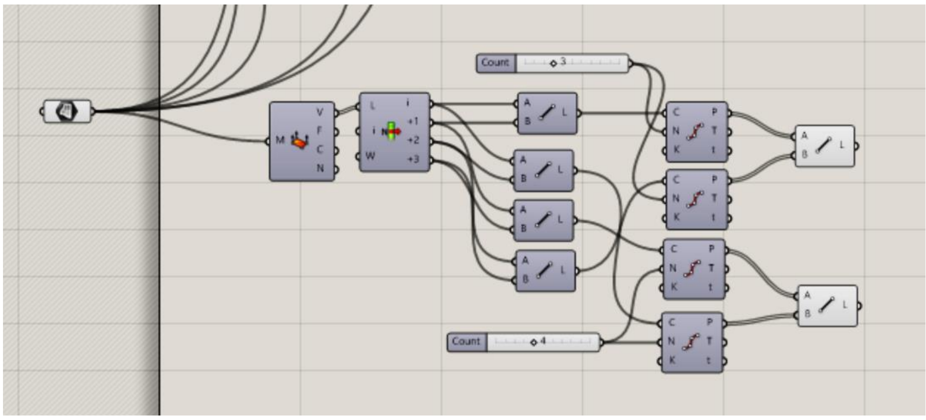


Figure 11-5: Method 3 - Grasshopper flow

The method shown is the last one obtained with only native components of Grasshopper. The starting point is always the surface which is analyzed with the component "Deconstruct Brep", which gives the vertices of a surface. The vertices are linked together to obtain the edges of the surface and then divided by the number of segments required, obtaining the vertex of the lines that will compose the grid.

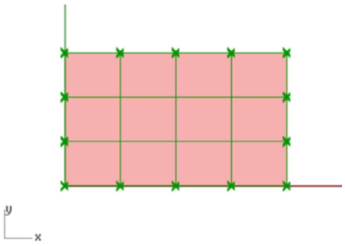


Figure 11-6: Method 3 - Rhinoceros output

Method 4 – Grid structure (Lunchbox)

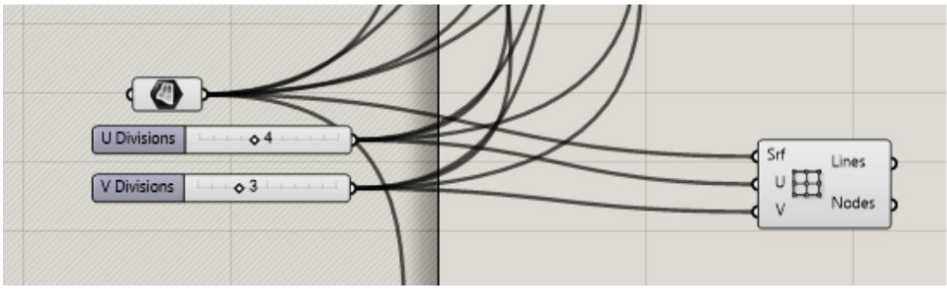


Figure 11-7: Method 4 - Grasshopper flow

This method uses a component of a plug-in for Grasshopper which is Lunch box. As it can be seen, the result of this output is a grid, where both the points on the edge of the surface and the inner ones are created.

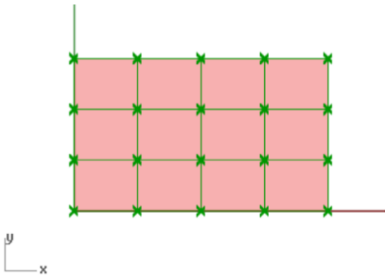


Figure 11-8: Method 4 - Rhinoceros output

Method 5 – Quad panels (Lunchbox)

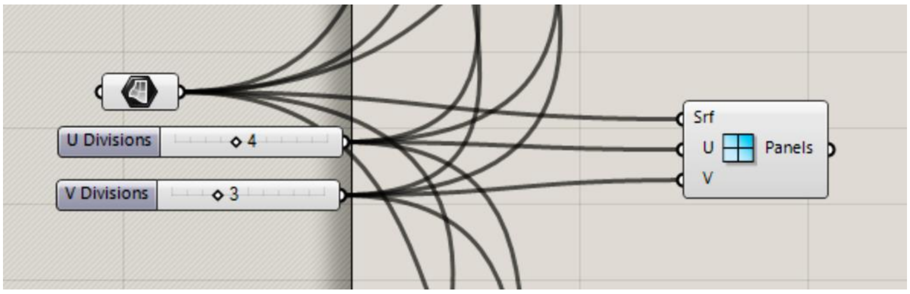


Figure 11-9: Metod 5 - Grasshopper flow

This is the last method shown and it uses as before a component from Lunchbox. The difference from the previous one is that the grid is not given as a collection of points, but it is used to divide the surface in rectangular sub-surfaces.

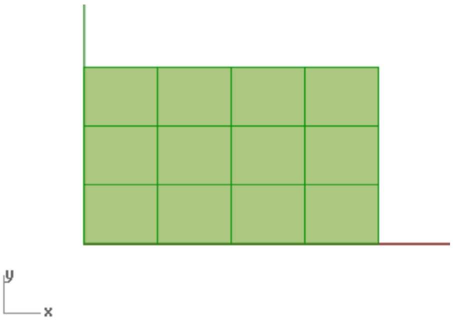


Figure 11-10: Method 5 - Rhinoceros output

11.2USER INTERFACE

As it can be seen from the previous examples, even an easy geometrical operation as the subdivision of a surface in a grid and relative sub-surfaces has many solutions and can be thought in different ways. As a consequence, a person at his first approach to a software like Grasshopper, who probably is not confident on the components may find difficult to work and use a flow which has been already defined and designed by someone else. This is due to the fact that some components combined together allow to obtain a specific result, which cannot be imagined with a superficial or basic knowledge of Grasshopper.

Moreover, as said in the previous paragraph, the environment of plug-ins for Grasshopper is wide and using some of them in the flow will require that the user has a knowledge also of these components. This aspect will imply the consideration of more variables, making the flow more difficult for the user to use. In addition, considering the most famous plug-ins used to perform daylight and energy analysis and making a comparison between them, even if the user has a knowledge on the use of one of them, the use of a different plug in performing the same simulations is not so immediate as it can be thought. Honeybee for example has a more complex definition of the room, of the surfaces and materials; each simulation has its own recipe and the climatic file can be used to derive many outputs also related on the direct, diffuse illuminance etc.. DIVA, on the other hand, is more intuitive, since many calculations are already performed in a single component; this has the disadvantage that the calculations take long time and some data are not directly available for the user, like the weather conditions.

As a consequence, it can be seen that is not so easy and intuitive to switch from one plug-in to the other; these issues lead to the decision of designing a tool which would be completely designed by our team, with no need of installation of third parts plug-ins for the calculation of daylight comfort or energy consumption and production.

As seen in the sensitive analyses between other tools and the Simplified Method (see Chapter 7.1.1.7), this choice leads also to a sensible reduction of the time needed for the simulations. In this case, the output is a flow, that could be easily grouped in components as for the majority of the plug-ins; nevertheless, the number of inputs that the user is called to give is high and the risk is not to be intuitive and to lead to mistakes. At this point, the challenge was making the flow friendly for a new user and deciding how to present information and how and in which moments let the designer make his choices. It was important to understand the needs of a designer and how much freedom in the expression of the choices give them.

On one hand, it is true that this plug-in should be used to obtain the best solution possible, so the flow should be independent and ask a little intervention of the user; on the other hand, the plug-in can lead to more than one solution, that can be different one to the other from the geometric point of view.

The final part of the work has been the introduction of a user interface, to make the interaction between the user and the flow in Grasshopper easier.

11.2.1.1 HUMAN UI

Human UI is a plug-in for Grasshopper, which has been used to develop the user interface. It has been developed by Andrew Heumann, the same developer who scripted the other plug-in used in this work which is Metahopper. Among the wide environment of plug-ins dedicated to different purposes for Grasshopper, Human UI is pretty unique; it allows to design an interface as a pop-up window, which is put beside the one of Grasshopper. This interface is two-ways since it allows to share information from the interface to the Grasshopper's flow and vice versa, so it gives the possibility of introducing inputs and visualize results, which was exactly the kind of exchange of data needed for this work.

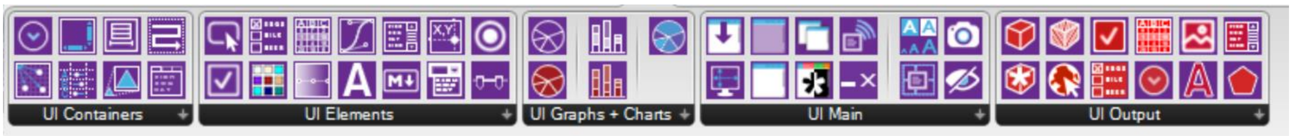
As a matter of fact, it was important for the good success of the plug-in that the user can define the starting boundary conditions, see the results also of the preliminary analysis and make his choices according to the results obtained.

Obviously, it could be possible to ask to the user to define the inputs simply as data in Grasshopper, but this would imply a higher risk of introducing information on the wrong way (e.g. introduce geometries as surfaces instead of breps etc..). On the other hand, if the user interface gave only the possibility to give inputs and not to see the results, it would imply that the user has to manually enable/disable preview components to see the outputs of the analysis.

The next paragraphs will explain briefly the tool, in order to make the reader aware of the possibilities that this plug-in offers in terms of customized interfaces and explaining which components have been used in this work.

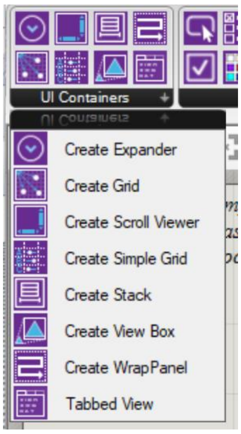
11.2.1.2 HUMAN UI COMPONENTS

Human UI has a variety of components that could be used to customize the appearance of the interface.



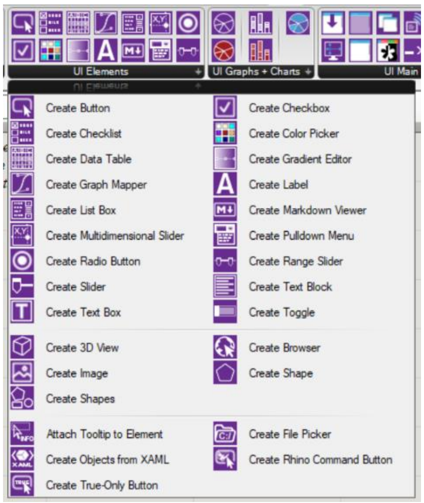
As it can be seen from the previous picture, the components are organized in five different groups: UI Containers, UI Elements, UI Graphs & Charts, UI Main, UI Output.

UI CONTAINERS



This category of objects is used to add to the interface some elements that can store information when used combined to other components. Some of them may be also used to change the organization of the objects added (e.g. Create stack allows to organize vertically or horizontally the more objects also belonging to different categories; Tabbed view can be used to organize the contents in different panels of the same window, grouping them according to their purpose, task, topic etc..)

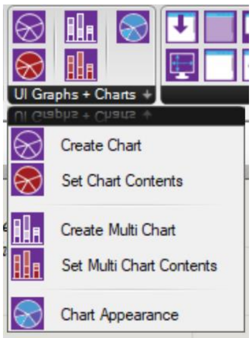
UI ELEMENTS



This group of elements is probably the heart of this plug-in, since it contains all of the commands and components that will compose the user interface. Most of them are used to ask the user to express his choice between a group of options; their use is pretty similar one to the other, since they will return a true or false to the Grasshopper flow if the element has been chosen or not. Some of these components simulate objects that are proper of Grasshopper, like the Slider, the Multidimensional Slider or the Graph Mapper; to explain their behavior they can be thought as “virtual sliders” which represent a “real slider” in Grasshopper. The user in the interface inserts the value of the slider which will be assigned as a value of the slider in the flow.

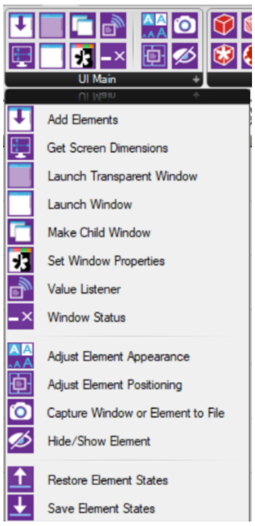
Some of the components moreover, can be used to create objects, view and shapes. In the project, in particular the option “Create the 3D view” has been used to show the results of the simulations. Important to report are some options like the “Attach tooltip to the element” which can be used to explain the use of some tools of the interface and give suggestion to the user for their use.

UI GRAPHS AND CHARTS



As it can be seen in the picture, the components belonging to this group appear in two ways: a "traditional" representation of the component (white drawing on purple background) and, the same drawing in red, marked with the prefix "SET". This is a crucial aspect of this tool; as a matter of fact, each time the user adds a new input, parameter, value etc.. some values of the interface can change. For example, if the interface gives a representation of a chart, if the input that the user gives change some values of the chart, it needs to be regenerated. The way the plug-in does the recalculation is to refresh the window. Using the "red" components avoids the recalculation, since the flows already store information and regenerate the chart in real time.

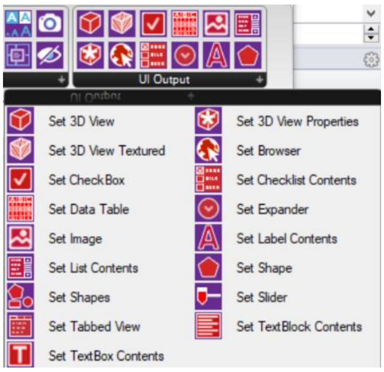
UI MAIN



This group of components is the one used to design the windows. It can be used to create a new window, a child one and to change the appearance of the existing ones.

One of the most useful components is the Value Listener, since the peculiarity of Human UI components is that they do not give any output as we could expect as tools of Grasshopper; each of them represents a "Human UI object" and does not give any information about the values obtained or inserted in the interface. In order to translate the Human UI object into a variable usable in Grasshopper is necessary to use the value listener; it gives back numbers, parameters, Booleans according to the type of component connected to.

UI OUTPUT



This is the last group of commands of HUMAN UI and it is composed only by the "Set Buttons"; as said before, the red components are the ones used to avoid the recalculation of the interface when one input changes. They can be used to update the values of the contents of the views created or the ones of the lists (e.g. labels, slider value, checkbox etc..).

After everything has been said before, it may seem a countersense to request the user to download and install a third part plug-in. Nevertheless, it was necessary to create a bridge between the flow and the user, otherwise the entire process would turn out to be complicated and probably mistaken.

11.2.1.3 Human UI in the plug-in

The use of Human UI to realize the interface has been complex mainly due to the differences between the components of Human UI and the general ones of Grasshopper. As said before, each component of this plug-in gives not back data values but represent an object of the interface and needs a *Value Listener* to insert in the flow the value chosen by the User.

This tool has been exploited up to its limits, since it is used to manage thousands of data, show complex geometries which need it to be refreshed continuously. Due to the complexity of this process, it was necessary to ask a little more intervention of the user in the Grasshopper canvas in some defined moments of the process. As a matter of fact, the transition from the preliminary analysis to the optimization is seen by the flow as a loop and the process will crash. As a consequence, it was necessary to use some components given by Metahopper which allow to break the loop, avoiding the crash of the program.

In fact, important to report is the use of Metahopper, plug-in of the same developer of Human UI, which has been used combined with components of Human UI also to enable/disable objects; this feature is expected and suggested by the developers as an integrated solution. With this tool, it was possible to avoid the slowdown of the plug-in. For example, when the user defines the inputs, instead of instantaneously assign them and activate the first calculations related to them, which implies that for few seconds the plug-in is stuck, they are assigned all together when the user confirms all the inputs defined.

12. CONCLUSIONS

This thesis report shown which have been the main steps of the process which lead us to the final definition of the tool. The route has not been completely straight, but especially at the beginning it was characterized by many deviations leading us to come back at previous stages and change assumptions, make other considerations in order to define the right procedure, since for some extents this is a quite unexplored path. This turned out to be a positive aspect, since it pushed us to deepen the nature of all the parameters used in the calculation, perform hundreds of different simulations only to validate some of our assumptions and calculating methods, allowing us to really "internalize", using a Grasshopper definition, this topic.

Chameleon can be considered as an innovative tool for designers, since its main aim is to help the designer in the early-stage of the design process, when the most of the focus is related to the form finding: it wants to introduce some aspects such as the visual comfort or the energy savings from the very beginning of the process, becoming integral part of the design and not only a final validation. On the other hand, it can be used also as a validation tool for the evaluation of the visual comfort and the energy consumption, allowing the user to define the shading system and performing also an optimization of the shading to improve the indoor comfort.

Even though we reached most of the set goals, such as the development of a plug-in with property methods of calculation, without leading on other plug-ins, the reduction of the time needed and the suitability to all the climates, we are conscious that there are some steps which need to be implemented for an optimal success of the tool. First of all, a great effort has been spent on some simplifications and approximations of the calculations in order to reduce the time needed for a complete optimization process, due to the computational power of desktop analysis; even though the results are satisfactory, if the plug-in is developed to work on a server, it would be possible a complete optimization of all the rooms. Moreover, it has been decided to use a user shell to be more intuitive for the designer, who may not be used to Grasshopper; the interface has been designed with a tool which is not suitable for the computation of thousands of data. The effort required to HUMAN UI, in order to manage all the results, preview and possibilities of choice is relevant and the interface really slows down the entire process.

Chameleon may be used for different purposes and become a really-used instrument for designers, nevertheless, an optimization of the scripting part needs to be done, since it was not our topic and a further optimization of the codes is out of our knowledge.

Lastly, the system studied may be deepened a little more in detail, new materials, shape and technology could be adopted to enrich the variety of possibilities offered to the user.

As far as the aesthetic is concerned, the optimization may be related to the introduction of new geometries or to the rearrangement of the existing ones using different tiling strategies; the plug-in has been designed to work with different systems and not only with the one used for its development: once a deeper study in the technology will be carried out, it will be just matter of drawing the parametric geometries, with no need of changing any of the parts of the flow.

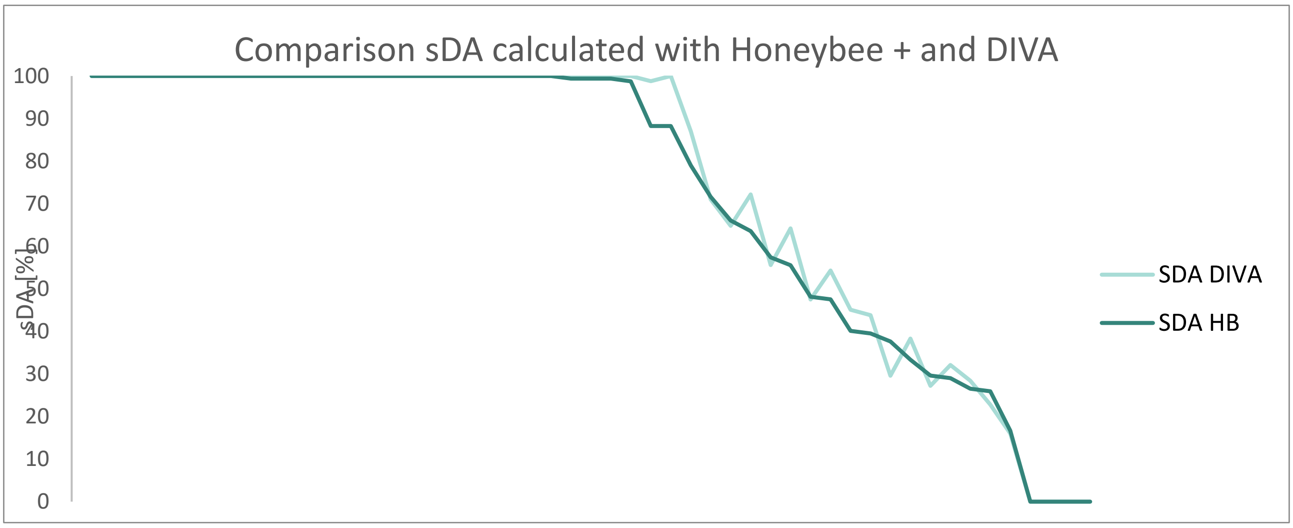
ANNEX I

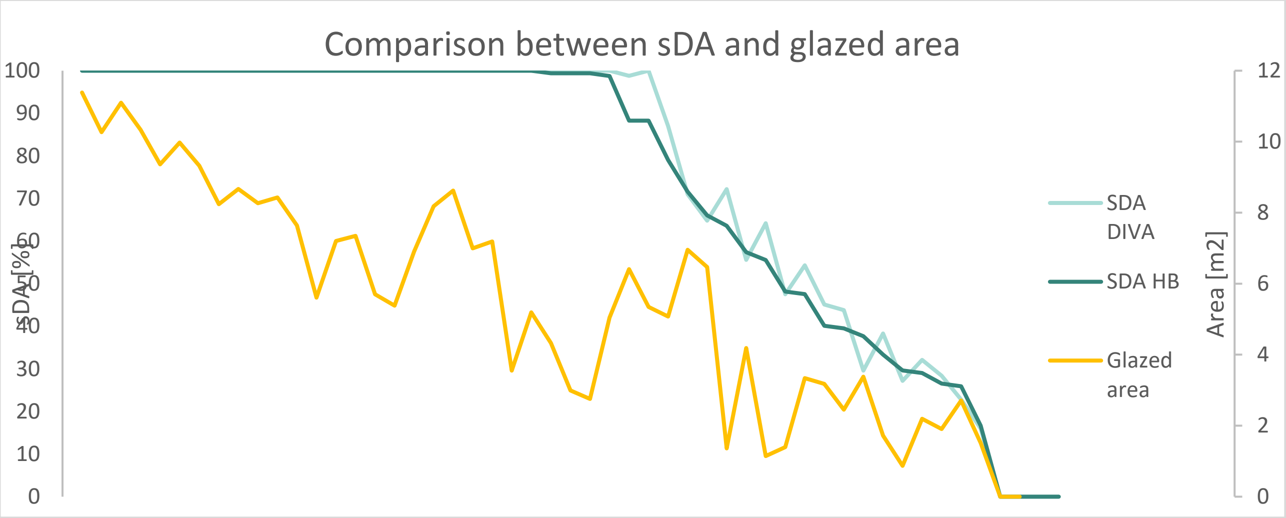
SPATIAL DAYLIGHT AUTONOMY VALIDATION OF THE CALCULATION FOR DIFFERENT CLIMATES

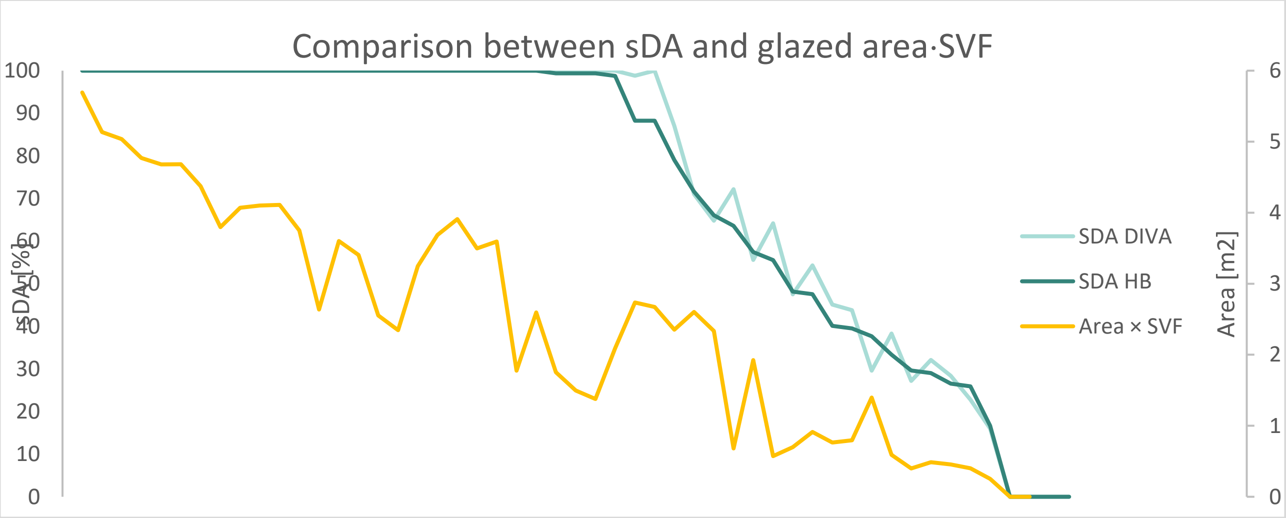
The validation of the calculation method for the sDA has been done testing different climates, in order to demonstrate that the Simplified Method can be suitable for all the climates and not only for a mild climate, like the one of Milano, which has been taken as reference at the beginning of this work.

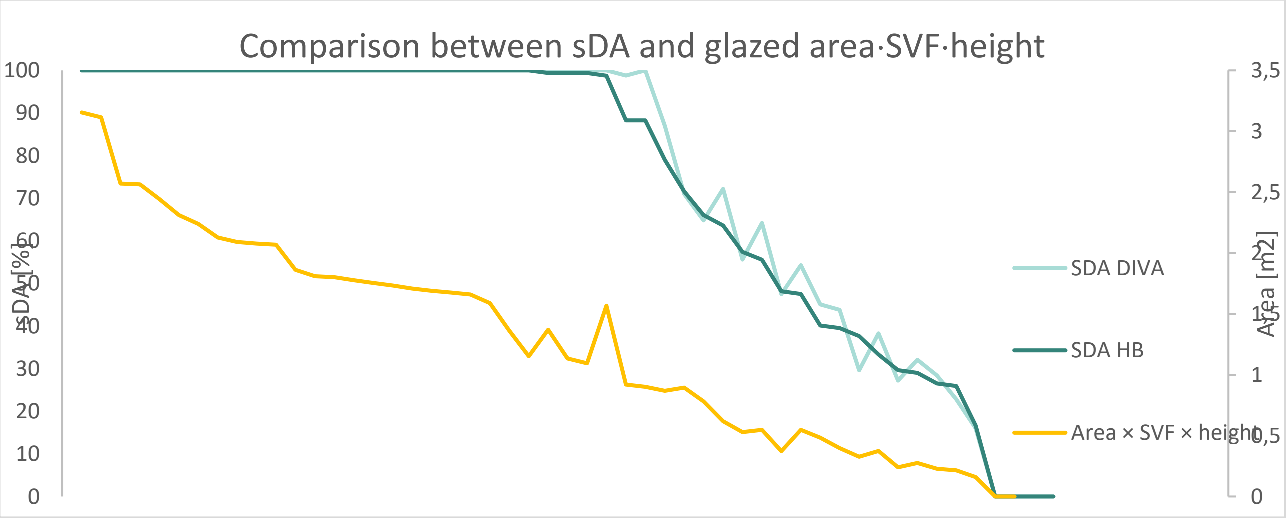
Here reported the graphs obtained during the different stages of the study:

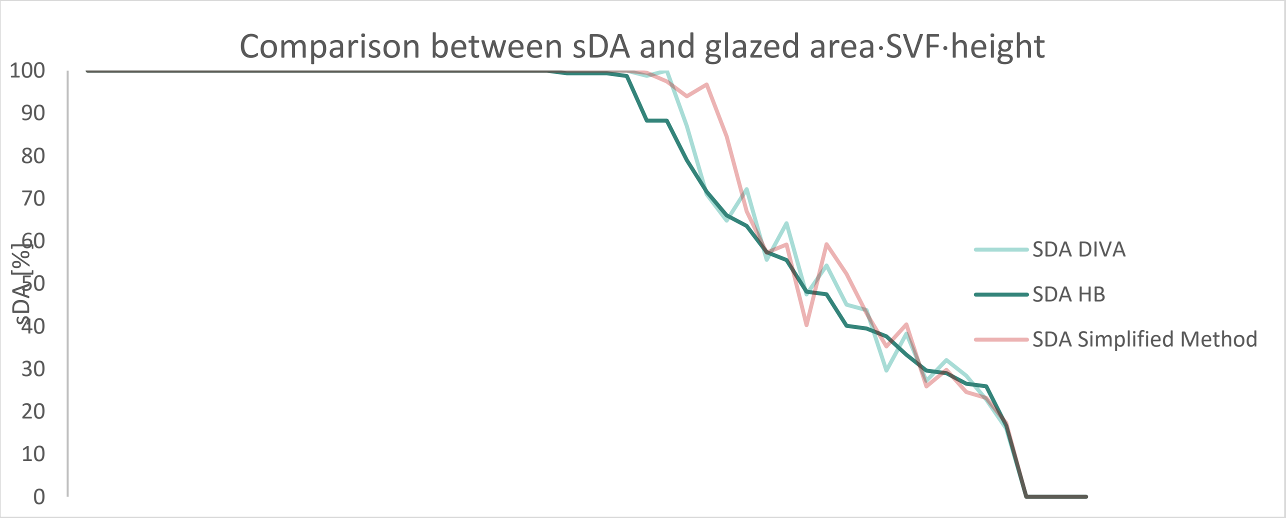
LONDON, 51° 30' 30 N



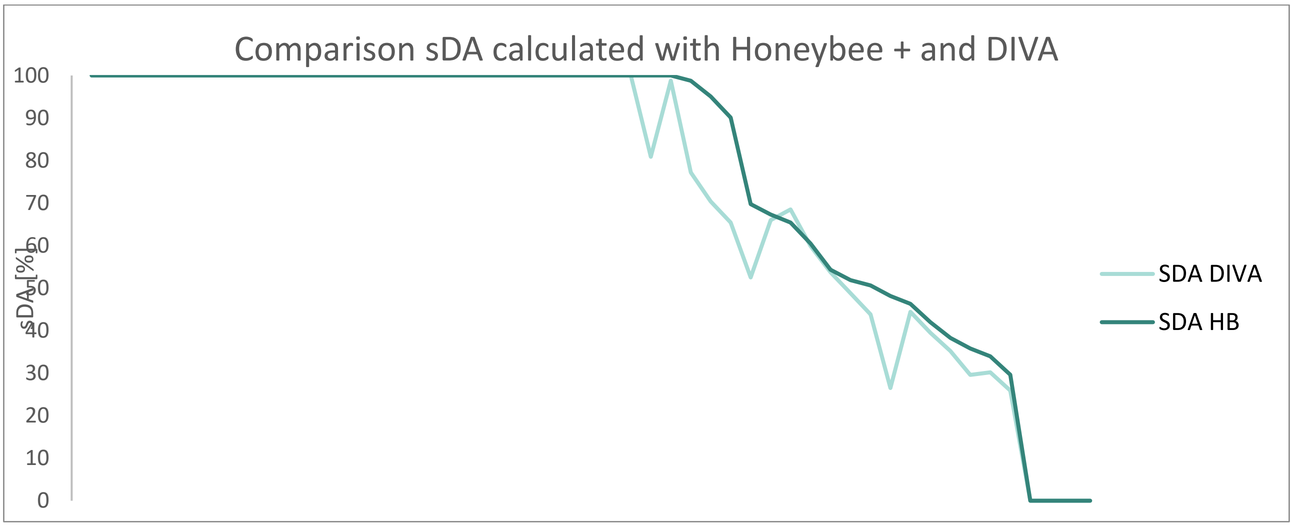

Comparison between sDA and glazed area
sDA [%]
100
90
80
70
60
50
40
30
20
10
0
Area [m2]
12
10
8
6
4
2
0
SDA DIVA
SDA HB
Glazed area

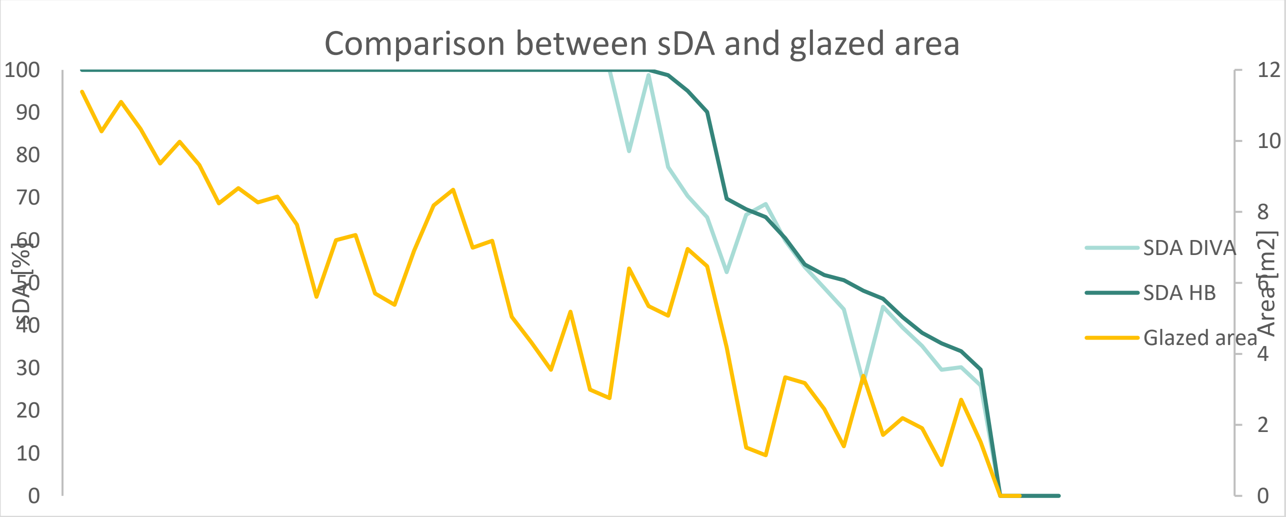

Comparison between sDA and glazed area·SVF
sDA [%]
100
90
80
70
60
50
40
30
20
10
0
Area [m2]
6
5
4
3
2
1
0
SDA DIVA
SDA HB
Area × SVF

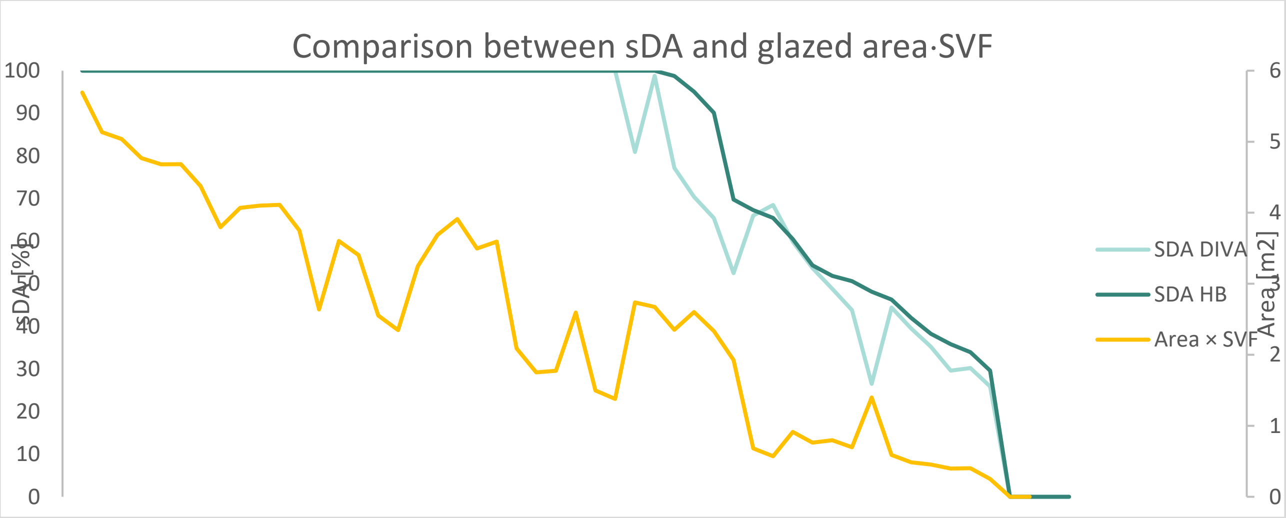

Comparison between sDA and glazed area·SVF·height
sDA [%]
100
90
80
70
60
50
40
30
20
10
0
Area [m2]
3,5
3
2,5
2
1,5
1
0,5
0
SDA DIVA
SDA HB
Area × SVF × height

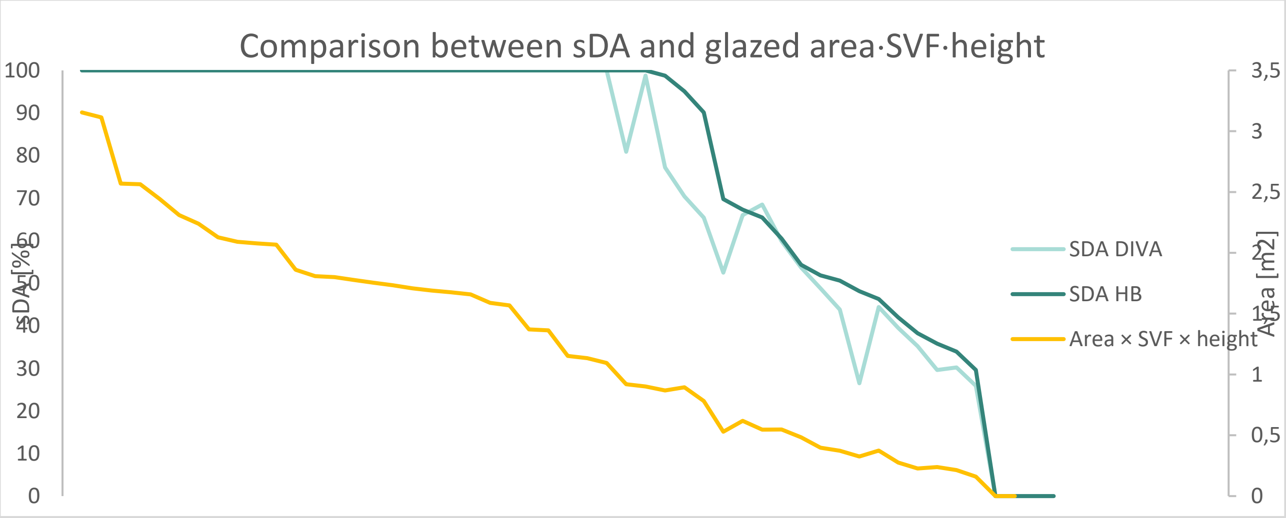


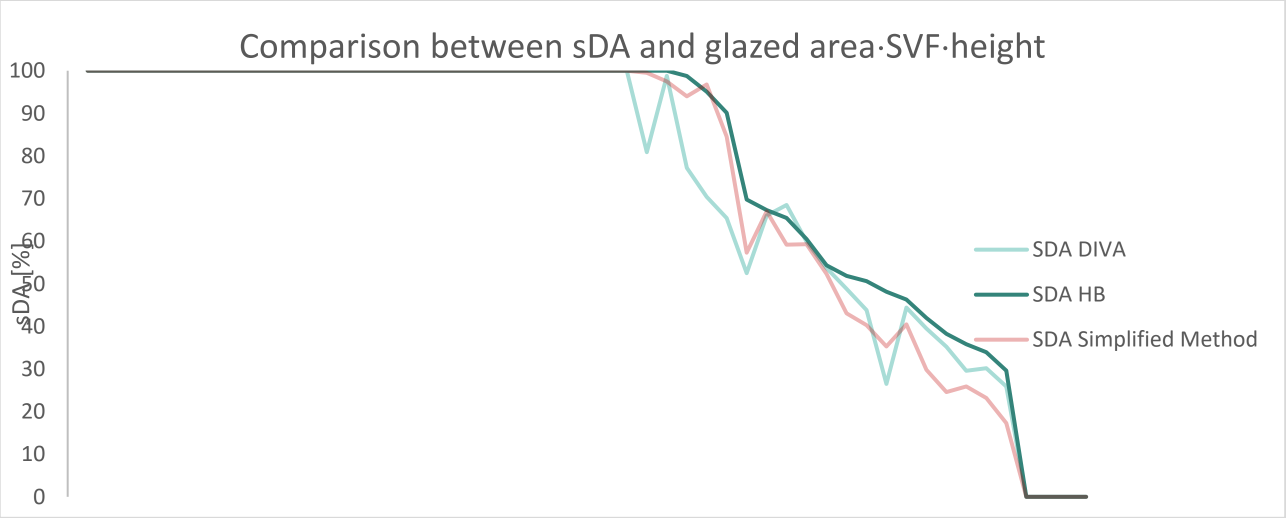
SINGAPORE, 1° 17' 22 N





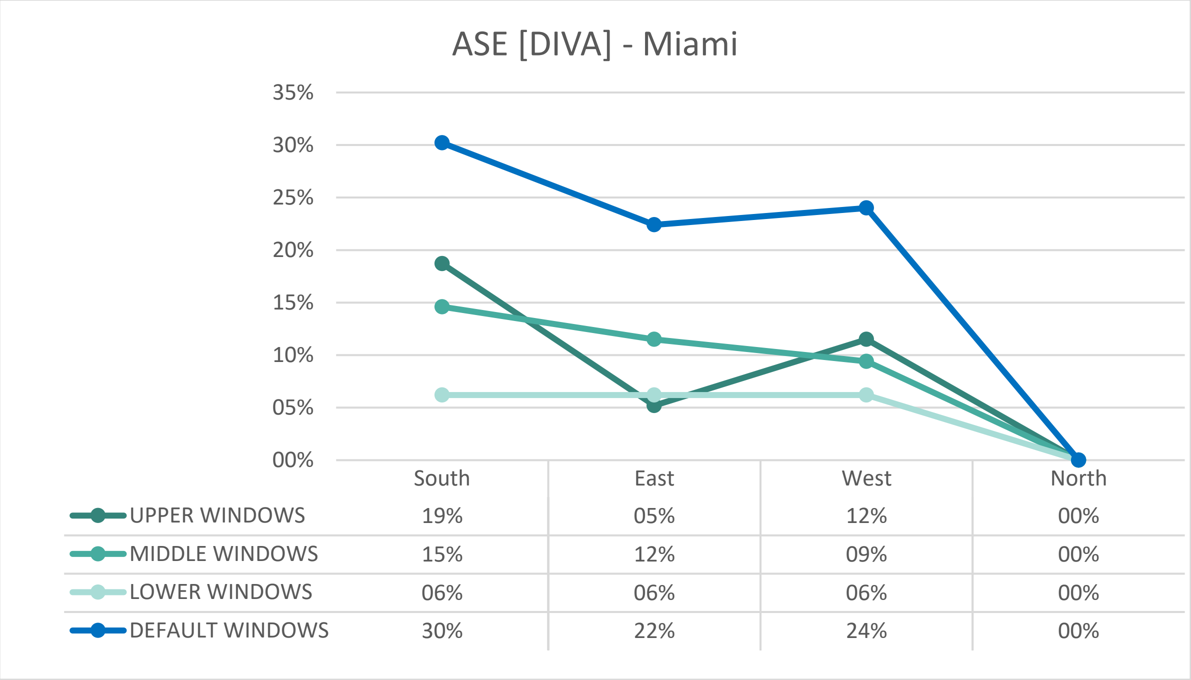

Comparison between sDA and glazed area·SVF
100
90
80
70
60
50
40
30
20
10
0
sDA [%]
6
5
4
3
2
1
0
Area [m2]
SDA DIVA
SDA HB
Area × SVF


Comparison between sDA and glazed area·SVF·height
100
90
80
70
60
50
40
30
20
10
0
sDA [%]
3,5
3
2,5
2
1,5
1
0,5
0
Area [m2]
SDA DIVA
SDA HB
Area × SVF × height

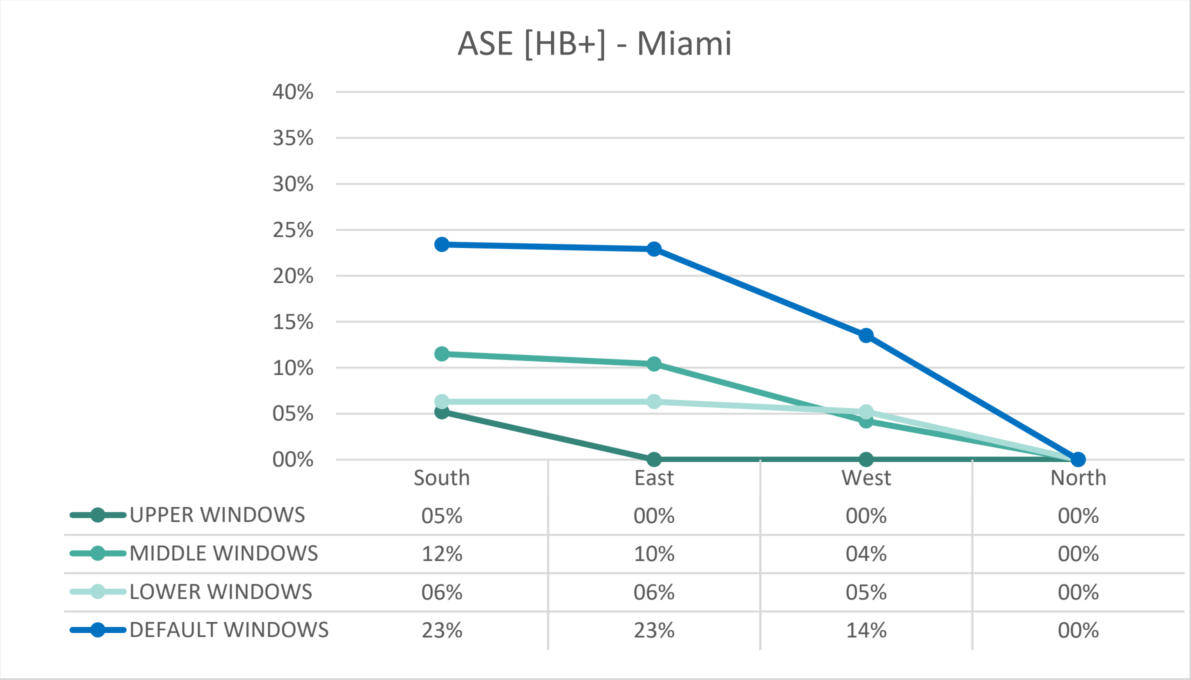

Comparison between sDA and glazed area·SVF·height
100
90
80
70
60
50
40
30
20
10
0
sDA [%]
SDA DIVA
SDA HB
SDA Simplified Method

ANNEX II

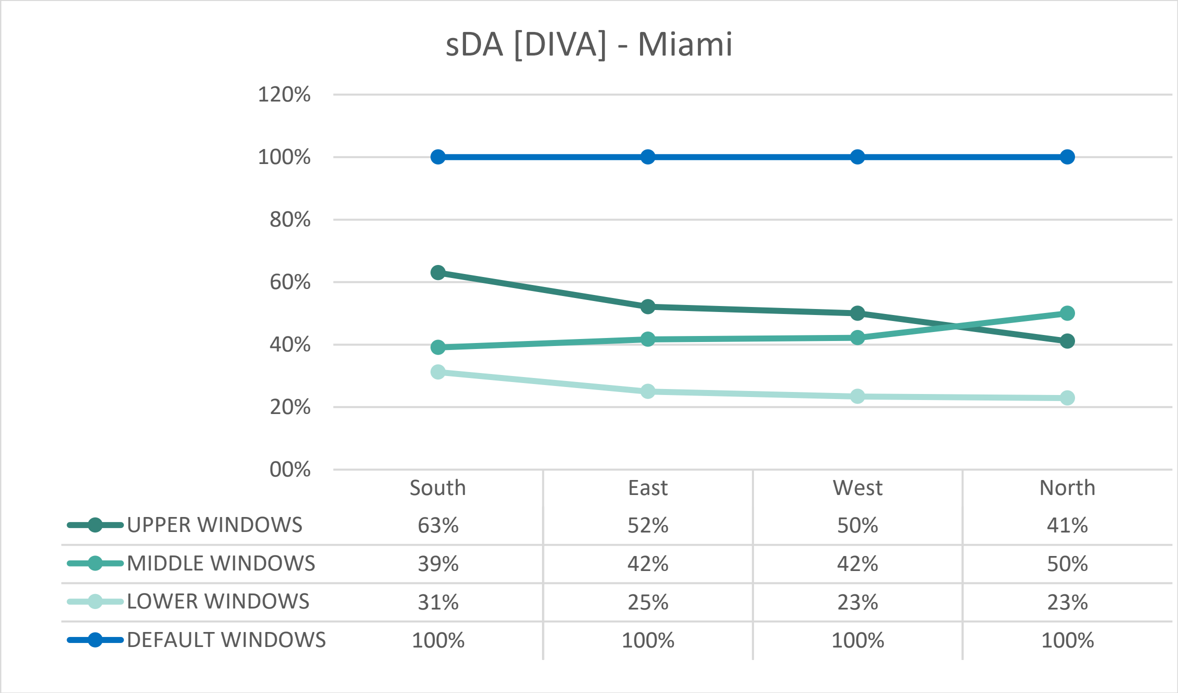
SOFTWARE COMPARISON – Miami



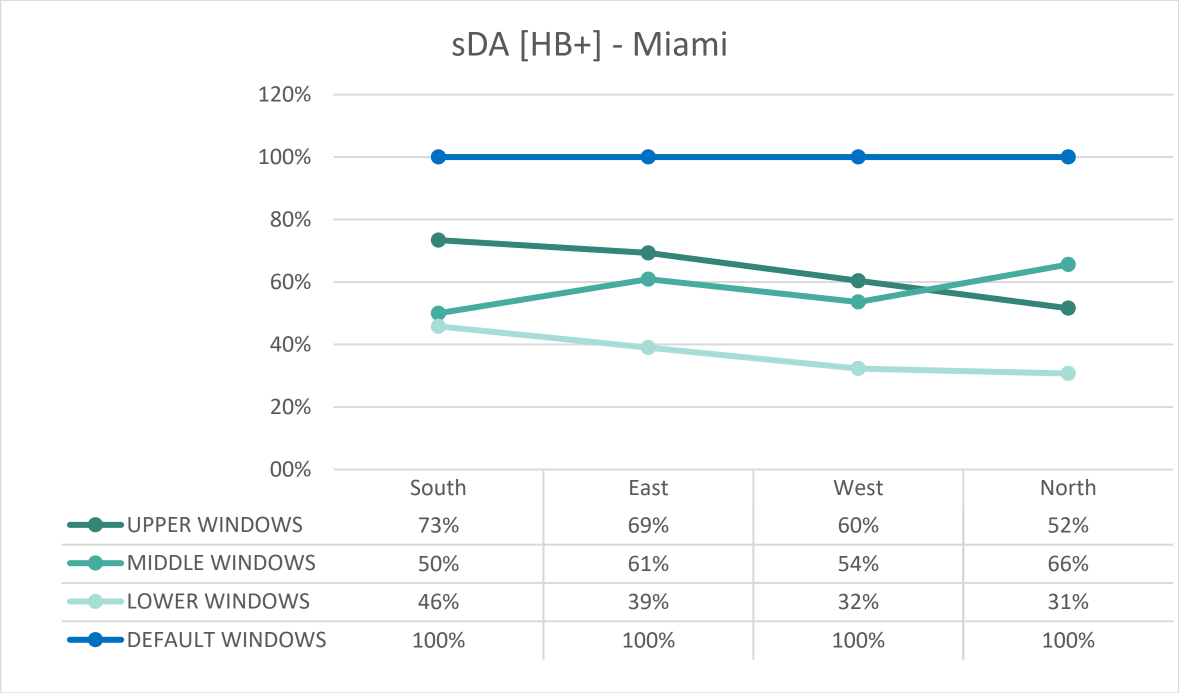
	South	East	West	North
UPPER WINDOWS	19%	05%	12%	00%
MIDDLE WINDOWS	15%	12%	09%	00%
LOWER WINDOWS	06%	06%	06%	00%
DEFAULT WINDOWS	30%	22%	24%	00%



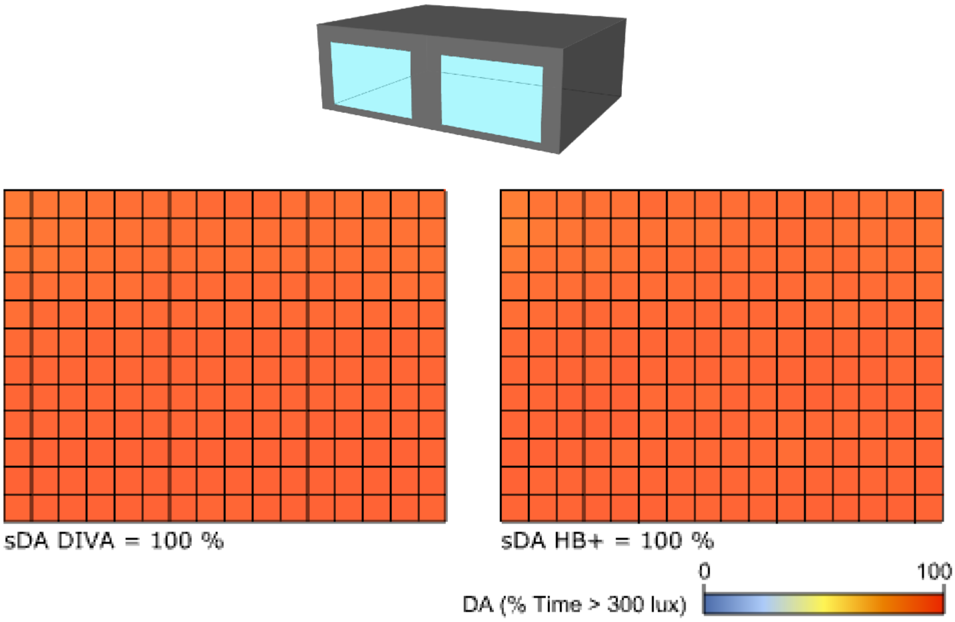
	South	East	West	North
UPPER WINDOWS	05%	00%	00%	00%
MIDDLE WINDOWS	12%	10%	04%	00%
LOWER WINDOWS	06%	06%	05%	00%
DEFAULT WINDOWS	23%	23%	14%	00%

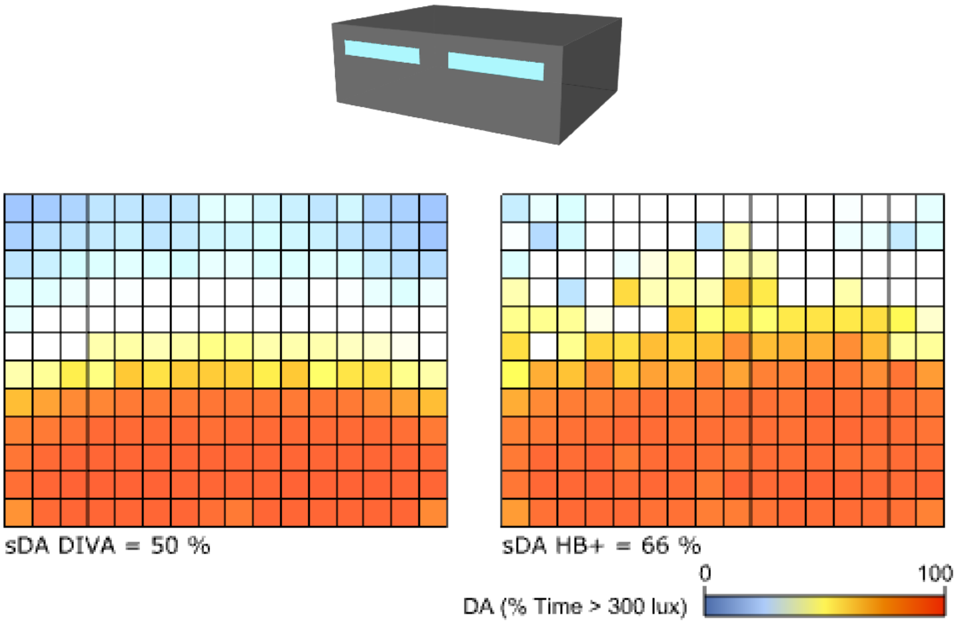


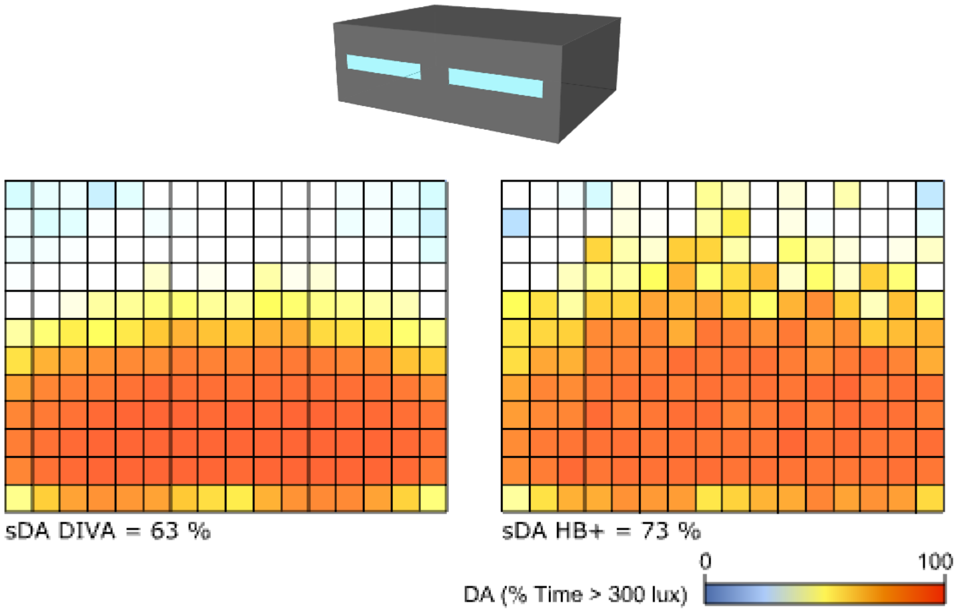
	South	East	West	North
UPPER WINDOWS	63%	52%	50%	41%
MIDDLE WINDOWS	39%	42%	42%	50%
LOWER WINDOWS	31%	25%	23%	23%
DEFAULT WINDOWS	100%	100%	100%	100%

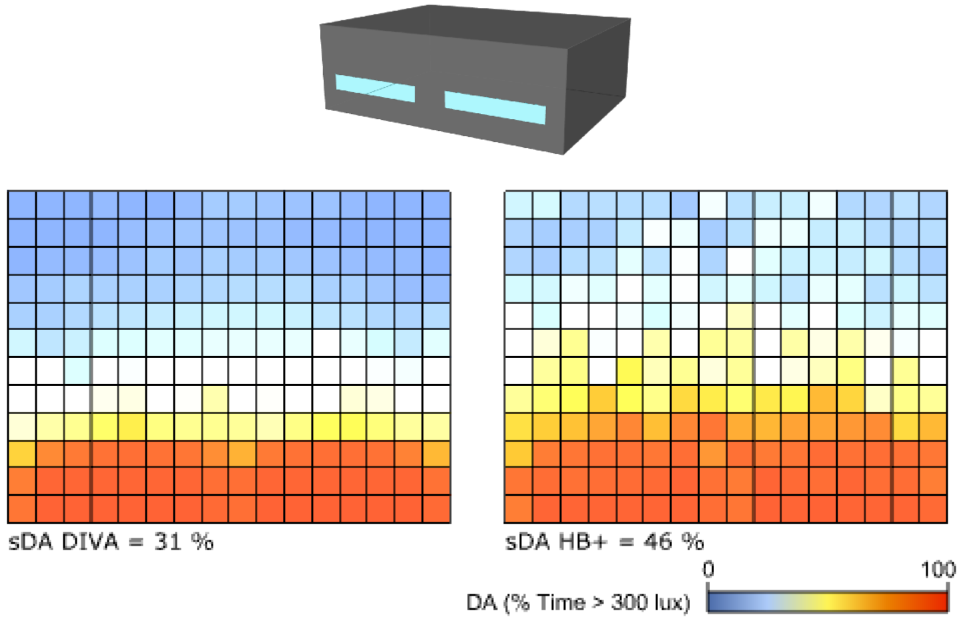


	South	East	West	North
UPPER WINDOWS	73%	69%	60%	52%
MIDDLE WINDOWS	50%	61%	54%	66%
LOWER WINDOWS	46%	39%	32%	31%
DEFAULT WINDOWS	100%	100%	100%	100%


sDA DIVA = 100 %
sDA HB+ = 100 %
DA (% Time > 300 lux)
0
100


sDA DIVA = 50 %
sDA HB+ = 66 %
DA (% Time > 300 lux)
0
100


sDA DIVA = 63 %
sDA HB+ = 73 %
0
100
DA (% Time > 300 lux)


sDA DIVA = 31 %
sDA HB+ = 46 %
0
100
DA (% Time > 300 lux)

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