Daylighting design strategies for visual comfort in classrooms

Ph.D Thesis

by

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by

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Abstract

Daylighting has taken on an important role in sustainable architecture, since it has a major impact on the energy efficiency of a building allowing, first, to reduce the load on artificial lighting and, at the same time, to reduce the internal gains of the buildings. It is important to point out that it also has a positive effect on human health, wellbeing, visual comfort and performance. In schools, it has been proven that daylighting plays an important role in the learning process and the behavior of the students.

The objective of this thesis is to define daylight criteria for the development of daylighting design strategies for classrooms, with the purpose of ensuring the visual comfort of the students. The specific objectives are: first, defining the standards for the application of the criteria, based on a dynamic daylight metric considering weather data, the different types of skies, seasons of the year and times of the day; second, conceiving, verifying and demonstrating the effectiveness of the developed strategies; and, finally, creating a consultation tool, that serves as a reference for classroom design, allowing for the understanding of light distribution and visual comfort conditions of the students, in a fast and easy way.

A new methodology for the conception of daylighting design strategies of classrooms was obtained, based on four criteria related to visual comfort; these are: the amount of daylighting, daylighting uniformity, presence of glare risk in the field of view and sunlight penetration in the classrooms. Given the dynamics and variability of the light, this is evaluated through new dynamic simulation methods, which take into account the amount of daily and seasonal variations of daylight, combined with weather data. The evaluation of these criteria, in classrooms, was determined by RADIANCE simulation, where the values are plotted in the temporal and spatial maps in order to evaluate daylight and visual comfort throughout the year. For these new criteria, two acceptance levels were stated: the *adequate* one, for all that falls within the expectations and that results in a good design; and the *optimal* one, for all that provides a high luminous quality environment using daylight effectively. We have used as case study in the application and verification of this methodology, five typologies with different localized strategies in the city of Concepción, Chile.

After carrying out the study, we can conclude that the new proposed methodology can be applied to other locations and types of buildings deeming necessary, eventually, to adapt the expected objectives to the different criteria. A daylight design that complies with the criteria, methods and standards defined in this thesis ensures a high daylight performance and a well daylit environment.

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To my husband Cristian. To my children Renato, Fernanda, Ignacia and Sebastián for the love they have always given me; to Cristian for his patience, support and permanent care for all the family during the time this research took.

I likewise, then, dedicate this thesis to my children, for all the family moments we have postponed.

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Dedico, asimismo esta tesis a mis hijos por todos los momentos que hemos pospuesto en el compartir.

Table of Contents

Figure List

Table List

1 Introduction

1.1 Background

In the last decade there has been a growing interest about the study and investigation of the conditions of people's comfort within a building, studying the environmental aspects more in depth, be they thermal, acoustic or luminal, that have an influence on the person's wellbeing. In addition, energy saving has become a popular topic, due to the growing environmental concern, which has promoted a more in depth study of these environmental aspects of sustainable architecture.

Daylighting has taken on an important role in sustainable architecture, being an environmental aspect that has a direct incidence on human health wellbeing, visual comfort and performance.

In the schools, it has been proven that daylighting plays an important role in the learning process and the behavior of the students. In 1996, 1,200 students were evaluated in North Carolina, demonstrating that those students attending daylit schools had a better performance, from 5% to 14% better, than those students who attended non-daylit schools (Nicklas & Bailey, 1996).

Between 1999 and 2003 the Heschong – Mahome group, which focused on establishing a relationship between better daylight qualities and an increase in student's performance, through standardized tests, carried out a sound study. They concluded that those students working with daylight increased their performance by 20% in math and 26% in reading. They also found that the students whose classrooms had bigger windows progressed between 19% and 20% faster. The students who had classrooms with operable windows progressed between 7% and 8% faster than those students who could not open their windows (2003). Peter R. Boyce (2004), states when referring to this study about the relationship between human performance and daylight, that a cause and effect relation has not yet been proven, but that it is possible to ascertain that daylight has a positive effect on human performance.

Through these studies, consistent proof about the importance of daylight in the architectonic design of a classroom was obtained. Daylighting is a free technology, which has an important impact on the educational experience of the students; if we apply it in a suitable way, it is possible to improve the environmental conditions in the classroom.

From an energy point of view, the reason why we should use daylight as a primary lighting source is simple: daylight provides a greater light to heat proportion than the electrical sources. This means that daylight delivers more light and less heat than electric lighting sources. As a consequence, we can significantly reduce the cooling costs in a building while, and more importantly, we generate a great energy saving (see Table 1.1-1).

Table 1.1-1: Comparison of the effectiveness of different light sources (measured in lumens per watt)

LightingSource	Efficiency (lumens/watt)
Beam Sunlight/ Diffuse Skylight	110-130
High-Intensity Discharge (high pressure sodium, metal halide)	32-124
White LEDs	80-140
Fluorescent Compact	50-60
Fluorescent	55-90
Incandescent	10-20

Source: Lawrence Berkeley National Laboratory Lighting Market Source Book for the United States

1.2 Statement of the Problem and Research Purpose

Several manuals have been developed to promote the application of energy efficiency and renewable energy in schools, such as the "National Best Practices Manual for Building High Performance Schools", available for seven different climate areas in the USA; "The future School" (2006), developed in England. We can also find works such as the "NYC Green Schools" (2009), "Washington Sustainable Schools Protocol" (2010), among others. They all include guidelines for sustainable design, construction and operation of new schools, as well as modernization and renewal projects for older schools. In these manuals we can find some recommendations about classroom daylighting design, which do not consider dynamic variability of the light. These are based on the average illuminance values only for certain moments of the year and evaluations based on the daylight factor designed for evaluation with the overcast sky only. They do not consider aspects such as the annual daylight performance and the local climate.

The dynamics of the light encourage us to study dynamic analysis methods in more depth; in other words, to use tools that allow us to create a design based on these daily, seasonal and annual dynamics, which incorporate the different climate aspects such as types of sky, which vary between one location and another. Sustainable Architecture aims at creating a design that considers the aforementioned aspects.

The Chilean Case:

In Chile, Law 19.532[1] was applied in 1997. It outlines the Jornada Escolar Completa (Full School Day, in English) for students between 6 and 18 years old, which covers elementary school and high school. Because of this Law, the Chilean Ministry of Education (MINEDUC) signed a collaboration agreement with UNESCO to develop a project called "Chilean Educational Reform: Optimization of the Investment in Educational Facilities", which generated a research process for new architectonic solutions that would contribute to a quality educational process. This generated an increase in the creation of new school facilities in Chile.

The Fondo de Inversiones en Infraestructura (FIE) (Facilities Investment Fund, in English) injected an important amount of economic capital for the construction and improvement of the facilities, capital with which more than 1,700 projects for school infrastructure have been financed. In Figure 1.2-1 we can see the increase of the investment for school facilities in Chile up to 2007.

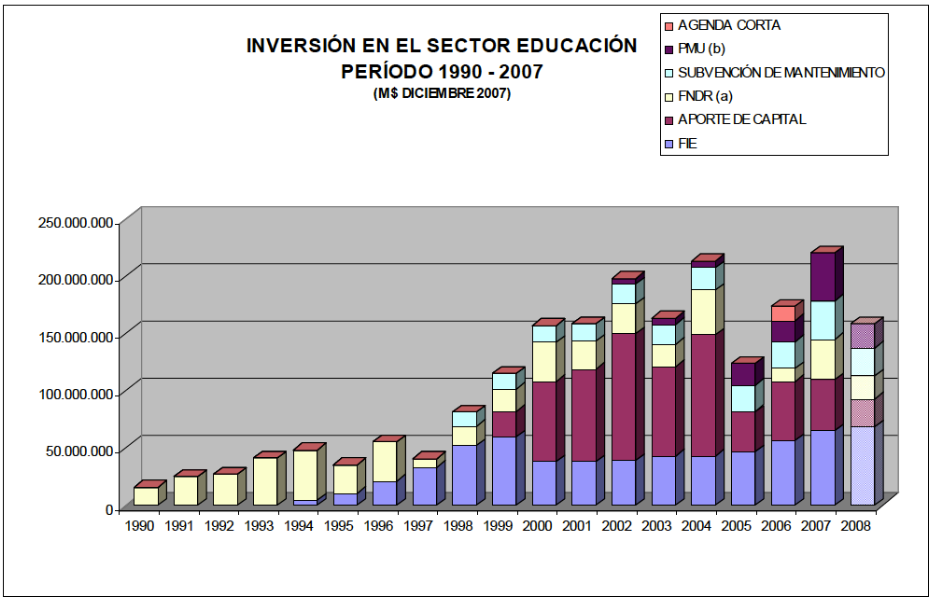


Figure 1.2-1: Graph for school infrastructure investment in Chile, 1990 -2007. (source: MINEDUC)

As a consequence of this state capital injection, MINEDUC and UNESCO edited a series of books called "Design Guidelines for Educational Spaces" (1999) and the "New Educational Spaces" (1999 – 2001, 2003 – 2005, 2007 – 2010), which contained the advances made in school facilities. It can be said that Chile has evolved a great deal in this matter but upon reviewing the classroom designs we can see that they have kept the same design parameters

[1] MINISTRY OF EDUCATION (MINEDUC) enactment 17-11-1997, Law 19532:It creates the full day and night full school day and norms for its application.
[2] CHPS: The Collaborative for High Performance Schools.

for daylight that appear in the aforementioned reform. No criteria including environmental parameters have been incorporated to the school facilities norm.

In 2009, the Chilean Government stated that, for the construction of school facilities, the starting point should be the sustainable architecture, in order to improve the environmental comfort, which would allow for an improvement on the quality of the educational process, taking its benefits into account and getting them involved (MINEDUC, 2009).

Figure 1.2-2: Classroom before the Educational reform, older schools. (source: personal archive, 2008)

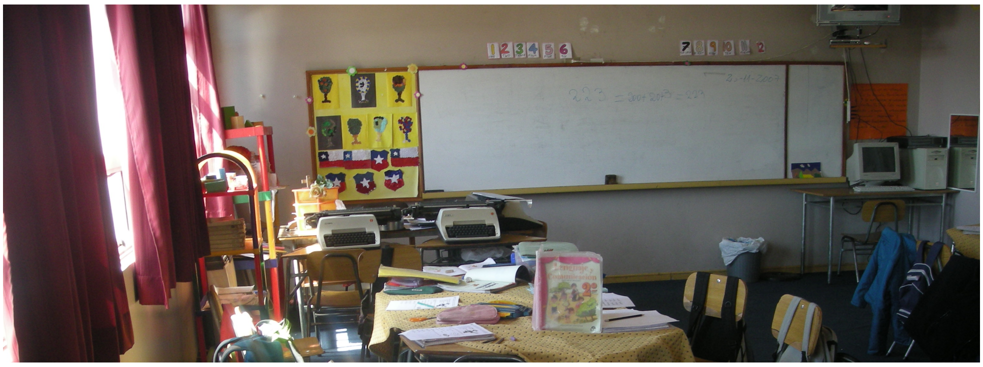


Figure 1.2-3: Classroom built after the reform, in 2001. (source: personal archive)

Because of all the previously shown, a study on daylighting in classrooms was implemented, in order to contribute to a more in depth knowledge of the matter as a part of sustainable architecture. It is necessary to create solid foundations to then create design recommendations and solutions applied to the architecture project. In addition, we look to contribute to the knowledge on the subject, generating the integration of weather and time variables with the luminous analysis of the classrooms.

The focus of this thesis is the definition of guidelines that can aid the architects with their design, to improve and enhance the quality of daylight in a classroom, based on visual comfort criteria, integrating dynamic analysis methods that allow for the quantifications of these criteria.

1.3 Research Objectives

The objective of this thesis is to define daylight criteria for the conception of daylighting design strategies in classrooms, with the purpose of ensuring the student's visual comfort. We created a new methodology using these new daylight criteria and integrating new objectives, allowing for the evaluation of daylight quality in classrooms, worldwide.

By daylight strategies, we mean the rules that guide daylight design. Daylight strategies are considered as an architectural proposal whose objective is to achieve an adequate use of daylight. How daylight is introduced in the classroom will be a determining factor when it comes to visual comfort. The strategies will affect the size and set-up of the windows (for example, the type, number and location of them).

The visual comfort is achieved when these conditions allow people to carry out visual tasks in a fast and easy way. It is considered as a contribution to the learning process of students and teachers. Through the architectural design, a suitable visual environment must be provided, which balances the amount and quality of the light in each classroom and that controls or eliminates glare.

The new objectives proposed for each criterion are the target values for daylit designs and the methods that are established in a structured and organized way, by which we obtain the results that allow for an evaluation and verification of these target.

In order to verify this new methodology, we applied it to the specific case of Chilean classrooms. However, if we adapt the goal values of the criteria to the local weather conditions of different locations around the world, this methodology can be used to evaluate different daylight scenarios to propose customized daylighting design solutions.

The specific objectives are:

- Defining the adequate and optimal standards for the application of the criteria, based on the dynamic metric of daylight, which consider weather and location aspects.
- Conceiving, verifying and demonstrating the effectiveness of the classroom's daylighting strategies.

- Creating a consultation tool, as a reference for classroom design, allowing for the understanding of light distribution and visual comfort conditions of the students, in a fast and easy way.

1.4 Research Methods

The method applied for the fulfilment of the objectives was divided in three stages. The first stage involved the review and diagnosis of the standards referring to daylight in norms and design guidelines for classroom design. The purpose of this was to generate the foundations for a definition of the analysis methods. The second stage consisted of the evaluation and diagnosis of the classrooms, onsite. The third stage consisted of the creation of criteria, the generation of simulations, the application of the analysis methods and the verification of the proposed daylight strategies.

1.4.1 Diagnosis of Lighting Standards

For this stage, a theoretical, analytical and synthetic method is used. The analysis is applied as an objective process that allows the division of the multiple components and of the relationships between them. Then, the synthesis stage occurs, where the union of the previously analyzed parts takes place, enabling us to find the essential relationships between them and their general characteristics. The synthesis leads to the criteria, metrics and application methods, which are based on the results obtained in the previous analysis. This stage is divided as follows:

- Analysis of the standards used for daylighting and of the design recommendations, as well as the identification of the criteria used for the national and international norms. The purpose of this is to contribute to the justifications and creation of each of the criterions to be defined.

- Exploration of the methods used for the execution of the simulations and evaluation of the lighting conditions. Analysis of the advantages and disadvantages of each one of them; definition of those applicable to this investigation.

- Definition of the metrics that will be applied for the evaluation of the visual comfort and of daylight lighting levels.

1.4.2 Diagnosis of the Current Situation

Due to the great investment made by the Chilean government in Schools, a diagnosis of the visual comfort conditions that came as a result in the new schools took place. The onsite study was carried out in the city of Concepción, Chile, using an empirical method to identify the context of this research. For the generation of this diagnosis, we proceeded in the following way:

- Evaluation of the lighting and visual comfort conditions through the "Post Occupancy Evaluation" method, which implies the application of surveys to teachers from 1st to 5th grade.
- Review and estimation of the luminous conditions in the classrooms by measuring the situations found, in situ and with photographs.
- Gathering of data to characterize the classrooms that will be evaluated in the preliminary study.

1.4.3 Application of the Strategies and Criteria for a Daylit Classroom.

This is the stage where the simulations applied to the new lighting strategies proposal take place. Given the dynamics and variability of the light, this is evaluated through dynamic simulation methods that allow the generation of an abstraction of reality, in order to evaluate daylight and visual comfort throughout the year. With this purpose, the following activities are carried out:

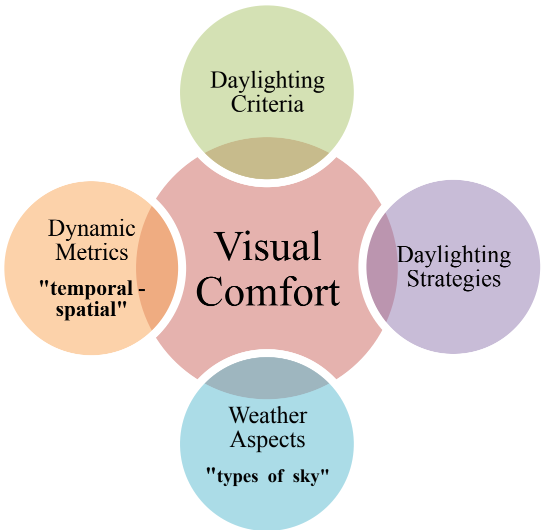
- Diagnosis of the classrooms found, initiating the preliminary study. Through this study, the simulations for this stage are explored and calibrated.
- Development and application of new metrics and methods that will lead to the analysis of the strategies for daylighting in classrooms.
- Definition and creation of the virtual architectonic models of the daylight strategies.
- Definition and evaluation of the criteria and dynamic analysis methods defined before.
- Optimization and verification of the strategies in the search for optimal solutions that allow us to ensure visual comfort.

- Generation and implementation of a database that gathers the results obtained from the applied simulations. In other words, creating a fast and easy consultation tool for architects.

1.5 Significance of the Proposed Study

The uniqueness of the present thesis lies in the development of a new methodology for the analysis and evaluation of daylight. It is based on criteria for daylight design and visual comfort. New dynamic metrics are included for the fulfillment of the objectives proposed in the criteria.

It is original, because it considers a complete cycle for the design process. Criteria are provided and we also indicate the steps to verify each one of them. In this cycle, four key components are integrated aiming towards the design, with the purpose of achieving visual comfort based on the real needs of the visual tasks. These components are integrated and organized as follows:



The criteria present a new way of applying this dynamic metric, and considers aspects such as the types of skies, the seasons of the year and the different moments of the day; that is to say, it includes the annual performance and the local weather conditions, all synthesized in a temporal and spatial representation through temporal maps developed, in a first stage, by Mardajelvic (2000) and later by Andersen (Kleindienst, Bodart, & Andersen, 2008) and Kliendienst (2010).

Also, standards are defined for the application of this metric for evaluation and analysis. Two levels of design standards are defined: one defined as "adequate", which corresponds to the fulfillment of the criteria; the other defined as "optimal", which corresponds to the design with high daylight performance. Finally, the information is triangulated, i.e., the design criteria, the standards and the dynamic metrics.

Additionally, this thesis proposes the generation of a database to gather the large amount of data that resulted from the simulations. We propose an order and way of reading this data. Also, we present the results of the different daylight strategies, generating a new consultation source aimed at communicating this information to the professionals who make the design decisions.

1.6 Thesis Structure

The thesis shows methods for daylight design and how these are applied for the evaluation of the criteria. It begins with a general introduction to provide the context of this research.

Then, in Chapter 2, the theoretical foundations are developed to elaborate the methodology. All the aspects of daylight, which have an incidence on visual comfort, in the design of classrooms, and on the variables and factors to be considered when designing, are analyzed. A more detailed review of the norms that regulate daylight takes place. Further ahead, the relevant observations on the preliminary study carried out, are exposed.

In Chapter 3, the dynamic analysis methods, which consider the weather variables for the city of Concepción, are presented; the fundamental criteria for the design of daylight in a classroom are proposed, and the daylight strategies used, are defined. We present the definition of the RADIANCE parameters, of the materiality of the case studies, of the analysis grid and of the definition methods of the environmental parameters.

In Chapter 4, the results obtained in the case studies are analyzed. This analysis is developed starting from the stated criteria. Here, four essential components come together: the classroom as an architectonic element, the orientation – which contextualizes the works, the types of skies typical to local weather and the incoming light. An accurate diagnosis of that found for each of the orientations is made.

The objective of Chapter 5 is to improve the case studies analyzed in Chapter 4, in order to find an optimal solution. The method by which we defined the classrooms to be optimized is shown, as well as the results obtained. Design recommendations are stated, and the applications of each one of the strategies comparing daylight criteria are presented in tables. These tables allow us to distinguish the advantages and disadvantages of each one of the strategies.

In Chapter 6, the consultation tool developed on a database is presented. This allows us to organize the large amount of information that resulted from the simulations. The demands the tool had to meet are indicated, as well as its general structure, and the order and way in which the information is visualized.

Finally, in Chapter 7 the conclusions of this thesis are developed, together with the conclusions derived from the different stages developed in our way to achieving the objectives. To finalize, future works that may be generated following this research are presented.

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2 Theoretical Framework

In the present Chapter 2, we set the foundations that will lead to the methodology proposed in Chapter 3 are presented. It begins with the presentation of the importance of daylight and its effects on human functions. Next, the different factors that have an influence on visual comfort, such as amount and distribution of daylight, uniformity and glare sources are addressed; the qualitative and quantitative aspects of each one of these factors are detailed. Finally, classroom variables are introduced which are those that have an influence on lighting strategies, such as classroom arrangements and window proportions, to then close the chapter with a design diagnosis, carried out in the classrooms of the city of Concepción.

2.1 Effect of Daylight on Human Functions

The presence of daylight affects human beings both physiologically and psychologically. Physiologically, it has an influence on our visual system and, at the same time, on the circadian rhythm. The circadian rhythm and the visual system respond differently depending on the characteristics of lighting: amount of light, luminous spectrum, spatial distribution and duration. It is also important to mention that lighting has a psychological effect, especially on our perceptive system, producing social behavior alterations and mood swings. The perceptive system is determined by the message sent to our brain, which depends on multiple factors such as cultural context, motivation, preferences, expectations, etc. and it is different for every individual, so understanding the luminous environment from the point of view of perception is a long and complicated task (Boyce, Human factor in Lighting, 2003).

The circadian rhythm involves the biological rhythms that repeat themselves every 24 hours, approximately; it is driven by an internal clock, which is synchronized with the solar cycle of light/darkness. The circadian rhythm regulates not only the evident behavioral patterns, such as activity and rest periods, but also the bodily functions at a cell level. Studies have shown that morning light, with a short wavelength (blue), provides more circadian stimulation in the classrooms; it was seen that students who are not exposed to the morning light would experience a more pronounced late circadian phase, which would result in going to bed later, sleep disorders and possible chronic sleep deprivation, stress and mood swings (Leslie, Smith, Radetsky, Figueiro, & Yue, 2010).

To this we have to add that researchers have discovered that our short-term memory works in an optimal way between 10am and 6pm, which has a favorable influence on school work and concentration. The period between 6pm and midnight favors studying, because during this moment our long-term memory works better. Children, more specifically, are very sensitive to daylight variations, so it is crucial to keep this rhythm and natural biological clock of the human body in the classroom (Boubekri, 2007).

Finally, it has been demonstrated that lack of daylight, like the seasonal reduction of the available daylight during the winter, in the extreme North and South latitudes, can lead to depression. The seasonal affective disorder (SAD), also known as the “sad winter days”, is recognized by the medical community as a psychiatric disorder (Rosenthal, 1998).

It is important to consider the photometric and architectonic variables that have a direct influence on the luminous environment, whose purpose is to favor and stimulate the aforementioned aspects. A good daylighting design is defined as the practice of efficiently taking daylight into a space, during the day, so that daylight substitutes or complements the artificial lighting inside that space.

2.2 Visual Comfort

Visual comfort is obtained when it is possible to see objects clearly in the environment, without suffering from visual fatigue. Correct classroom lighting should allow us to see the contents on the whiteboard, the information panel and the learning materials used in class, clearly.

Visual comfort is defined in relation to the amount, quality and distribution of light. P. Boyce refers to those luminous aspects that can cause visual discomfort and, in general terms, visual discomfort occurs when: there is little light, there is too much light, there is too much illuminance variation –even more through the workplanes, the presence of disturbing glare, uncomfortable glare, veil reflections on the surfaces, the presence of shadows and those defects of the artificial lighting systems (flickering) (2003).

The aforementioned aspects coincide with those defined by Veitch, who specified the general lighting aspects that are related to visual comfort, and they are (Veitch & Newsham, 1996):

- Lighting and uniformity,
- Illuminance and its distribution,
- Glare,
- Flickering of lamps,
- Spectral distribution of light,
- The lighting system,
- The possibility of having individual lighting control,
- The presence of daylight.

The IESNA Lighting Handbook gives formalized recommendations of lighting quality in schools; this manual describes the quality of lighting as the integration of human needs, architecture, economy and the environment. In the section about educational buildings, it suggests that the most important factors that contribute to good quality lighting in schools must include: the integration of daylight and its control, avoiding reflections and direct glare, flicker (and strobe), light distribution on surfaces and light distribution on the workplane (uniformity) (IESNA, 2000).

From a design point of view, a bad lighting conception can result in a greater use of energy, as well as other unwanted visual comfort situations, or typical ones for visual tasks. From this point of view, Rogers defines that the following lighting aspects are to be considered to achieve a successful design (Rogers, 2008):

- Daylight amount: the necessary requirements to provide daylighting levels for great part of the year.

- Daylight quality: daylight uniformity in order to reduce high, disturbing glare; the control of direct sunlight; and the use of sunlight contributions when necessary.

- Ensuring the Access of enough daylight for all the occupants of the room and allowing a connection with the outside.

Starting from all the defined aspects, we considered addressing this research from the three factors that are related to daylighting design and visual comfort. These are:

1 *The amount of daylighting:* it is related to the design objectives and how they generate the best luminous condition to improve the performance of visual tasks.

2 *Daylighting uniformity:* it is related to the spatial distribution of lighting. In the uniformity recommendations, illuminance and luminance proportions have been defined.

3 *Presence of glare sources:* the presence of too high illuminances in the visual field, or not very uniform luminance distributions, can cause discomfort. There is a large variety of predictive models for glare perception that have been developed both for lighting and for daylighting.

It is important to add that there are parameters that affect visual comfort, that are related directly to the people. They do not depend on daylight design, and they include: age, visual sharpness, time available for the execution of a task and those parameters own to the objects, such as their size.

2.2.1 Amount of Lighting

The amount of light received on a surface is measured by the illuminances. It is the easiest and most used way of quantifying light performance. By illuminance or illuminance level, we understand the luminous flow (lumens) emitted by a light source, reaching a surface vertically or horizontally, divided by such surface. Its measuring unit is the lux. It is, thus, a set of quantitative parameters that states if an area is more or less illuminated (IDAE, 2001).

The metrics for the evaluation of lighting levels have evolved a great deal. We have a daylight factor, which has been used; however, it is a very limited static metric, based on a unique overcast sky condition. The negative aspects of this metric have been discussed by several researchers: it is weather independent, because it does not consider the orientation of the building or its use.

The development of dynamic light simulation tools have allowed the creation of other metrics that integrate variables such as weather, orientation, real illuminance needs and the use of the space. Mardljevic developed the "Annual Daylight Profile" (2000), same as Reinhart and Walkenhorst (2001)wrote "Daylighting Autonomy", among others. These dynamic metrics became an alternative for light factor calculations, which is addressed in Chapter 3.

J.Veitch states that the lighting concepts are related to the luminance concepts, meaning that when the lighting reaches certain point, its illuminance in a given direction increases proportionally, concluding that the observations carried out on that referring to lighting are, thus, also valid for the luminance (Veitch & Newsham, 1996). Therefore, it is important at the same time to understand what luminance is. It is defined as the relation between a luminous intensity emitted from a source in one direction, and the surface it is reflected on, as seen by an observer located in the same direction. It is expressed as candela/m^2. The luminances on a surface depend on the lighting received by it, on the reflection coefficient and the glare of the surface. It is a phenomenon that is difficult to quantify and evaluate.

With the purpose of producing a satisfactory environment, comfort and visual performance we recommend to balance the illuminances and luminances within the visual field. The ideal situation is that the existing luminances and illuminances around the workplane are gradually reduced, thus avoiding strong contrasts (Boyce, Human factor in Lighting, 2003).

- *Daylighting levels for classroom*

In relation to whether the lighting levels have a direct influence on visual performance, some studies show that there is a relation between these two parameters: visual performance increases fast with the lighting level; however, it reaches a maximum limit and, starting from here, the increase of lighting does not induce more variation of the visual result (Veitch & Newsham, 1996). Nonetheless, there are other studies that do not show a correlation between the two parameters, finally stating that people adapt to new luminous conditions and have good results, independent from the lighting level. An increase of the illuminance levels over that considered as optimal cannot be justified and, on the contrary, it may lead to an excessive use of energy. This is why it is important to clearly refer to the necessary lighting levels in relation to the visual tasks in a classroom.

In classrooms, in general, the activities are organized in respect to the whiteboard or projection screens, besides the general class work. Because of this it, is necessary to consider the horizontal illuminances, with respect to the workplane of the students, and the vertical illuminances, with respect to the whiteboard or projection screens.

The illuminance level must be set with respect to the type of task to be carried out (visual sharpness needs), the level of optimal lighting corresponds to that which results in a greater performance with a minimum fatigue (CEP, 2002). In general, the greater the visual perception difficulty, the greater should the lighting level be. The European Committee for Standardization (CEN/TC 169) suggests the illuminance values for the different visual tasks that can be seen in Figure 2.2-1.

Based on Figure 2.2-1, IESNA recommends illuminance values, which consider the performance of visual tasks of high contrast and small size, or visual tasks of low contrast and large size for a classroom. According to this, the illuminance range fluctuates between 300 lux and 2000 lux. It is recommended, for activities own to a classroom such as reading and writing, to have an illuminance of 500 lux (50 fc) and remain in a range of 10% within these values (IESNA, 2000).

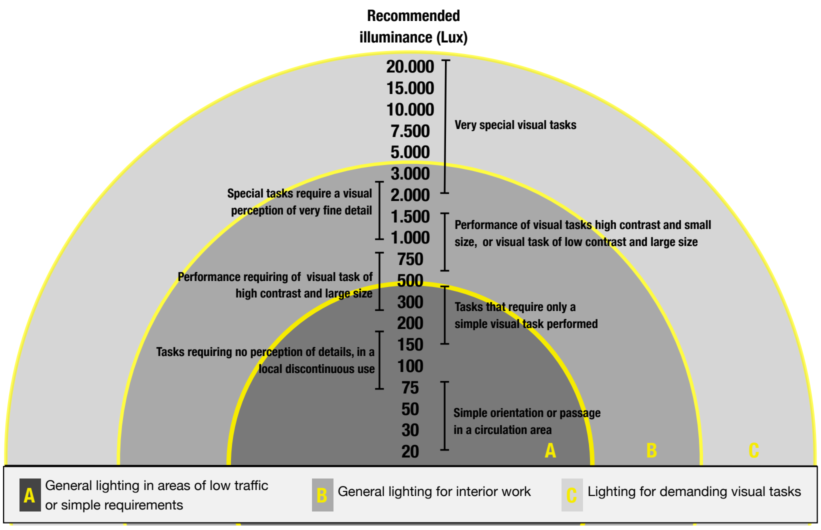

Figure 2.2-1: Recommended illuminance levels per activity type

A review of the norms and recommendations for the illuminance values in classrooms was carried out. There are great differences, which are summarized in Table 2.2-1. We have to point out that the illuminance values shown are determined for artificial.

Table 2.2-1: International standards for classroom lighting.

Areas	Chile DS 548	Argentina	Mexico CAPFCE Norm	Brazil	United Kingdom	Australia	Finland	European EN 12464-1	IESNA
General	500 lux classroom	500 lux	Pre-school: 150 lux Primary: 150 lux Secondary: 175 -250 lux		300 lux classroom 500 lux complex tasks	240 lux	150-300 lux	> 300 lux	Maximum 1500-2000 lux (±150-200 fc) Minimum 300 lux (30fc)
Whiteboard	---	1000 lux	---	300 - 750 lux	---	240 lux	300 -750 lux	> 500 lux	±500 lux (45 fc)
PC	---	750 lux	---	---	---	160 lux	150 -300 lux	50 lux	±160 lux (15 fc)
Reading	---	---	---	200 - 500 lux	---	320 lux	500 -1000 lux	> 500 lux	±500 lux (45 fc)
Drawing	---	1000 lux	---	3000 lux	---	600 lux	1000 -2000 lux	>500 lux	±500 lux (45 fc)

The standards we see in the table, in the Chilean case, are below the minimum values recommended for simple tasks. The European norm EN 12464-1 states values that are required for tasks with a medium visual performance. Based on this norm, a group of researchers proposes to differentiate classroom activities and also to organize them, according to the requirements of the task for teachers and students, organization expressed in Table 2.2-2 (de Bruin-Hordijk & de Groot, 2010).

Table 2.2-2:Overview of tasks in a classroom together with the requirements for the illuminances.

Task	The Teacher	The Student	Standard Illuminance	
			In class	In general
1	Writing on blackboard	Reading on blackboard	500 lux (vertical)	200 lux
2	Talking to the students	Paying attention to the teacher	300 lux	300 lux
3	Showing a presentation (slides, powerpoint,television, etc.)	Looking onto the screen	300/10 lux	10 lux
4	Paying attention to working students	Writing, reading drawing, etc.	300 lux	300 lux
5	Coaching computer activities	Looking to the computer screen and the paper	50 lux	300 lux above the computer
6	Preparing lessons	Not present	300 lux	50 lux

By the methodology stated in Chapter 3, an illuminance range is defined for the design considerations, with daylighting, in a classroom. We defined, according to that stated by

IESNA, and with the purpose of this research, a minimum of 300 lux (simple task) and a maximum limit of 2000 lux (exact visual perception), according to the maximum limit recommended.

2.2.2 Lighting Uniformity

The lighting uniformity will depend on the space and activity to be carried out in the room. Even though the exposition to a completely uniform visual field is undesirable, it is also undesirable to have too much lack of uniformity. For this reason, the recommendations for uniformity are generally in respect to the minimum illuminance or luminance uniformities. These two photometric amounts are appropriate for the description of the uniformity of the local luminous conditions.

The recommendations are with respect to the task and its surroundings, in terms of the minimum, average and/or maximum illuminance through the workplanes (desk). In the case of the uniformity, when it comes to the luminances, these recommendations are with respect to the task and its background.

- *Proportion of illuminances:* the uniformities of the horizontal and vertical lighting depend on the average and minimum illuminance, obtained from each measuring sensor matrix defined in the horizontal or vertical plane of the classroom.

  The relation of uniformities to be used to evaluate each calculation plane is:

  Average uniformity (Au) = Minimum illuminance (E_{min}) / Average Illuminance (E_{av})

With respect to the illuminance proportion, in Table 2.2-3 it is possible to see the recommended uniformity values by code and lighting norms (EN12464-1 2003, CIBSE 1997, IESNA 2000). For this research, the uniformity is considered based on that recommended by Norm EN 12464-1.

Table 2.2-3: Uniformity recommendations

Source	Illuminance uniformity over task
CIBSE Code for Interior Lighting (1994)	Emin/Eav> 0.8
British Standard BS 8206: Part 1	Emin/Eav> 0.7
Code of Practice for Artificial Lighting	Emin/Eav> 0.67
EN 12464-1 (2003)	Emin/Eav> 0.7 (task area) Emin/Eav> 0.5 (around area)
DIN 5053 (2003)	Emin/Eav> 0.6 (classroom)

- *Luminance proportion:* the researches with respect to the luminance proportion have been applied for artificial lighting, especially in offices, with a study of the luminance proportions between the task and the background.

  Inanici (2005) defines the different methods for the evaluation of the luminance proportions in office spaces, based on High Dynamic Range (HDR) photographs and the per-pixel lighting data, which is a technique of computer analysis. In this study, for the evaluation in relation to the task and the background, they define the proportions as: Luminance variation across the immediate task has to be kept within 3:1 range, where the task luminance is suggested to be higher than the immediate surroundings. Distant room surfaces are preferred to be within 10:1 luminance range (40:1 maximum).

  For a classroom, then, we should have a luminance proportion equivalent to: task – desk relation (1:3) and task – background relation (1:10) (maximum).

  For the evaluation of luminance based on the contrast between the task (luminance target) and its surroundings (luminance background), it is considered advisable to have a contrast greater than 0.4, since this value can be selected as a minimum objective of the design; however, this has been studied for office spaces (Inanici, 2005).

  Boyce (2003), upon referring to the luminance proportions, recommends the need to establish a luminance hierarchy, where the task to be carried out should have the highest luminance, its immediate surroundings an equal or less luminance and the background should have an equal or even less luminance.

  With respect to daylight, the luminance proportion in the visual field is influenced by the window. It has direct incidence on the visual comfort of the students, depending on the visualization direction and the position of the user, aspects that are the foundation of the analysis applied for glare, which is addressed below.

2.2.3 Glare

The visual discomfort in a space is related to high contrasts and high luminance within the visual field. An excessive glare can cause visual discomfort. Lighting professionals distinguish two types of glare: *disability glare* and *discomfort glare* (Rea, 1993).

- *Disability glare:* describes the effect of light, lamps or bright surfaces, when it reduces the contrast between a seen object and its background. This disturbance is cause by the disperse light in the eye (Vos, 1984). Disperse light forms a luminous veil on the retinal image of the parts adjacent to the scene, reducing the luminance contrasts of the image of these parts on the retina.(Boyce 2003)

- *Discomfort glare:* it refers to the experience of symptoms associated to glare sources, in the visual or reflection fields. Uncomfortable glare occurs when people complain about visual discomfort when facing bright light sources, lamps or windows (Boyce 2003).

For these two types of glare, we can distinguish their behavioral effects: disability glare has an effect on visual performance and discomfort glare has an effect on visual comfort. Each of them is associated to a particular glare source (Veitch & Newsham, 1996).

Glare is a much more extreme form of non-uniformity and is generally immediately evidenced. Very high luminances in the field of view, or very highly non-uniform luminance distributions, can cause discomfort.

According to that observed in the study of Chilean classrooms, presented in Appendix A, windows are one of the main direct glare sources, but we can also see many veiling and reflected glare situations produced by the color and finishing of the surfaces that appear in the visual field, generally bright surfaces such as the whiteboard and the desks (see Figure 2.2-2).

Figure 2.2-2: Pictures showing different glare situations

Glare Index

Essentially, the two forms of glare –disability glare and discomfort glare- are just two different results to the same stimulation pattern, that is to say, a wide luminance variation through the visual field. Upon considering the probability that glare occurs in a given lighting situation, it is advisable to consider both the disturbing glare as well as the uncomfortable one (Boyce, Human factor in Lighting, 2003).

Indexes have been developed in order to predict the degree of discomfort produced in different lighting situations. They describe the subjective feeling of glare experienced by an observer in a given position. These indexes are: Visual comfort probability (VCP), British Glare Index (BRS or BGI), Discomfort glare rating (DGR), Unified Glare Rating (UGR), Cornell equation or Daylight glare index (DGI), CIE Glare Index (CGI) and Daylighting Glare Probability (DGP).

The formulas for all these indexes are different, but they all concur with the following form:

$$\text{Glare sensation} = (L_s^{a} \cdot \omega_s^{b}) / (L_b^{c} \cdot p^{d})$$

Where L_s is the illuminance of the glare source (cd/m^2), ω_s is the solid angle subtended in the eye by the glare source (steradians), L_b is the luminance of the environment (cd/m^2), and *p* the deviation of the glare source from the line of vision. Each component of the formula has a different exponent and these differ in the different formulas. This formula indicates the effect of the different components; that is to say, the increase of the luminance in the glare source, the reduction of the luminance of the environment and the reduction of the deviation of the glare source from the line of vision are factors that increase the sensation of glare (Boyce, Human factor in Lighting, 2003).

Most of these different indexes were developed in reference to artificial lighting systems, except the DGI and the DGP. Since the objective of this thesis is to study daylighting glare, new metrics developed by Wienold and Christoffersen called "Daylighting Glare Probability" (DGP) were considered.

The DGP is a numeric evaluation of an image in high dynamic range (HDR), using a mathematical formula that comes from human subject studies. It was demonstrated that the DGP has a strong correlation (squared correlation factor of 0.94) with the user's response as for their glare perception (Wienold & Christoffersen, 2006).

DGP is defined by the following equation:

$$\mathrm{DGP} = 5.87 \times 10^{-5} E_v + 9.18 \times 10^{-5} \log\left(1 + \sum_i \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{1.87} P_i^2}\right)$$

Where E_v is the vertical eye illuminance; $L_{s,i}$ is the luminance of source 'i'; $\omega_{s,i}$ is the solid angle of source i and P is the position index, a weighing function that varies with the distance of a glare source form the field of vision (Reinhart & Wienold, 2011).

The command tool of RADIANCE called *evalglare* allows us to carry out these evaluations and detect, effectively, all possible reflections or glare sources in the scene.

The validity of the equation is within the test range, which implies a DGP value of between 0.2 and 0.8. A DGP value higher than 0.2, approximately, corresponds to a vertical eye illuminance higher than 1000 lux. According to the authors, values higher than 0.8 could be considered to some extent, because the comparison of 10 cases with high DGP values gave reasonable results (average DGP to have people completely disturbed was 80%). Unless the validity of the formula can be confirmed for that range, values below 0.2 should not be considered. (Wienold & Christoffersen, 2006).

Most of the glare indexes attempt to estimate the glare sensation of the so-called "standard observer". Wienold, based on the results of the correlation between DGP and the glare rating scale of the user's evaluation, proposes DGP ranges in which human subjects rated the glare within their field of view to be imperceptible, perceptible, disturbing and intolerable.(See Table 2.2-4)

Table 2.2-4: DGP glare rating scale

	imperceptible	perceptible	disturbing	intolerable
DGP limit	≤ 0.35	≤ 0.40	≤ 0.45	> 0.45

This glare rating classification was based on simulations and frequency distributions. The data were acquired within a comprehensive user assessment study in test rooms (Wienold & Christoffersen, 2006).

This glare rating allows us to observe the comfort sensation the students will experience when facing a scene determined for the DGP evaluation, which is described in detail in Chapter 3.

2.3 Daylighting in classroom

A badly designed daylight strategy, as well as a badly designed artificial light strategy, can create visual discomfort and glare. A good daylight design requires the understanding of local weather patterns and the orientation of the classroom. Also, daylight strategies will depend on the arrangement of the classrooms with respect to the building and their internal arrangement too, which at the same time will depend on the teaching methods applied by each school.

Wu and Ng, upon carrying out a bibliographic review of the development of daylight in schools, concluded that a daylight quality study is a subjective matter, which has focused on human reaction in respect to daylight. Therefore, it is questionable if the discoveries with respect to daylight, window size, vision quality and the need for privacy apply to students from different countries, cultures and weather, since most of daylight research has taken place in Europe and North America (Wu & Ng, 2003).

Besides the research duties, the principles recommended to obtain a good daylight quality were examined. These involve principles related to visual comfort, explained in section 2.2. Six principles related to daylight design in schools, in general, were proposed by the CHPS[2] (2006), and these are:

- *Avoiding direct sunlight penetration.* It speaks of understanding the aspects associated to weather and orientation, in order to organize protection systems. It suggests that care must be taken, upon designing, with direct sunlight penetration on the whiteboard.

- *Providing uniform daylighting.* It states that a uniformly spread daylighting will provide better visual quality. A diffuse daylight, balanced through a space is one of the greatest achievements for a good daylighting designer.

- *Avoiding glare sources.* Excessively high contrast of daylight will cause glare. Direct glare is the presence of a bright surface within the scope of the visual field, causing discomfort or loss of visual functions.

- *Allowing teachers to control daylight using curtains or blinds.* Daylight is highly variable, so an appropriate design for the maximum amount of hours is needed. It is recommended that teachers have easy access to controls, such as curtains or blinds, so they can adjust daylight levels.

[2] CHPS: The Collaborative for High Performance Schools.

- *Designing an electric lighting system to complement daylight design.* Daylight is considered as the main lighting source, so electrical lighting systems should be designed as complement.

- *Planning the arrangement of interior spaces to take advantage of daylight conditions.* A good daylighting design should include the layout of the interior space. As daylight can vary considerably within that space, it is important to locate the work areas so that there is an appropriate daylight, as well as defining the visual tasks, especially the location of the whiteboard, in order to reduce the discomfort or glare probabilities.

2.3.1 Classroom Arrangement

Classroom arrangement inside the building complex will have an influence on the lighting strategy to be used. There are two basic ways that are generally used in schools: basic organization with a central corridor and classrooms on both sides of it, and basic organization with a corridor and classrooms only on one side of it (see Figure 2.3-1).

Numerous schools use this organization system, with a central corridor, but this arrangement makes lighting classrooms difficult, and even more so the lighting of the corridor. This arrangement limits a unilateral lighting inside classrooms, if the building has many stories.

The arrangement of classrooms on one side of the corridor allows the creation of an intermediate situation between the exterior, the interior public space (corridor) and the classrooms. This allows for daylight contributions into the classroom, being able to use the indirect light coming from the corridor as a lighting strategy.

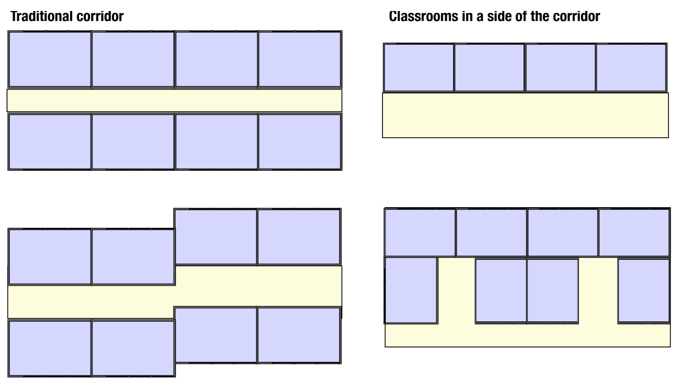

Figure 2.3-1: Different classroom arrangements with corridors.

2.3.2 Arrangement of the Interior Space

The classroom layout is determined by the teaching methods of each school and each teacher. The way in which a classroom is organized is crucial to define the daylighting strategies. Because of this, before facing the design itself we must try to define the kind of organization of it. The international trend is to define different areas, a classroom that allows for a large variety of activities. Two types of organizations are presented, the traditional classroom and the open-plan classroom.

- *Traditional classroom.* Formal scheme with rows for students, where teachers have to remain in one spot, essentially teaching from the front of the classroom and where, in general, furniture cannot be moved. The interest point here is the whiteboard and the teacher's area.

  With respect to the lighting system for a traditional classroom, there are some who propose to organize the classroom based on three different areas: the whiteboard area, with independent lighting; and the classroom area, subdivided into two areas, the window area and the corridor area, parallel to the facade wall in order to create the possibility of using independent lighting systems (de Bruin-Hordijk & de Groot, 2010). This contributes to organizing the electric lighting systems for the classrooms that are comfortable and efficient from an energetic point of view.

  In Chile, the traditional arrangement has been used in general, which has led to the use of unilateral daylighting strategies with slight contributions from the corridor, in some cases. The classrooms have great student density, because the Chilean norm considers 1.1m^2 per student, allowing up to 45 students inside it.

  Since the objective of this research is to use the traditional context, we chose this type of arrangement for the lighting strategies presented in Chapter 3.

- *Open-plan classrooms.* Their internal organization aims to provide more flexibility and adaptability for the different activities that can be carried out in them. This type of classroom allows teachers to group students and to organize different work ways, encouraging the students to fully participate of the activities.

  The trend for this type of classroom organization is to have a square open plan, which allows for the zoning of different activities and the using of skylight-based daylighting systems. An "innovative design" group created a lighting system that allows reaching the center of the classroom with diffuse light for this type of flexible classrooms, called "roof monitor", which has been implemented in the USA. It consists of a monitored system that allows for the regulation on the entry of daylight, allowing diffuse light in, eliminating the direct radiation, demonstrating that it is a very efficient system. (InnovativeDesign, 2004).

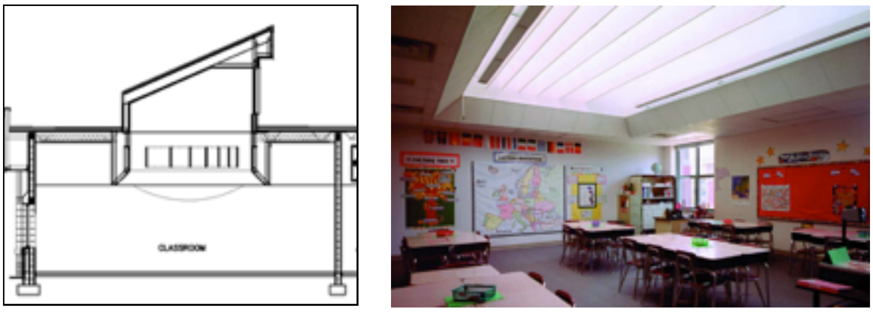

Figure 2.3-2: Picture showing the "roof monitor" system.

As for the design considerations, there are some who propose to set up the classroom so that the floor area used by people stays within the "daylight area". A typical daylight area is 15ft (4.75m) away from the window wall, or to set it up in such a way that the whole of the classroom floor is under a skylight (Leslie, Smith, Radetsky, Figueiro, & Yue, 2010).

The use of "clerestory windows" is recommended by researchers, since it helps daylight to reach deeper into the back part of the classroom, creating a more uniform daylight distribution, complementing the side window (Barrett & Zhang, 2009).

Others propose setting up the classroom so that there are two areas, one for the students and one for the whiteboard. An independent strategy is incorporated for the whiteboard, and an architectonic element is placed to intentionally shadow the area in order to control direct daylight penetration on the projections plane (Atre, Zubizarreta, Eckerlin, & Manning, 2008).

2.3.3 Window Proportions

The amount of daylight that comes into a space, and its distribution within that space, is determined mainly by the size of the windows, their arrangement in the space, the type of glass, their shape and number.

Even though everyone agrees that having a view of the outside contributes to improve visual comfort conditions, it is recommended to have two strategies for the windows: one that allows a relationship between the inside and the outside, and one for lighting purposes (CHPS, 2006).

With respect to the size of the windows, there are some who recommend having a smaller percentage facing the orientations that have sunlight incidence, and a larger one facing that without sunlight incidence (Tregenza & Loe, 1998). Others, on the other hand, recommend avoiding window areas in the East and West facades; however, North and South-facing windows must be big enough to provide daylight and views, because sunlight control is easier to achieve for these orientations.

This contradicts that proposed by other researchers, who propose a reduction of the percentage of glass area, since this increases the construction costs, becoming more expensive than a wall. They state that large glazing areas, even though having positive aspects as for the view and daylight entry, have negative effects such as glare and higher heating or cooling costs. They define the window surface in relation to the percentage of the window area and the total area of the classroom, the window to floor ratio (WFR), by which they define as good having a WFR under 10%, as medium one between 10 – 20% and as not advisable one over 20% (Leslie, Smith, Radetsky, Figueiro, & Yue, 2010).

The Ordenanza General de Urbanismo y Construcción (O.G.U.C), (General Town Planning and Construction Ordinance, in English) defines, for Chilean classrooms, a Window to Floor ratio (WFR), which divides the country into three areas, as can be seen in Table 2.3-1, requesting this WFR% as the minimum for each of these areas.

Table 2.3-1: WFR requested by the O.G.U.C for the different regions of Chile.

Window-Floor ratios (WFR)	
REGIONES OF CHILE	**CLASSROOMS WFR**
I a IV XV	14%
V a VII y RM	17%
VIII a XII	20%

The objective of this thesis is to contextualize the study for the Chilean reality, so we considered appropriate for this research to follow that stated by the O.G.U.C., who provide the minimum WFR requirements for the city of Concepción, and that is explained in section 3.5 of Chapter 3.

2.3.4 Design Diagnosis of Chilean Classrooms

The classroom diagnosis was carried out only in the city of Concepción, in the context of this research. The problems associated to daylight were indentified in new schools, which were built after the Chilean education reform (JEC). The indentified problems are:

- We indentified the presence of excessive glare in the visual field of the students, especially on the whiteboard of most classrooms, which, independent from their orientation, presented reflections on it, being one of the main sources of glare. The influence of exterior reflective elements, such as the roofs of neighboring buildings, was observed, which generate discomfort situations.

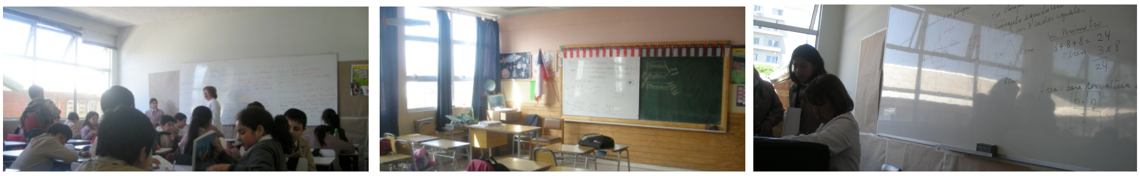

Figure 2.3-3: Pictures of excessive reflections and glare on the field of view of the students.

- Lighting contrast problems were found due to small windows and incorrect use of curtains. As a result, high contrast areas are obtained on the workplane. Fabric curtains are the only sunlight protection classrooms have, and many of them are dark colored, which leads to greater contrast and coloring of interior light.

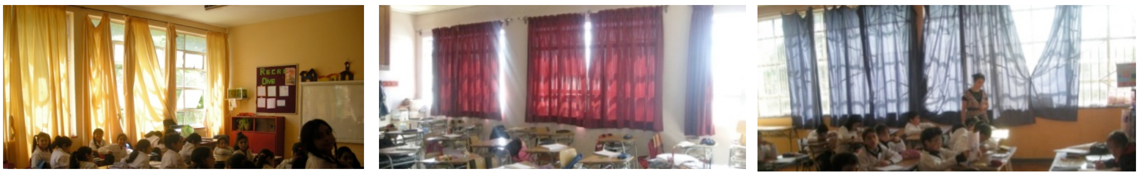

Figure 2.3-4: Problems found with lack of architectonic devices for sunlight control.

- Lack of sunlight control in the whiteboard area, since there are no control elements for direct sunlight penetration. The whiteboard area is really affected by direct sunlight radiation and, as a consequence, we could see that teachers rearrange the curtains and furniture to protect the whiteboard.

Figure 2.3-5: Teacher's self-made control system to protect the whiteboard area.

- Lack of electric lighting control systems based on real needs. We could see electric lighting being used even when daylight alone was enough.

Figure 2.3-6: Pictures showing the incorrect use of lighting systems.

- The most used daylighting strategies were the unilateral ones with indirect lighting from the corridor. Well daylit corridors are obtained, but contrast problems between the corridor and the classroom are produced. Also, the use of small windows on the wall placed between the corridor and the classroom does not allow the maximization of the use of this indirect daylight inside the classroom.

Figure 2.3-7:Unilateral daylight strategies with slight contribution from the corridor.

In the diagnosis carried out, classrooms with different orientations were observed, where we could verify that the classrooms do not present differences based on their orientations. All the classrooms present a large façade window that complies with the WFR stated by the O.C.G.U. We can infer, then, that strategies that would allow for a prevention of the aforementioned problems are not included.

For a better understanding of daylighting quality in Chilean schools, some measurements were taken in the visited schools. Glare was evaluated based on High Dynamic Range (HDR) images, which can be found in Appendix A, which were created with different expositions on a static scene, in order to rebuild an image that was as close to reality as possible. From this specific measurement, we found that the maximum DGP is high for students at all the different views and particularly for those seated by the window, where it reaches a maximum DGP of 28% to 44%, i.e. in a class of 45 students, between 12 and 20 are exposed to the risk of glare.

It is important to mention that comparisons between classrooms were difficult to carry out with this evaluation, because the classrooms belong to different contexts. Also, the measurements could not be done simultaneously, i.e., under the same weather conditions.

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3 Methodology for Assessing Daylighting in Classrooms

This chapter outlines the methodology used for assessing and analyzing daylit classrooms, based on a dynamic analysis method that considers the climatic variables for the city of Concepción, referring to the frequency of the skies in it. In addition, the basic criteria for the design of classroom daylighting are proposed, and the following are defined: case studies, strategies used and the RADIANCE parameters. These case studies are analyzed in Chapter 4. The objective of this chapter is to suggest criteria that could be considered for the design and implementation of a strategy for classrooms' daylighting. In this way, the use of the available light could be made more efficient and, at the same time, it could prevent problems of visual discomfort for the students.

3.1 Dynamic Daylight Performance Metrics

There are numerous factors that could cause daylighting to be extremely variable including: the movement of the sun, the changing seasons and the different weather conditions.

Because of this variability, we looked for a dynamic method that was able to integrate the climatic conditions of the research context, using as the basis and starting point the "Lightsolve" methodology (Kleindienst, Bodart, & Andersen, 2008) which, in turn, uses the data of weather diversity through a combination of the distribution of the sky, using the ASRC-CIE model.

Such a method of analysis raises the challenge of being able to provide all necessary information to make decisions in the pre-designing stage, in a way that is easy to manage, and keeping the continuity of the annual data, located in a specific place and weather.

The metrics developed and used in daylight dynamic performance measurement are based on the time interval in which the baseline levels of illuminance and luminance within a building are reached. These time intervals extend typically over the full year, based on external data such as the annual solar radiation, according to the location of the building. The key advantage of the metrics of dynamic light output, compared with static measurements, is that for a given building they take into account the amount of daily and seasonal variations of daylight, combined with weather data (Reinhart, Mardaljevic, & Rogers, 2006).

3.1.1 Revision of Dynamic Daylight Performance Metrics

Among the metrics whose analyses are based on the time variable, we have the Daylighting Autonomy (DA), the Useful Daylight Illuminance (UDI) and the Continuous Daylight Autonomy (DAcon). These are defined as follows:

> *"The daylight autonomy at a point in a building is defined as the percentage of occupied hours per year, when the minimum illuminance level can be maintained by daylight alone. In contrast to the more commonly used daylight factor, the daylight autonomy considers all sky conditions throughout the year. The minimum illuminance level corresponds to the minimum physical lighting requirement which has to be maintained at all times so that a certain task can be carried out safely and without tiring the working occupant". (C. Reinhart 2006, p. 10)*

> *"Useful Daylight Illuminances (UDI), proposed by Mardaljevic and Nabil in 2005, is a dynamic daylight performance measure that is also based on work plane illuminances. As its name suggests, it aims to determine when daylight levels are 'useful' for the occupant, i.e. neither too dark (<100 lux) nor too bright (>2000 lux). The upper threshold is meant to detect times when an oversupply of daylight might lead to visual and/or thermal discomfort. The*

> *suggested range is founded on reported occupant preferences in daylit offices. Based on the upper and lower thresholds of 2000 lux and 100 lux, UDI results in three metrics, i.e. the percentages of the occupied times of the year when the UDI was achieved (100-2000lux), fell-short (<100 lux), or was exceeded (> 2000 lux). The last bin is meant to detect the likely appearance of glare." (C. Reinhart 2006, p.12)*
>
> *"Continuous Daylight Autonomy (DAcon), recently proposed by Rogers, is another set of metrics that resulted from research on classrooms. In contrast to conventional daylight autonomy (see above), partial credit is attributed to time steps when the daylight illuminance lies below the minimum illuminance level. For example, in the case where 500 lux are required and 400 lux are provided by daylight at a given time step, a partial credit of 400lux/500lux=0.8 is given for that time step. The result is that instead of a hard threshold, the transition between compliance and non-compliance becomes softened. This change to the metric can be justified by field studies that indicate that illumination preferences vary between individuals and that many office occupants tend to work at lower daylight levels than the commonly referred 300 or 500 lux. Essentially, the metric acknowledges that even a partial contribution of daylight to illuminate a space is still beneficial." (C. Reinhart 2006, p.12)*

The calculation of DA, UDI and DA_{con} delivered valuable information for performance metrics links between daylight and spatial data; these can be calculated at different points within a spatial grid. Several programs, such as S.P.O.T, Daysim and Daylight1–2-3 can be used to calculate them. They allow us to know the percentage of annual working hours at one point or several points of the grid to obtain the desired illuminance; however, it is not possible to tell how this will behave over time, as it loses the temporary variable.

Due to the aforementioned, a new concept for "Lightsolve" was developed by Andersen and others in 2008, which aims to give the user the temporal and spatial information at a certain point in time. Through temporal maps, they can show how performance varies in space and time.

For the construction of temporal maps, the year was segmented into periods of similar seasonal and daily moments; each moment is then analyzed for sky type frequency and the average brightness of each sky type. They divided the year into 56 periods, the seasonal in 8 periods and the days into 7 intervals. They analyzed sky type frequency according to ASRC-CIE model and the Typical Meteorological Year Weather climate data (TMY2). With the climate database it is possible to know the frequency of occurrence of the different sky types during each of the 56 temporal periods.

For Lightsolve they developed a metric in order to display goal-based performance information for an entire area of interest on a single temporal map (Kleindienst S. A., 2010). This metric shows that the percentages in the areas of interest are within the targeted range illuminance and its variations over time, along the temporal maps. The proposed measurement is structured first by establishing the targeted illuminance range, defined by a lower limit, and an upper limit of illuminance target. Values within this range will have 100% of the credits. They established an adjacent buffer zone to have an upper and lower buffer zone limit, which could be of any size. The credits for this area will be partial. Partial credits decrease linearly from 100 % until the limit value of 0% at the buffer zone limit (Kleindienst, Bodart and Andersen 2008).

From the proposed methodology for Lightsolve, the method for representing temporal and spatial information of this research was developed. Temporal maps are considered as the tool for data representation. We used a different time segmentation that reduces the moments of the year and the climate information is based on the same ASRC-CIE sky model with climate data for the city of Concepcion, Chile, which is located in the central part of the country, in latitude 36° 46′ 22″ S, 73° 3′ 47″ W. It is a city with an oceanic, mild weather and an abundance of rain. Its average annual temperature is 12.7°C having averages, in the summer, of 17°C and 8°C, in the winter.

The variables used here are described in the following sections.

3.1.2 Division of the Year

In order to apply this methodology of dynamic analysis, the segmentation of the year, suggested in Lightsolve, was adapted to the academic calendar of elementary schools in Chile, where classes begin on the first week of March and end by the third week of December, in average, with a 2-week winter break in July.

The year was divided in four periods and each period represented by a specific date:

- The first period covers the months of February, March and April, and is represented by the 21st of March (autumn equinox).
- The second period covers the months of May - June - July and is represented by June 21 (winter solstice)
- The third Period covers the months of August - September - October and is represented by September 21(spring equinox).
- The fourth Period covers the months of November - December – January and is represented by December 21(summer solstice)

To cover the entire school day, each representing day is divided into five two-hour periods, adjusted for Chilean standard school time: 8am, 10am, 12pm, 2pm and 4pm. Finally, the year is represented by 20 moments (see Figure 3.1-1).

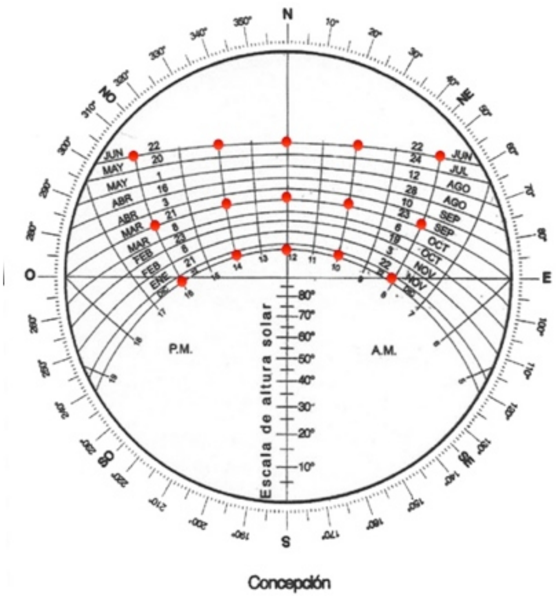

Figure 3.1-1: Sun course diagram of Concepción City (source: UBB)

3.1.3 Definition of the Sky for Daylighting Analysis

The definition of the sky for daylighting analysis and application of dynamic metrics is based on the ASRC model developed by Perez. A weighting of each of the skies used by Perez in his model is done using data obtained from the climatic database "Typical Meteorological Year" (TMY2), in a similar way as in Lightsolve (Kleindienst S. A., 2010). From the weather data file, the occurrence of different types of sky is determined using the ASRC-CIE sky model developed by Perez (Perez, Seals and Michalsky 1992).

The ASRC-CIE model integrates the four standard models of a CIE sky into one angular distribution of the sky luminance. These are the overcast sky (Hopkins), the intermediate sky (Igawa & Nakamura, 2001), the clear sky (CIE standard) and the CIE clear sky atmosphere, polluted with high turbidity factor (Commission Internationale de l'Eclairage (CIE), 1994). These skies are defined by CIE as follows (see Figure 3.1-2):

- Overcast Sky: the luminance of the standard CIE overcast sky changes with altitude. It is three times as bright in the zenith, than near the horizon. The nomenclature that we used for the climatic database is called 'o' and in RADIANCE is defined as '-c'.

- Intermediate Sky: the standard CIE intermediate sky is a sky for which the luminance of any given sky element will be defined, for a given sun position, under an intermediate weather condition which occurs between the clear and overcast sky CIE standard. The nomenclature that we used for the climatic database is called ‘i’, and in RADIANCE is defined as ‘+i’.

- Clear Sky: the luminance of the standard CIE clear sky varies over both, altitude and azimuth. It is brightest around the sun and dimmest opposite it. The brightness of the horizon lies in between those two extremes. The nomenclature that we used for the climatic database is called *‘c’* and in RADIANCE is defined as ‘+s -t 2.45’, as it includes the illuminance turbidity factor.

- Clear-turbid Sky: is a clear sky with high illuminance turbidity factor. The turbidity factor is the cloudiness or haziness. The nomenclature that we used for the climatic database was called ‘ct’ and in RADIANCE it is defined as ‘+s -t 5.5’.

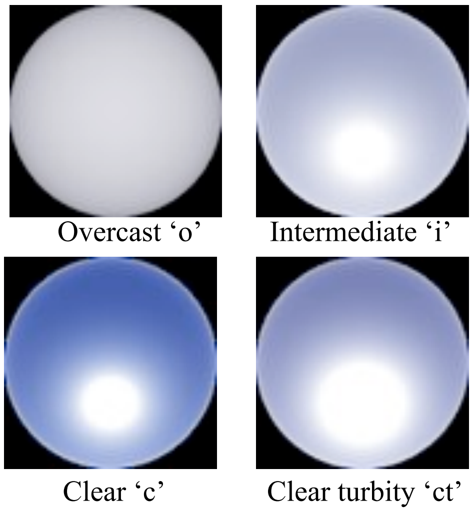

Figure 3.1-2: Standard skies CIE (Lightsolve program sky icons)

The ASRC-CIE model is considered as the most appropriate model for sky temporal data reduction thanks to its accuracy and the average of different types of sky (Littlefair, 1994).

The governing equation of the model is

$$L = bc\,\mathrm{Lc} + bct\,\mathrm{Lct} + bi\,\mathrm{Li} + bo\,\mathrm{Lo} \qquad (1)$$

Coefficients *bc, bct, bi* and *bo* depend on sky clearness and brightness determined in the ASRC-CIE model while Lc Lct Li and Lo (clear ‘c’, clear turbid ‘ct’, intermediate ‘i’ and overcast ‘o’ respectively) are provided by Pérez. Calculations are carried out on the basis of weather data files containing direct and diffuse irradiance data over the year.

The methodologies suggested in this PhD work are inspired by the Lightsolve project but are simplified, to reduce the calculation moments throughout the year, in order to reduce calculation time.

Based on the weather data file, TMY2 weather data and the governing equation (ASCR-CIE model), the coefficients *bc, bct, bi* and *bo* were determined, calculated for the entire year. Then, the average for the four periods defined for each sky was estimated. These coefficients gave the frequency of each sky in each period.

Unlike in Lightsolve, the luminance of the sky for each period of the year is not averaged based on the weather data file. For this study, it is determined using Radiance, which describes the skies according to the CIE standard sky distribution, for each type of sky.

The illuminance measurement at each sensor, at the workplane and whiteboard, in classrooms for the 20 moments defined, is calculated as follows:

$$E = bc\ Ec' + bct\ Ect' + bi\ Ei' + bo\ Eo' \qquad (2)$$

where bc, bct, bi and bo are mean coefficient for the considered period, and Ec’, Ect’, Ei’ and Eo’ are illuminance under each kind of sky. The illuminances are then averaged for each period and time in the following manner:

$$E_{p(1)}8h = bc{*}Ec_{p(1)}\,8h' + bct{*}Ect_{p(1)}\,8h' + bi{*}Ei_{p(1)}\,8h' + bo{*}Eo_{p(1)}\,8h' \qquad (3)$$

$$E_{p(1)}10h = bc{*}Ec_{p(1)}\,10h' + bct{*}Ect_{p(1)}\,10h' + bi{*}Ei_{p(1)}\,10h' + bo{*}Eo_{p(1)}\,10h' \qquad (4)$$

$$E_{p(1)}12h = bc{*}Ec_{p(1)}\,12h' + bct{*}Ect_{p(1)}\,12h' + bi{*}Ei_{p(1)}\,12h' + bo{*}Eo_{p(1)}\,12h' \qquad (5)$$

$$E_{p(1)}14h = bc{*}Ec_{p(1)}\,14h' + bct{*}Ect_{p(1)}\,14h' + bi{*}Ei_{p(1)}\,14h' + bo{*}Eo_{p(1)}\,14h' \qquad (6)$$

$$E_{p(1)}16h = bc{*}Ec_{p(1)}\,16h' + bct{*}Ect_{p(1)}\,16h' + bi{*}Ei_{p(1)}\,16h' + bo{*}Eo_{p(1)}\,16h' \qquad (7)$$

Simulations are carried out using the Radiance software and the gensky command-line, which produces a scene description for each of the four sky distributions, at the specified month, day and time. The dates are: March 21/ September 21 (equinox), June 21 (winter solstice) and December 21(summer solstice). So, zenith brightness of the sky vault is not specified but automatically computed with the gensky command.

Sky definition for the city of Concepción

For the city of Concepción, the representative periods can be seen in Figure 3.1-3, whose formulas are defined as follows:

- First Period (1): February- March - April

$$\mathbf{E_p} = 0{,}20_c\mathbf{Ec_p} + 0{,}25_{ct}\mathbf{Ect_p} + 0{,}31_i\ \mathbf{Ei_p} + 0{,}24_o\mathbf{Eo_p} \quad (8)$$

- Second Period (2): May - June - July

$$\mathbf{E_p} = 0{,}01_c\mathbf{Ec_p} + 0{,}15_{ct}\mathbf{Ect_p} + 0{,}30_i\ \mathbf{Ei_p} + 0{,}54_o\mathbf{Eo_p} \quad (9)$$

- Third Period (3): August - September - October

$$\mathbf{E_p} = 0{,}11_c\mathbf{Ec_p} + 0{,}20_{ct}\mathbf{Ect_p} + 0{,}35_i\ \mathbf{Ei_p} + 0{,}34_o\mathbf{Eo_p} \quad (10)$$

- Quarter Period (4): November - December - January

$$\mathbf{E_p} = 0{,}25_c\mathbf{Ec_p} + 0{,}26_{ct}\mathbf{Ect_p} + 0{,}32_i\ \mathbf{Ei_p} + 0{,}18_o\mathbf{Eo_{po}} \quad (11)$$

In the formulas above, the skies have frequency variations across different periods they show more or less weight according to the formula.

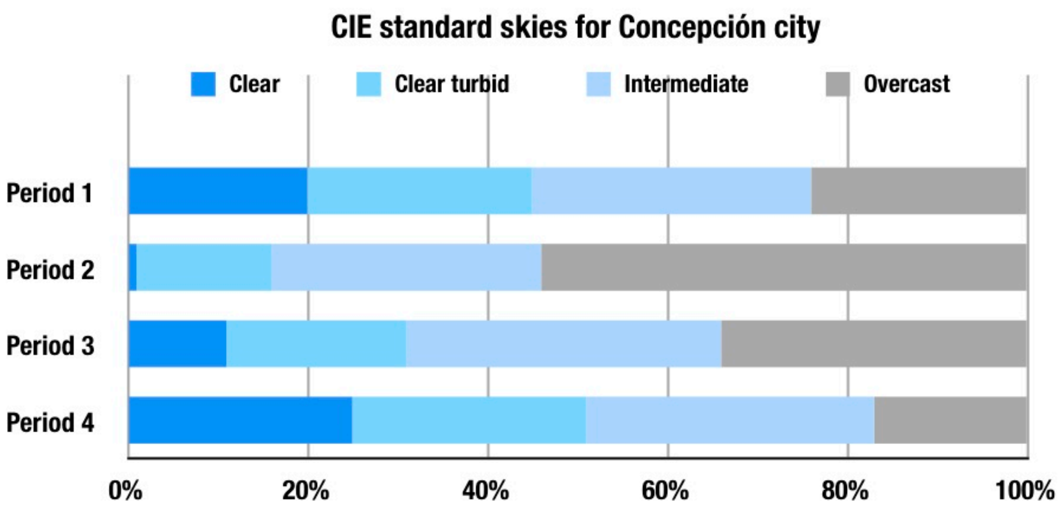

Figure 3.1-3: Frequency plot of the four CIE standard skies for Concepción city, TMY2 based on weather data.

When it comes to the frequency of the skies for Concepción city we can say that for the first period, which corresponds -in the case of this location- to the end of the summer and the beginning of the school year, the most predominant sky is the intermediate one with a frequency of 31% over the period. Then, the clear turbid sky and clear sky have a frequency of 25% and 20%, respectively. In the second period, which corresponds to the middle of the academic calendar, the predominant sky is overcast, with a frequency of 54% over the period; then, the intermediate sky, which has a frequency of 30% with a similar frequency to that of the previous period. For this period, the frequency of clear skies is low; the clear turbid and clear sky has a frequency of 15% and 1%, respectively. During the third period, the predominant sky is the intermediate sky with a 35% of frequency over the period, then it is the overcast sky, with a frequency of 34%, the clear and clear-turbid skies have a weighting of 20% and 11 %, respectively. In the fourth period, which corresponds to the end of the year and early summer, the predominant sky is the intermediate sky, with a frequency of 32% over the period, then the clear turbid sky with a frequency of 26% and the clear sky with 25%, and the overcast sky with 18%. In the graph we can see that for the city of Concepción, the most constant sky is the intermediate, as it occurs at a similar proportion in all periods.

3.2 Illuminance Metric for Daylighting in Classrooms

The previous section describes the process followed to divide the year and in what way the weight of the skies was determined, to in this way determine the final weight of the illuminance values in each period. This section explains the definition of iluminance ranges for the application of the method of dynamic analysis.

The performance goal, for classrooms, was to create appropriate lighting conditions during the school day in order to illuminate the work plane in the classroom using only daylight.

According to the average illuminance values and standards set out in Chapter 2, the desired illuminance, ie., target values, were defined from 500 to 1500 lux; illuminance values in this range will have 100% of the credits.

A value of 300 lux illuminance was established as the lower limit. Illuminance values below the lower limit value are considered as "too low". An illuminance of 2000 lux was established as an upper limit. Illuminance values above the upper limit value are considered as "too high".

The illuminance values varying from 500 lux to 300 lux and from 1500 lux to 2000 lux are partially considered; partial credits are given to values in this range.

The aforementioned is summarized as follows:

"too low"	"in range"	"too high"
< 300 lux	500-1500 lux	> 2000 lux

These illuminance values were considered suitable for the development of visual tasks in the classrooms. While the recommendations usually vary between 500 - 700 lux, these are defined for artificial light.

However, the light spectrum of the daylight is so broad, and also day variations are so wide that on a clear day one can have, outside, 100000 lux. In contrast, on an overcast day one can have 10000 lux, outside. This is why we decided to allow a wider range of illuminance, establishing the target values of 500 -1500, which allows us to take in variations produced by daylight.

The illuminances in classrooms were determined by RADIANCE simulation, for each sky type and at each moment. They were then weighted according to formula (7 to 10) in order to determine a single value for each moment. These single values are plotted in the temporal and spatial maps.

Two types of graphs were chosen in order to visualize the results: the graphs representing the temporal evolution of the weighted internal illuminances (horizontal on the desks and vertical on the whiteboard) and a graph representing the spatial distribution of the % of time when the weighted illuminance was evaluated as "in range", in the classroom, specifically on the working plane level. A temporal map is a tool that enables powerful and intuitive representation of the evolution of the metric over a full year (Mardaljevic, 2004, Kleindienst, Bodart, & Andersen, 2008). On the other hand, a spatial map is a tool that allows you to evaluate the distribution of the illuminance in space during the year. The temporal information is, in this case, lost, benefiting the spatial information. Hence, the spatial and temporal maps are complementary. All temporal and spatial maps were produced using the MATLAB[3] program.

3.2.1 Temporal Illuminance Maps

The structure of the temporal maps is as follows: the day of the year is plotted along the x-axis and the hours of the day along the y-axis. To make their reading easier, the hours are represented as standard (standard time, EST) with the winter time in the y-axis on the left, and the summer time in the x-axis, on the right as shown in Figure 3.2-1.

[3]MATLAB® is a high-level technical computing language and interactive environment for algorithm development, data visualization, data analysis, and numeric computation.

Temporal maps of internal illuminances were drawn in order to integrate the objective values, following a goal-oriented approach. The aim of the goal-oriented approach is to set a target range of values and assess the percentage of space, whose performance is within that range. This approach has the advantage of including both spatial and temporal information in one graph, representing the percentage of the work plane that meets the objectives.

The values shown are the percentage of the space which achieved the target values, defined above (between 500 and 1500 lux), considering that partial credits are given for values between 300 lux and 500 lux and between 1500 lux and 2000 lux.

The scale used in the temporal maps is the triangular scale proposed for "Lightsolve" by Kleindienst (Kleindienst S. A., 2010). This triangular scale has the great advantage of aggregating three different temporal maps into one; a temporal map considering the % of space whose points are in the range, a temporal map considering the % of space whose points are too high (above 2000 lux) and a temporal map considering the % of the space whose points are too low.

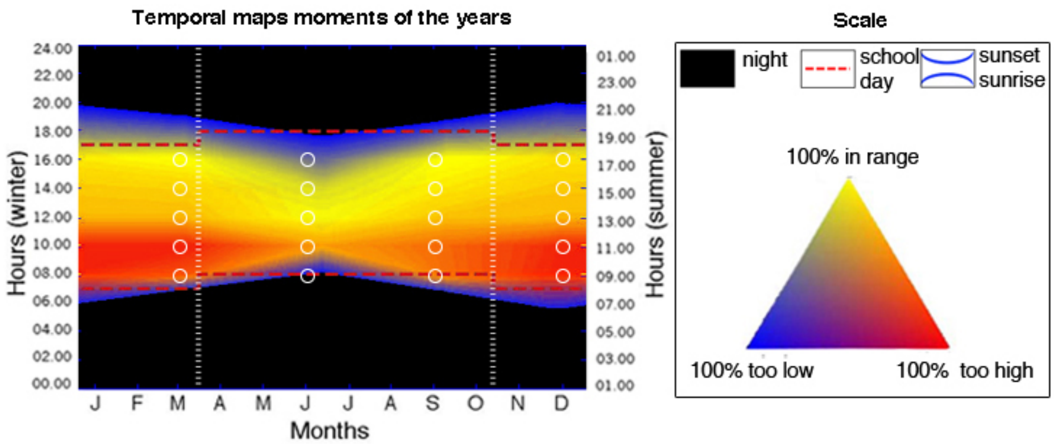

Figure 3.2-1: Example of temporal maps, points out the 20 moments measured and the triangular scale

In summary, the results are presented as follows:

- "% in range": represents the % percentage of the task area between 500-1500 lux.
- "% too low": represents the % percentage of the task area below 300 lux.
- "% too high": represents the % percentage of the task area above 2000 lux.

Temporal maps allow condensing the large amount of data obtained from illuminance calculations made for the 20 moments of the year and the four skies defined before.

As stated before, for the study of daylighting in the classrooms two temporal maps were drawn, a temporal map of the weighted horizontal illuminances calculated at the working plane level, which is called *Horizontal Temporal illuminance maps,* and the second temporal map, of vertical illuminance values on the whiteboard, which is called *Vertical Temporal illuminance maps*.

3.2.2 Annual Distribution of Illuminance Values in the Space.

In order to understand the distribution of light within the classroom, a spatial map was built including the architectural space, and it was organized in such a way that it makes it possible to illustrate the weighted distribution of illuminance in the classroom. This chart complements and enriches the information already developed.

This chart has been called *Spatial Illuminance distribution map.* This map was constructed as follows: the x-axis represents the meters along the grid, while the y-axis represents the width in meters of the grid, which corresponds to the total size of the working plane.

The illuminance distribution is related to the horizontal grid of illuminance measurement that was used. The same triangular scale as the one used in the temporal maps is employed.

The spatial map in Figure 3.2-2 represents the weighted illuminance values, allowing an easy identification of areas within the classroom that meet target illuminance values or, in the same way, knowing which areas have too much or too little daylight, during the whole year.

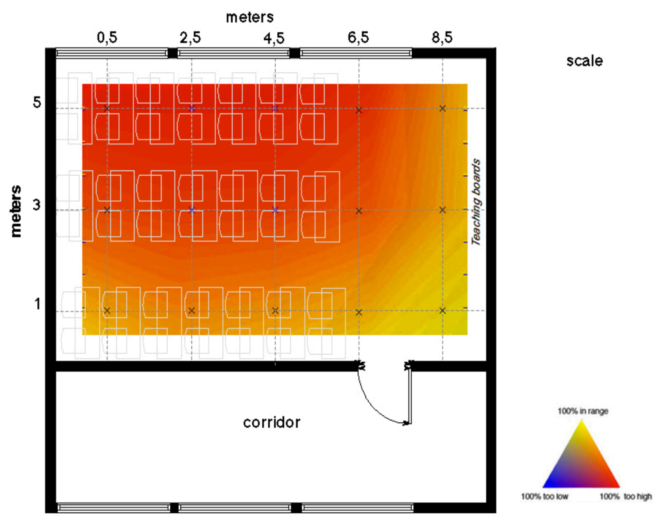

Figure 3.2-2: Organization of the Spatial Illuminance distribution map.

In addition, spatial maps are completed with the three summarizing pieces of information: the percentage of space over the year whose values are in range, too low and too high. This synthesized the findings of all “in range”, “too low” and “too high” values can be seen in Table 4.1-2 of Chapter 4, which allows us to compare the different values obtained for each typology, simultaneously.

3.3 Glare Metric for Daylighting in Classrooms

The analysis was carried out considering the glare luminance distribution that affects the field of view of the students.

As defined in Chapter 2, the glare directly affects visual comfort; for that reason, it was decided to assess the risk of glare in the classrooms.

An assessment of risk of glare is done by measuring the "Daylighting Glare Probability (DGP)” index, which is understood as the probability that someone would be disturbed by the glare coming from daylight. The DGP is calculated using the assessment tool called evalglare, used as a command line in RADIANCE (Wienold J. , 2004).

Evalglare validation is presented in Chapter 2. It showed that the DGP is validated for values ranging from 0.2 to 0.8. This means that values lower than 20% or higher than 80 % cannot be taken into account.

For this analysis, the position of the observer and their view direction were defined from a preliminary study, studying all the possible positions of the students, looking towards the whiteboard. Different moments of the year and different skies were considered.

In order to limit the calculation time for the following study, the most unfavorable position within the classroom was searched for, and was found to be "V2", as shown in Figure 3.3 1. The details of this preliminary study can be found in Appendix A.

The DGP was assessed for this position by making accurate luminance views for every hour and day chosen, corresponding to 20 times in the year and for the four sky types. The images were made according to a fisheye view of 180 degrees (image size: 500 x 500pixels), representing the human field of view.

Temporal maps of the DGP were then made, following the same principle as that applied for the construction of temporal illuminance maps.

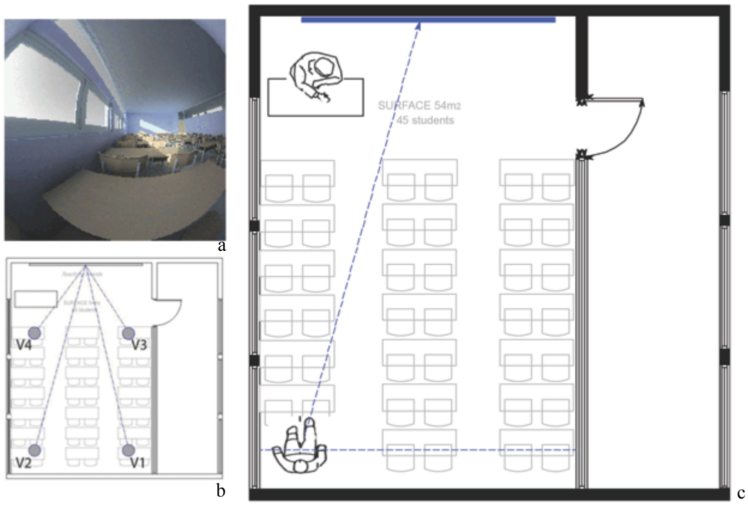

Figure 3.3-1 : (a) Field of view(b) Plant with four views of the preliminary study (c) Worst position

This representation was organized in the same way as the weighted illuminance maps: the x-axis represents the hours, while the y-axis represents days. We used a linear scale that represents the percentage of glare in relation to the DGP obtained, as illustrated in Figure 3.3-2.

Two maps were made: the "*temporal DGP maps*", which is made from the values obtained for each sky and weighted in the same way as it was done for the weighted illuminance values. The second map is the "*temporal* DGP_{max} *maps*", which represents the DGP obtained for the most glaring skies.

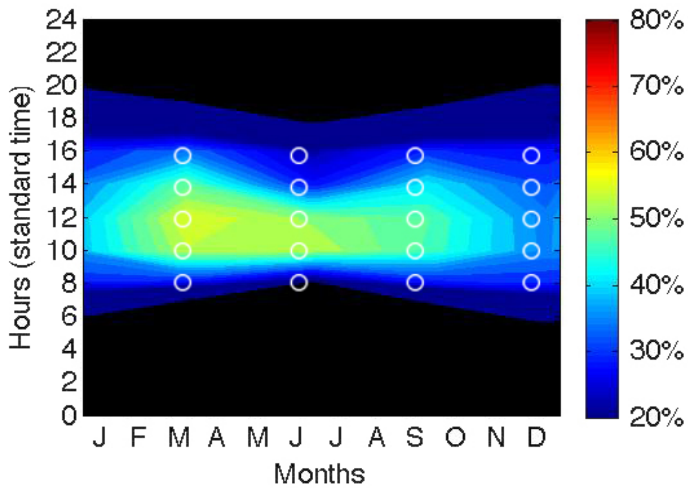

Figure 3.3-2: temporal DGP maps, organization and distribution of the 20 moments measured.

3.4 Daylighting Criteria for the Analysis of Classrooms

The following section defines the basic criteria for the design of daylighting in classrooms, hoping that such criteria[4] may eventually allow us to design guidelines and recommendations for good daylighting in Chilean classrooms.

Four criteria were proposed, based on the principle of daylighting in classrooms, developed by CHPS (outlined in Chapter 2). (CHPS, 2006)

For each criterion, we proposed two different levels: *adequate*[5] *and optimal*[6]in order to achieve the two different levels of daylighting conditions in a classroom. A criterion evaluated as *adequate* is to be reached in order to ensure a minimum standard of daylighting quality. A criterion evaluated as *optimal* ensures reaching the best daylight conditions.

> *"Improve student productivity and building energy efficiency through quality daylighting designs that minimize glare and direct sunlight penetration, and integrate views in daylighted spaces. Provide a connection between indoor spaces and the outdoor environment through the introduction of daylight and views into the occupied areas of the building. Daylighting is fundamentally important to high performance design, from the standpoint of student and teacher preference, and should be the primary source of illumination in classrooms". (Washington Sustainable Schools Protocol 2006, page 50)*

3.4.1 Daylighting Levels

We define this criterion to establish daylighting levels within the classrooms through the measurement of illuminance. The criterion is proposed and defined below:

Criterion 1. Providing the adequate amount of daylight in the classroom

The main aim of this criterion is to achieve an illuminance level considered to be appropriate for the considered visual tasks. This daylight level was evaluated from the annual distribution of illuminance weighted by the dynamic method as explained in Section 3.1.

The evaluation was conducted in the area of the workplane and in the area of the whiteboard which are considered as an integral part of the work area in the classroom. Two sub-criteria are thus defined:

- *a. Providing an adequate amount of daylight on the workplane:* this was measured considering the horizontal illuminance on the area of the workplane. This assessment

[4]Criteria: a principle or standard by which something may be judged or decided.(Concise Oxford English Dictionary © 2008 Oxford University Press)
[5] Adequate: satisfactory or acceptable (Concise Oxford English Dictionary © 2008 Oxford University Press)
[6]Optimal: best or most favorable.(Concise Oxford English Dictionary © 2008 Oxford University Press)

has been carried out using two tools: Horizontal temporal Illuminance maps and the Spatial Illuminance distribution maps.

- *b. Providing an adequate amount of daylight on the whiteboard:* which was defined as the area of primary interest. It was measured through the vertical illuminance on the whiteboard. Vertical Temporal illuminance maps are used in order to perform this assessment.

It was considered appropriate for this research to define the time within the school year, where the target illuminances were meant to be obtained (in range values). Based on that proposed by Nicklas and Atre (2007), who state that we must make an effort to achieve the target illuminances for two-thirds of the school year, as first objective, reaching a 50% of the complete year with target illuminances was aimed for. Considering that the Chilean school year is made up of 40 weeks of classes, this objective allows us to ensure a minimum of 26 weeks with just daylight. As a more ambitious objective, and looking to obtain the maximum daylight performance, we look to obtain 55% of the time, along the year, with target illuminances, ensuring 28 weeks of classes using daylight.

The recommendations on the levels of lighting that should be applied in the evaluation and analysis of Chilean classrooms are defined as the following:

- *Adequate daylight levels*: when the target illuminance is reached for at least 50% of the time of the year.

- *Optimal daylight levels*: when the target illuminance is reached for at least 55% of the time of the year.

The second category of recommendations refers to the illuminance level from the information contained in the spatial maps, as explained in section 3.2.2. It is important to analyze the spatial distribution in the classroom to complement the analysis of horizontal illuminance described here above.

Three levels of compliance are defined for this criterion. These levels considered the percentage of space whose values are in range throughout the year.

The three levels are defined as:

- "*irregular*[7] *spatial distribution*". The distribution of daylighting is defined as irregular if there is less than 50% of the space whose values are "in range" throughout the year. This means that much of the space of the classroom has very high or very low illuminance levels;

- "*regular*[8] *spatial distribution*". The distribution of daylighting is defined as regular if it is between 50% and 75 % of the space whose values are "in range" throughout the year. This means that about half or more of the space of the classroom will have illuminance within the target range

- "*optimal spatial distribution*". The distribution of daylighting is defined as optimal if there is more than 75% of the space whose values are "in range" throughout the year.

3.4.2 Daylighting Uniformity

In the same way as we should obtain the right daylight levels and the correct distribution of such light in the classroom, it is also necessary to consider that this light should be uniform. The goal, therefore, is to achieve a properly balanced daylighting illumination, both in the area of the workplane and in the area of the whiteboard.

For this purpose, the following criterion was established:

Criterion 2. Achieving the adequate daylight uniformity in the classroom

In artificial lighting standard, the light uniformity in a room is defined as the ratio of the minimum illuminance reached in this room on the average illuminance of the room. Although, as explained in Chapter 2, the European standard EN 12464-1 requires a light uniformity greater than or equal to 0.7, on the workplane itself and greater than or equal to 0,5 in the surrounding area; for classrooms, more specifically, the German standard defines that uniformity for classrooms should be greater than or equal to 0.6 (ZVEI Electric 2005).

In order to evaluate the resulting uniformity in the classrooms lit only by daylighting, goal uniformity values are suggested. These values will be moderated later, thanks to the results of the case studies analyzed in Chapter 4.

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[7]Irregular: uneven, has defects.
[8] Regular: well proportioned intervals in space, at regular intervals (Concise Oxford Spanish Dictionary © 2005 Oxford University Press)

The proposed uniformity values are the following:

- An *adequate level of uniformity* is reached when higher than 0.6.
- An *optimum level of uniformity* is reached when higher than 0.7.

The expectation is that there are no major variations in the classroom's daylighting illuminance. Uniformity is important in relation to task lighting to prevent the eye from having to make involuntary accommodations for different levels whilst trying to focus. A very high level of uniformity can lead to problems of perception and, by contrast, very low uniformity may lead to contrast areas that can cause possible fatigue and visual discomfort (Projet EFFENS, 1992).

In order to evaluate this criterion, we calculate the uniformity on the workplane and, separately, on the whiteboard. This was analyzed throughout the year, with the four types of sky.

In Chapter 4, the analysis of case studies will be done in the following way: first we observed the uniformity with the overcast sky, which is the sky that gives the most uniformity, then for the clear skies, which are skies that generate higher contrast, and finally the intermediate sky, which is the most constant, as shown in section 3.1.3.

3.4.3 Glare

As defined by IESNA, glare is the sensation produced by luminances within the visual field that are sufficiently greater than the luminance to which the eyes are adapted, which causes annoyance, discomfort, or loss in visual performance and visibility. Therefore, any light source can cause glare by being much brighter than the rest of the room. If a daylight source that can be seen directly is more than 10 times brighter than the immediate surrounding surfaces, this may be a source of discomfort (Clearvision Lighting Ltda, 2010). In relation to visual comfort, explained in Chapter 2, it was important to determine the criterion that controlled and assessed the visual comfort for the students in the classroom. The following criterion is proposed:

Criterion 3. Ensuring visual comfort in the student's field of view

Compliance with this criterion was measured through the evaluation of potential sources of glare in the field of vision; it sought to anticipate and avoid direct light or glare and to identify the discomfort generating scenarios in the classrooms.

The evaluation of the sources of glare, as explained in section 3.3, was made using the DGP index, presented in temporal maps, that provides insight into their distribution throughout the year. We evaluate the visual comfort for the predominant sky (DGP) and for the most glaring sky (DGP_{max}).

In order to simplify the understanding of the DGP index, this analysis was complemented with a graph of the DGP ranges, which is detailed in Chapter 2. The DGP ranges developed by Wienold (Reinhart and Wienold, 2010), provided the DGP qualification in which human subjects rated the glare in relation to the perception of brightness in their field of vision, in four categories: *imperceptible, perceptible, disturbing and intolerable.*

According to what the human subjects rated, as proposed by Wienold, we suggest as an "appropriate" visual comfort in the classroom, the DGP values of less than 35 %, these values having been rated as "imperceptible" by Wienold.

The optimum would be to not have any glare source in the field of view of the students, which means DGP values of less than 20 % (having in mind that 20% is the minimum limit of validation of the DGP).

3.4.4 Sunlight Penetration

It is essential, for good lighting, to minimize the penetration of direct sunlight, keeping it from entering the area of the workplane and the area of the whiteboard. When that occurs, it causes light spots that affect the normal execution of visual tasks and induce intolerable glare. The following criterion is proposed:

Criterion 4. Preventing direct sunlight penetration in the classroom

As a requirement for this criterion, the only proposal is to avoid direct sunlight on the workplane and on the whiteboard.

To assess this criterion, it was necessary to create images of the entire classrooms in order to detect the times and periods when there is sunlight on these workplanes.

This was developed through a quick render in RADIANCE, with images of *"fish-eye view"*. The chosen view was the one that allows to encompass the settings of the components of architectural space, where a panoramic view was required, looking from the top down (with the window on top of each image) in order to visualize the patterns of patch sunlight from the windows. The images of the 20 moments were built for the analysis in intermediate sky conditions, because this is the most constant sky in all periods and it allowed us to clearly visualize the solar penetration.

3.5 Summary Table

Design criteria		Goal design		
1	Daylight levels within workplane and whiteboard	***Adequate*** daylight levels: ≥ 50 % time "in range" throughout the year		***Optimal*** daylight levels: ≥ 55 % time "in range" throughout the year
	Daylight distribution	***Irregular*** spatial distribution: ≥ 50% area "in range"	***Regular*** spatial distribution: 50% -75% area "in range"	***Optimal*** spatial distribution: ≥ 75% area "in range"
2	Daylight uniformity within workplane and whiteboard	***Adequate*** uniformity ≥ 0,6		***Optimal*** uniformity ≥ 0,7
3	Low glare	***Adequate*** = DGP ≤ 35%		***Optimal*** = DGP ≤ 20%
4	Sunlight penetration	***Avoiding direct sunlight*** on the workplane and on the whiteboard.		

3.6 Case Studies

Case studies were defined from a preliminary study of existing classrooms in Chile. This preliminary study, showing the different situations found, is detailed in section 2.3.4. These case studies are defined by typologies, whose difference is their daylight strategies.

Five classroom typologies were constructed, using different daylight strategies. For their design we considered, as a starting point, the problems found in the preliminary study of the studied classrooms. Therefore, the architectonic design was thought as an "*improvement"* of the existing classrooms.

These cases studies have in common six architectural aspects, which are defined as follows:

1. The size of the classrooms is determined by the Ordenanza General de Urbanismo y Construcción[9] (General Town Planning and Construction Ordinance, in English), which refers to school buildings and student homes. The classroom area for 45 students was defined for this study as $56m^2$, measuring 9 meters long and 6 meters wide.

[9] Títle IV, Chapter 5, Article 4.5.6 of the General Urban Development and Construction Ordinance, established with the objective of securing a minimum area of 1.1 m^2 per student in the classroom (extract from article)

2. Although student's workplanes are often rearranged in the classroom, we decided to put them in the traditional way, where the whiteboard and the area for the teacher are the main point of interest.

3. The dimensions of the facade windows are adjusted to a 17% WFR. The O.G.U.C. demands a 20% WFR minimum for the total area of the windows. In the observed classrooms that apply this percentage to the façade window, it results in having a great pane that extends from one wall to the other, which has negative consequences on the whiteboard, as shown in Section 2.3.4 of Chapter 2. It was necessary to adjust the façade window to leave what was defined as a minimum distance and, to fulfill that demanded by the O.G.U.C., it is complemented with the window are of each daylight strategy, expressed in Section 3.5.1 of this Chapter.

4. The window of the main façade is divided into two parts: a view window corresponding to a window in the field of view of a student seated, designed to provide the visual link with the outside and a high window above the view window. The view window corresponds to 7% window-to-floor ratio (WFR), according to the minimum requirements defined in CHPS Volume III *"Criteria"* (CHPS 2006).

5. To control the solar penetration at the level of the whiteboard, the window was kept at a distance of 1,55m from the perpendicular wall where the whiteboard is placed.

6. Classrooms structure must meet seismic criteria, because the city of Concepción is located in a highly seismic zone. Therefore, structures using inverted beams are designed, to prevent them from becoming an element of obstruction of light.

Typologies were modeled in the ECOTECT[10]program, and then the models were exported to RADIANCE. The material file, which is not well exported by ECOTECT, was then corrected in order to adjust the material characteristics (color and reflectance as well as transmittance of windows).

For this study, the four main directions are studied: North, South, East and West. The objective is to make a first diagnosis for each of these cases, in order to optimize them separately afterwards, according to their orientation and the criteria defined here above.

[10] Autodesk Ecotect, Analysis. sustainable design analysis software.

3.6.1 Daylighting Strategy for Each Typology.

Five classroom typologies, with different strategies for daylight illumination, were chosen. The daylighting strategy used for each type is intended primarily to have a good distribution of light inside the classroom, and to avoid creating situations that could result in too low daylight in the area farthest from the window.

The following describes each of the daylighting strategies corresponding to the typologies of study mentioned:

- **Typology g1** is called "basic window". It is the most widely used in Chile and it is easy to implement on a project, since it allows several floors above it. It is a simple bilateral strategy of illumination. On the main façade, direct light penetrates, and the opposite side of the classroom receives indirect light from the corridor. The window of the classroom that looks into the corridor is considered at a height of 0.9 meters and, along the entire wall, there is no structural beam that may obstruct the light. (see Figure 3.6-1)

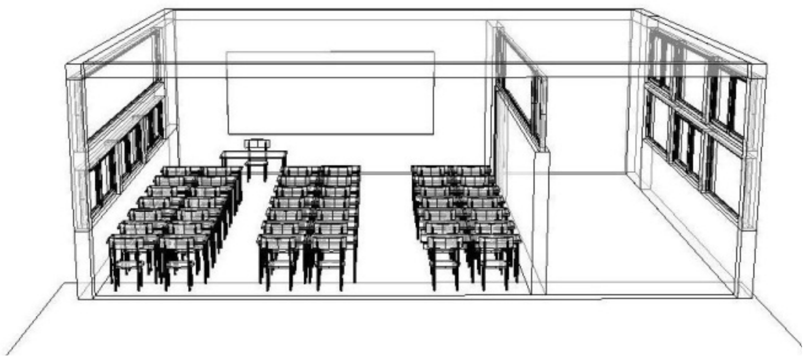

Figure 3.6-1: 3D Model Typology g1 "basic window".

Table 3.6-1: Window-to-floor ratio (WFR) of Typology g1

Facade window	m^2	Indirect Daylight	m^2
Daylighting window	6,2	Corridor- class window	5,2
View window	3,1	Door window	0,99
Window area(W)	9,3	Window area(W)	6,19
WFR	*17%*	*WFR*	*11%*
		Total WFR	28%

- **Typology g2** is called "bi-lateral clerestory window". Its strategy is to combine the classical lateral window with a clerestory located on the opposite wall, above eye level. The height of the second window is 1.50 meters. Combined with this window, an interior horizontal element of 0.6 meters wide protects the students from potential glare. This typology allows bi-lateral daylighting (see Figure 3.6-2).

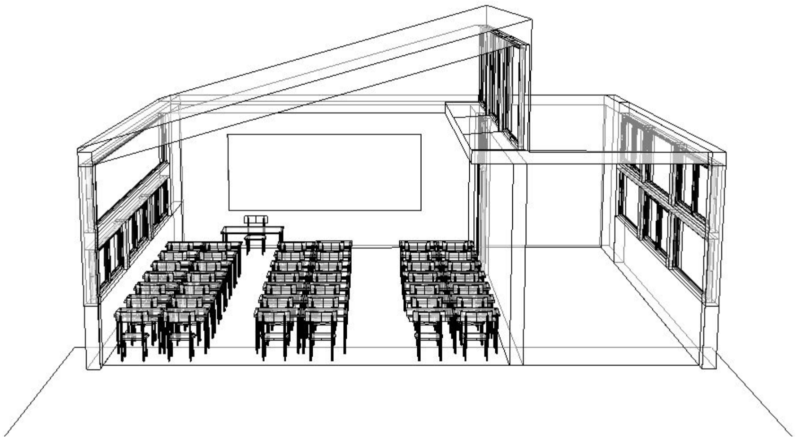

Figure 3.6-2: Typology g2 bi-lateral clerestory window.

Table 3.6-2: Window-to-floor ratio (WFR) of Typology g2

Facade window	m^2	Direct Daylight	m^2
Daylighting window	6,2	Clerestory window (W)	8,91
View window	3,1		
Window area(W)	9,3		
WFR	*17%*	*WFR*	*16%*
		Total WFR	33%

- **Typology g3** is called “unilateral clerestory window”. It bathes the opposite wall with greater daylighting, in order to balance the daylight coming through the main lateral window. The window is 1 m high and 7.55 m long, along the area of the workplane. The strategy followed aims to improve the daylight uniformity in the classroom. (see Figure 3.6-3)

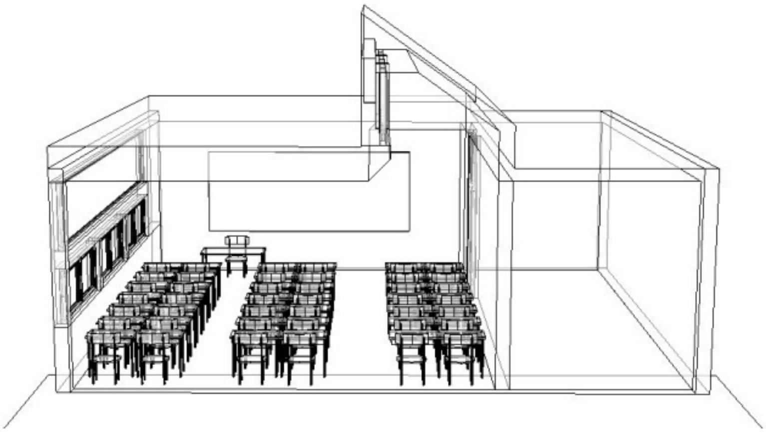

Figure 3.6-3: Typology 'g3 unilateral clerestory window.

Table 3.6-3: Window-to-floor ratio (WFR) of Typology g3

Facade window	m^2	Direct Daylight	m^2
Daylighting window	6,2	Clerestory window(W)	6,2
View window	3,1		
Window area(W)	9,3		
WFR	*17%*	*WFR*	*11%*
		Total WFR	28 %

- **Typology g4** is called "bi-lateral clerestory window with corridor daylight contribution". The strategy was to use a clerestory, similar to that on Typology g2, but smaller. The height of the high window is 0.80 meters and its length, 7.55 meters. The lighting coming into the classrooms was supplemented with a window looking into the corridor. This is the same as the g1 Typology window, which provides indirect daylight. (see Figure 3.6-4)

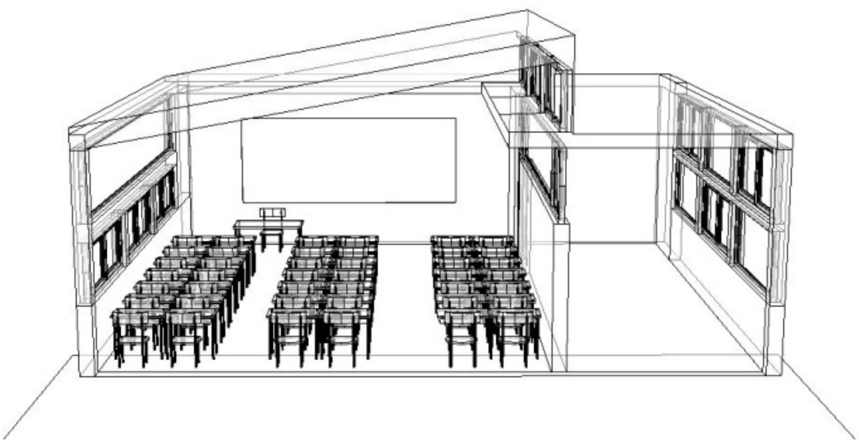

Figure 3.6-4: Typology g4 bi-lateral clerestory window with corridor daylight

Table 3.6-4: Window-to-floor ratio (WFR) of Typology g4

Facade window	m^2	Indirect Daylight	m^2
Daylighting window	6,2	Corridor- class window	5,2
View window	3,1	Door window	1
Window area(W)	9,3	Window area(W)	6,2
Direct Daylight	m^2	*WFR*	*11%*
Clerestory	2,2		
WFR	*21%*	Total WFR	32 %

- **Typology 'g5'** is called "skylight window". The strategy was to use a top light that operates through a small skylight, providing an area of high intensity daylight levels, in the area directly below it. (see Figure 3.6-5)

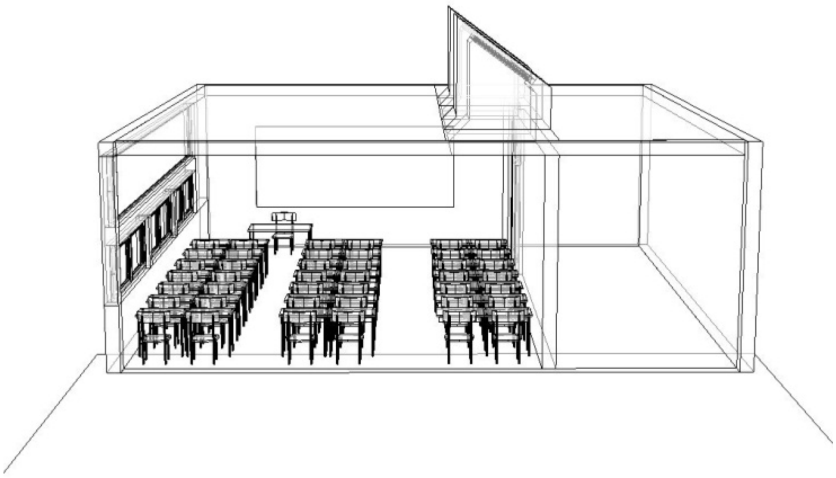

Figure 3.6-5: Typology g5 "skylight window"

Table 3.6-5Window-to-floor ratio (WFR)of Typology g5

Facade window	m^2	Direct Daylight	m^2
Daylighting window	6,2	Skylight	7,2
View window	3,1		
Window area(W)	9,3		
WFR	*17%*	*WFR*	*13%*
		WFR	*30%*

Finally, to close this section, it must be stressed that the strategies of Typologies g2, g3, g4 and g5 are applicable to buildings of a single floor or, on the upper floor of a multistory building.

3.6.2 Definition of Materials for the Typologies

For the definition of the materials for each of the proposed typologies we decided to use the existing materiality of a classroom evaluated in the preliminary study. We considered, for all the Typologies, the same materials and coefficients of reflection, which became a study constant.

Below, we have a table with the materials of the different parameters, with their colors and the reflection coefficients (ρ) for each one. In addition, we express the characteristics of these materials as used in the script of RADIANCE, for daylighting evaluation.

Color	ρ	RADIANCE script
Ground	25%	voidplasticConcSlab_OnGroun 5 0.25 0.25 0.25 0.0 0.0
Corridor wall	85%	void plastic ConcBlockPlaster 5 0.79 0.89 0.95 0.0 0.0
Door	70%	voidplastic SolidCore_PineTimber 5 0.78 0.70 0.38 0.0 0.0
Floor	60%	void plastic ConcFlr_Suspended 5 0.74 0.83 0.82 0.0 0.0
Walls	75%	void plastic GenericWallForLighting 5 0.67 0.74 1.01 0.0 0.0
Ceiling	80%	void plastic GenericCeilingForLighting 5 0.55 0.64 0.73 0.0 0.0
White board	80%	void plastic Plastic 5 0.7 0.83 1.0 0.07 0.0
Tables and chairs	55%	void plastic Linoleum 5 0.69 0.56 0.37 0.07 0.05
Chair frames		void plastic StainlessSteel 5 0.66 0.8 0.79 0.0 0.0
Window Frame		void plastic SolidTimber 5 0.66 0.8 0.79 0.0 0.

The glass used was a typical single-glazed unit with clear glass; it was the most common glass used in the classrooms of Chilean schools. Compared to all other glazing options, single-glazed windows with clear glass allow the highest transfer of energy while permitting the highest daylight transmission. This is described below:

Visible transmittance[11]	RADIANCE script
VT= 90%	`void glass GenerigSingleGlazing90` `3 0.98012226960.98012226960.9801222696`

3.6.3 Definition of Illuminance Calculation Grid

We defined two grids for the calculation of illuminance. The first grid, for the calculation of horizontal illuminance values, is defined as a grid with 15 sensors located at a height of 0.7m from the workplanes, which are distributed symmetrically on the workplane surface of the classroom. We left, in the perimeter, a 0.5 m wide marginal strip. The sensors were placed 2m from each other.

For the second grid, which was used to calculate vertical illuminance values on the surface of the whiteboard, a line of five sensors located at a height of 1.50m above the whiteboard was built.

To measure the illuminance outside the classroom, an external sensor was placed, for each typology, thus obtaining the sky illuminance for each analysis.

It is important to note that two factors were considered when defining the grid: one was that it should cover most of the workplane in the classroom, and the other was that it should be adjusted by the available calculation time.

The time RADIANCE would take to calculate the illuminance values of each sensor of the grid was determined. We began, in the preliminary study, with a grid of 45 sensors, then with a 27 sensors analysis grid and later we determined that 15 sensors were enough to cover the two factors, especially with the time available for calculations. The result was that, for each sensor, RADIANCE took 43 minutes of calculation, which considering a grid of 15 sensors, would translate into 11 hours of calculation, and a grid with 5 sensors would take 3.5 hours of calculation. Given the large number of calculations, it would take a

[11] Visible transmittance or visible light transmitted: A measure of the amount of visible light that passes through the glazing material of a window.

considerable amount of time to determine the 20 moments of the year for each typology and each orientation.

It is important to highlight that the simulations for each model, per orientation and for the 4 types of sky contemplated 880 hours of calculation for each horizontal grid and 280 hours for each vertical grid. In total, we talk about 4,640 hours for all the basic typologies simulated. The additional time used for the calculation of the optimized versions of the same typologies has not been considered.

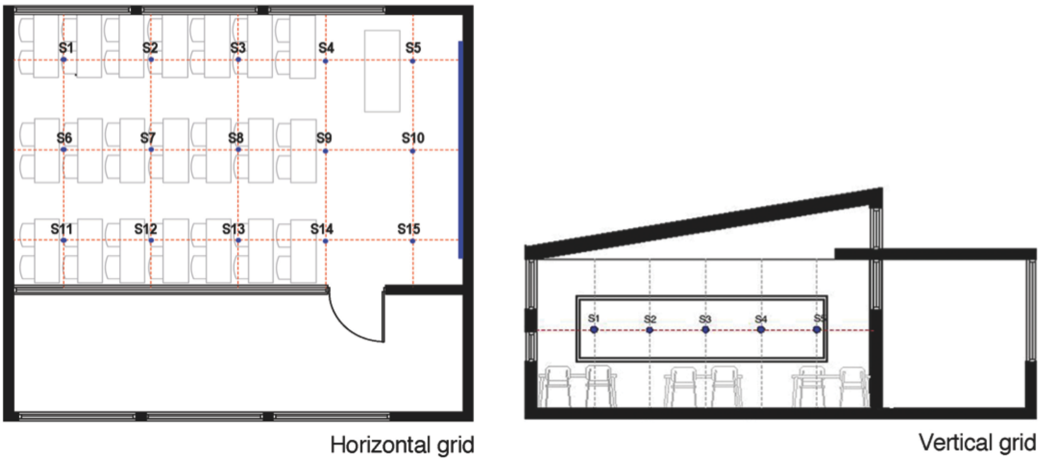

Figure 3.6-6: Horizontal, 15 sensors grid and vertical, 5 sensors grid

3.6.4 Definition of RADIANCE Parameters

The quantitative results obtained from the RADIANCE simulation program depend, to a large extent, on the successful configuration of the input parameters for this program. The large number of parameters available allow for an infinite combination of possibilities. Therefore, RADIANCE parameters were specified, in order to ensure the photometric accuracy of the results. Actually, the great cost of implementing each of these trials and the time involved in them were considered.

For this research, we used commands of view and pixels, mainly from an image quality perspective, which were highly relevant to the production of images by `-rpict`, as well as for digital data output and illuminance values calculated by `-rtrace`.

For its part, in the field of environmental parameters, indirect lighting components were considered. The indirect calculation within RADIANCE is done by diffuse *inter-reflection* between the surfaces and phenomena such as color and classification of the shadows (Lash, 2004). The calculation for this analysis is controlled by four key parameters: Ambient divisions (`-ad`), ambient super sample (`-as`), ambient resolution (`-ar`), ambient accuracy (`-aa`).

These calculation parameters were selected through a convergence study that was conducted in order to obtain very accurate results. This study is detailed in Appendix B.

In order to evaluate the accuracy of the results, they were calibrated by measuring the error parameters of cases with different parameters, and comparing them with a reference case. The degree of error is measured through the *root-mean-square error (RMSE)* and the relative mean bias error (MBE).

The RMSE is defined as follows:

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{n}\left(\frac{X_{i,\,\mathrm{meth}} - X_{i,\,\mathrm{ref}}}{X_{i,\,\mathrm{ref}}}\right)^{2}} \qquad (2)$$

where N is the number of data points, $X_{i,meth}$ is the calculated value for the considered parameter combination and $X_{i,ref}$ is the value calculated by RADIANCE with parameters chosen in order to have very accurate results, but that results in a very long calculation time. The RMSE is a good measure of the overall magnitude of the errors. It reflects the size of the errors and the amount of scatter, but it does not reflect any overall bias in the data (Liu, et al. 2003).

The MBE is defined as follows:

$$\mathrm{MBE} = \frac{1}{N}\sum_{i=1}^{n}\left(\frac{X_{i,\,\mathrm{meth}} - X_{i,\,\mathrm{ref}}}{X_{i,\,\mathrm{ref}}}\right) \qquad (3)$$

where $N = \Sigma^{n}$. The positive and negative errors in the MBE cancel each other out, so the MBE is an overall measure of how biased the data are (Liu, et al. 2003).

Based on this analysis, we chose the parameters used to determine the illuminance values, a process that took place with *–rtrace*. It is worth mentioning that the RADIANCE parameters were modified in function of the type of sky, as the resulting light distribution is modified. High light variation needs more precise parameters. The calculation of illuminances was performed as follows:

- Overcast and intermediate sky: `rtrace -ab 7 -av 0.0 0.00.0 -dp 4096 -ad 8192 -as 4096 -ar 160 -ms 0.085 -ds 0.2 -dt 0.05 -dc 0.75 -dr 3 -sj 1 -st 0.1 -aa 0.08 -lr 12 -lw .005 -I+ -h config.oct<grid.pts |rcalc -e '$1=179*($1*0.265+$2*0.67+$3*0.065)' > ill_03_08.dat`

- Clear and clear-turbid sky: `rtrace -ab 8 -av 0.0 0.00.0 -dp 4096 -ad 8192 -as 4096 -ar 160 -ms 0.085 -ds 0.2 -dt 0.05 -dc 0.75 -dr 3 -sj 1 -st 0.1 -aa 0.08 -lr 12 -lw .005 -I+ -h config.oct<grid.pts |rcalc -e '$1=179*($1*0.265+$2*0.67+$3*0.065)' > ill_03_08.dat`

The construction of the images was performed using de–rpict. With them, the PGD was calculated using *evalglare*. – `pcond` was applied afterwards, with the aim of regulating the human vision of the scene:

- Overcast and intermediate sky images: `rpict -x 500 -y 500 -vta -vh 180 -vv 180 -vp 1.0 5.0 4.0 -vd 3.0 0.7 0 -vu 0 0 1 -ab 8 -av 0.0 0.00.0 -dp 4096 -ad 8192 -as 4096 -ar 160 -ms 0.085 -ds 0.2 -dt 0.05 -dc 0.75 -dr 3 -sj 1 -st 0.1 -aa 0.08 -lr 12 -lw .005 config.oct> view`

- Clear and clear-turbid sky: `rpict -x 500 -y 500 -vta -vh 180 -vv 180 -vp 1.0 5.0 4.0 -vd 3.0 0.7 0 -vu 0 0 1 -ab 7 -av 0.0 0.00.0 -dp 4096 -ad 8192 -as 4096 -ar 160 -ms 0.085 -ds 0.2 -dt 0.05 -dc 0.75 -dr 3 -sj 1 -st 0.1 -aa 0.08 -lr 12 -lw .005 config.oct> view`

- DGP values and glare source image: `evalglare -c color_view -d view >view.glr`

- Human vision in the actual scene: `pcond -h view >h_view`

- False color image scale: `falsecolor -ip view-s 2000 -l cd/m2 > fc2000_view`

The images of solar penetration, as described in Section 3.4.4, were carried out considering the environmental parameters of RADIANCE, with medium resolution, thus reducing the time used in this task. Below, the considered parameters can be found:

- `-rpict -x 300 -y 300 -vta -vh 180 -vv 180 -vp 4.5 3.0 5.5 -vd 0 0 -1 -vu 0 1 0 -ab 5 -av 0 00 -dp 1024 -ad 768 -as 512 -ar 256 -dt .1 -dc .5 -dr 2 -sj 1 -st .1 -aa .1 -lr 8 -lw .001 -ds .2  config2b.oct> imagen.pic`

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4 Simulation of Design Options

In this chapter, the analysis of the results obtained from the classroom daylighting simulations, carried out using RADIANCE and the studied Typologies proposed in chapter 3, is presented. The analysis was organized starting with the four evaluated directions; first, the results and the analysis of the North-facing classrooms are presented; then, those of the South-facing classrooms; later, those of the East-facing classrooms; and finally, the West-facing classrooms. The goal was to examine each classroom following the four criteria explained in the previous chapter, evaluating those classrooms that achieved an adequate daylight level and, furthermore, those classrooms that achieved an optimal daylight level, to contribute to the daylighting design of the classrooms in the city of Concepción. Finally, the conclusions of this analysis are presented, allowing for the creation of foundations for new architectural approaches in the search for optimal solutions for each direction, which will be shown in chapter 5.

4.1 Daylighting Analysis of North-facing Classroom Typologies

4.1.1 Analysis of Daylighting Levels for North-facing Classrooms typologies

Criterion 1. Providing the adequate amount of daylight in the classroom

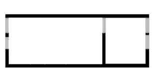
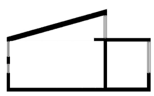
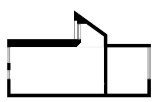
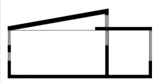
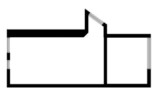
a. Providing the adequate amount of daylight on the workplane: the Horizontal Temporal Illuminance maps, shown in Figure 4.1-1 and the averages of the temporal maps shown in Table 4.1-1 were analyzed. In addition, the Spatial Illuminance distribution maps in Figure 4.1-2 were revised, and the % of the reaching target illuminance is shown in Table 4.1-2

This analysis is described below:

- *Analysis of Horizontal Temporal Illuminance maps:* with the results obtained it was possible to prove that none of the evaluated typologies reaches *adequate daylighting* levels; in these typologies, the times of target illuminances were lower than 50% throughout the year. In the temporal maps, we could verify that the typologies presented a "% too high" for the most of the year, this being more noticeable during the first period (February, March and April) and the third period (August, September and October).

  When looking at the table, it can be seen that Typology g3 presented illuminances rated as "too high" 44% of the time throughout the year, and that it only presented 25% of the time with the illuminances rated as "in range", becoming the least favorable Typology. Typologies g4 and g5 were able to sustain 39% of the time with target illuminances. Typology g1 reached only 42% of the time with illuminance rated as "in range", being seen as the one, which achieved a greater control of high illuminances in the classroom. We consider that none of the proposed daylighting strategies ensure adequate daylight in North-facing classrooms.

Table 4.1-1: Summary of Horizontal Temporal Illuminance maps of North-facing classrooms.

North									
TYPOLOGY g1		TYPOLOGY g2		TYPOLOGY g3		TYPOLOGY g4		TYPOLOGY g5	
									
Too Low	34%	Too Low	32%	Too Low	32%	Too Low	32%	Too Low	34%
In range	42%	In range	32%	In range	25%	In range	39%	In range	39%
Too high	24%	Too high	37%	Too high	44%	Too high	29%	Too high	27%

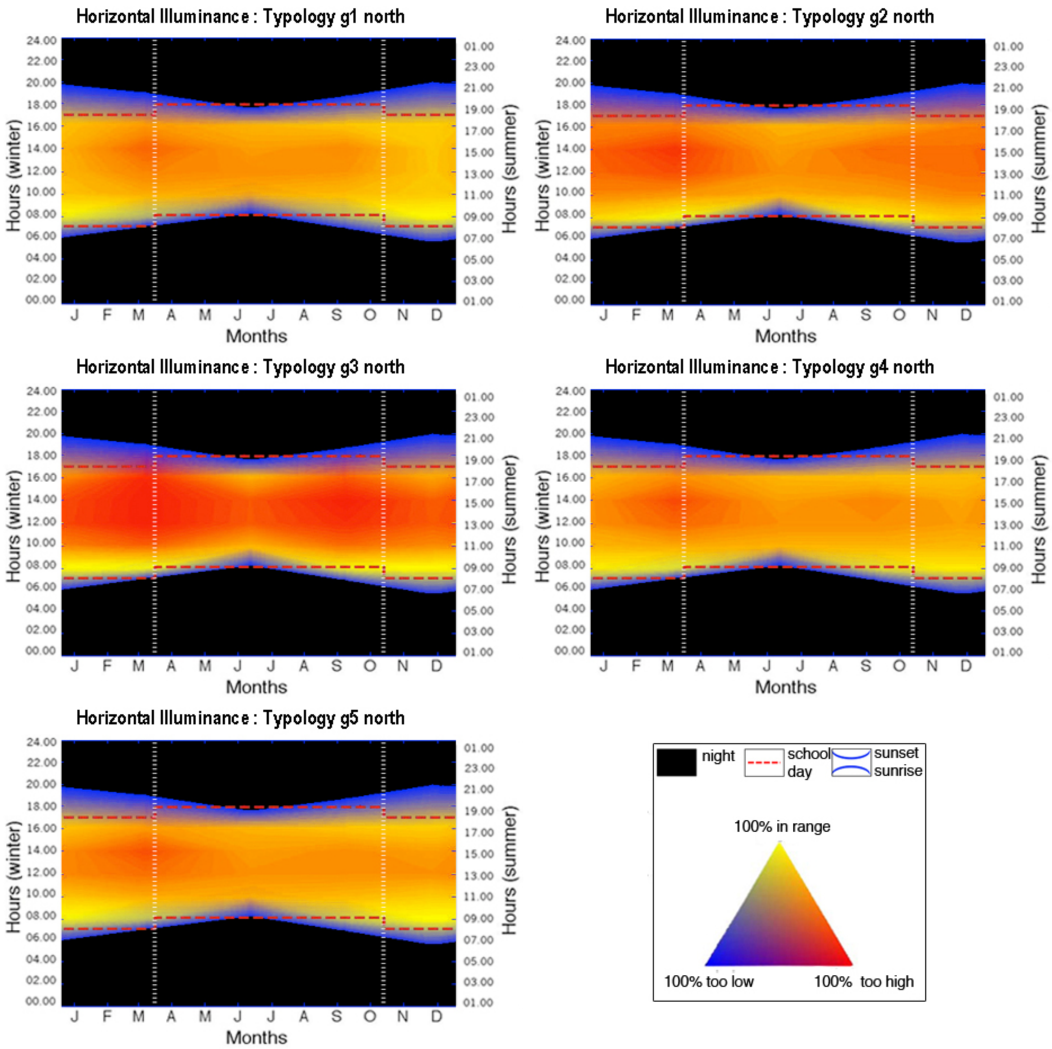
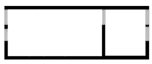
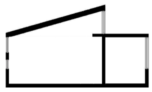
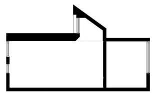
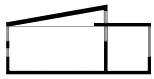
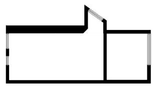


Figure 4.1-1: Horizontal Temporal Illuminance maps of all the North-facing Typologies.

- *Analysis of Spatial Illuminance distribution maps*: in the spatial distribution it was possible to see that Typologies g1, g4 and g5 achieved a *regular spatial distribution*. In the temporal maps it was possible to see that these typologies presented, similarly, an important area of the classroom with "% too high", mainly next to the window. Typologies g2 and g3 obtained an *irregular spatial distribution.* In their spatial maps it is possible to verify that a great portion of the classroom presented "% too high" confirming that Typology g2 obtained 49% and that Typology g3 obtained 60% of the area with an illuminance rated as "too high" throughout the year.

Table 4.1-2: Summary of Spatial Illuminance distribution maps of North-facing Classrooms.

North									
TYPOLOGY g1		TYPOLOGY g2		TYPOLOGY g3		TYPOLOGY g4		TYPOLOGY g5	
									
Too Low	9%	Too Low	6%	Too Low	6%	Too Low	7%	Too Low	9%
In range	57%	In range	45%	In range	34%	In range	53%	In range	54%
Too high	34%	Too high	49%	Too high	60%	Too high	40%	Too high	37%

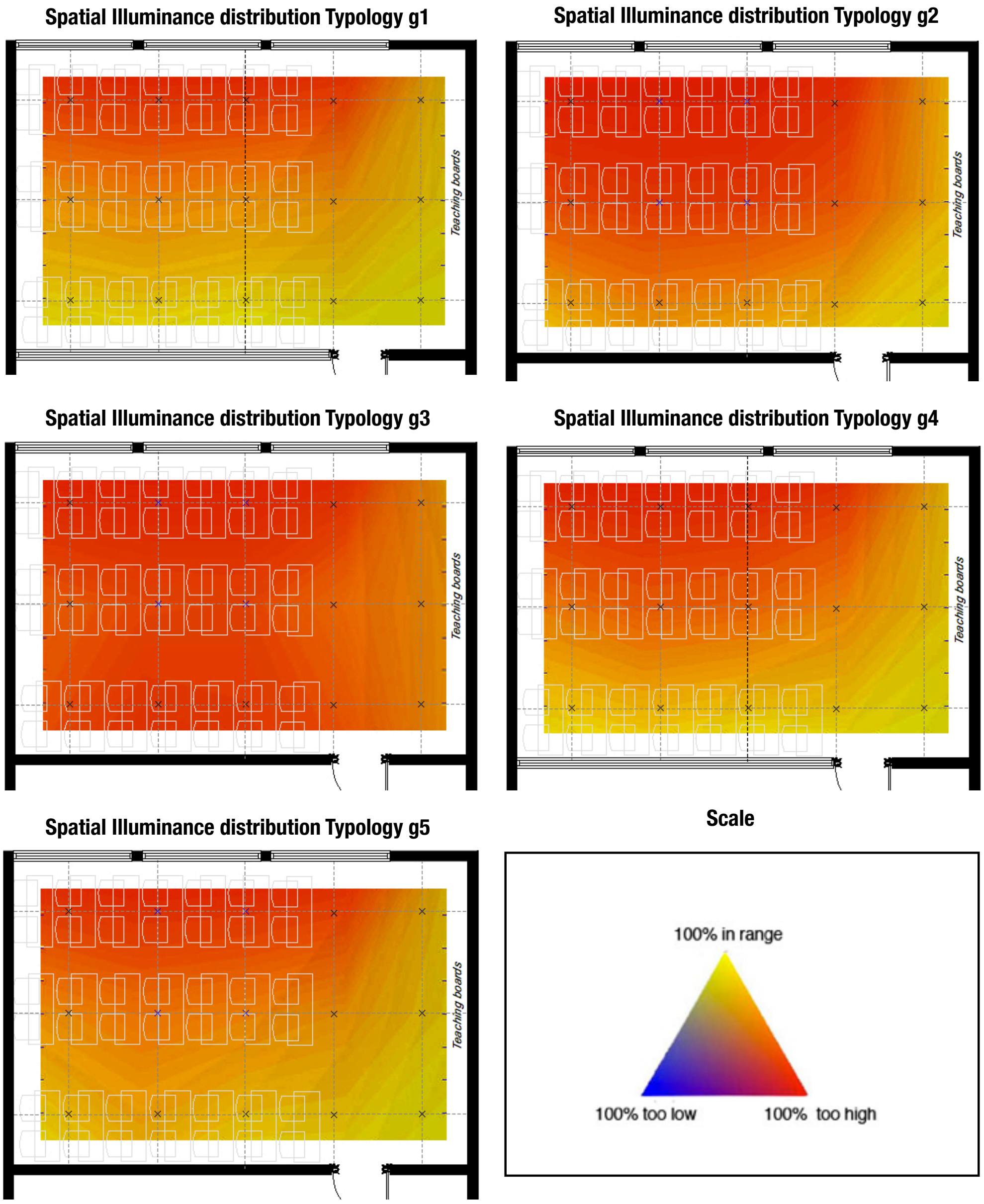


Figure 4.1-2: Spatial Illuminance distribution maps for all the North-facing Typologies

b. Providing an adequate amount of daylight on the whiteboard: the results are expressed in the temporal maps on **Figure 4.1-3** and the percentages of time within target ranges are expressed in **Table 4.1-3**. All that was observed after this analysis is described below.

Typologies g1 and g5 achieved *adequate daylighting* levels, obtaining more than 50% of the time with "in range" illuminances. In the temporal maps, it was possible to see "% too high" in the first and third period after midday. When verifying the "% too high", these typologies obtained a 16% of the time within this range, which is very brief.

In the results for Typologies g2, g3 and g4 we see that they did not achieve enough time with "in range" illuminances. It could be seen that these obtained "% in range" during the mornings, but from midday onwards they presented "% too high". In particular, with Typology g3 it could be seen that a great part of the whiteboard presented, during the first, second and third periods, a "% too high" starting from midday.

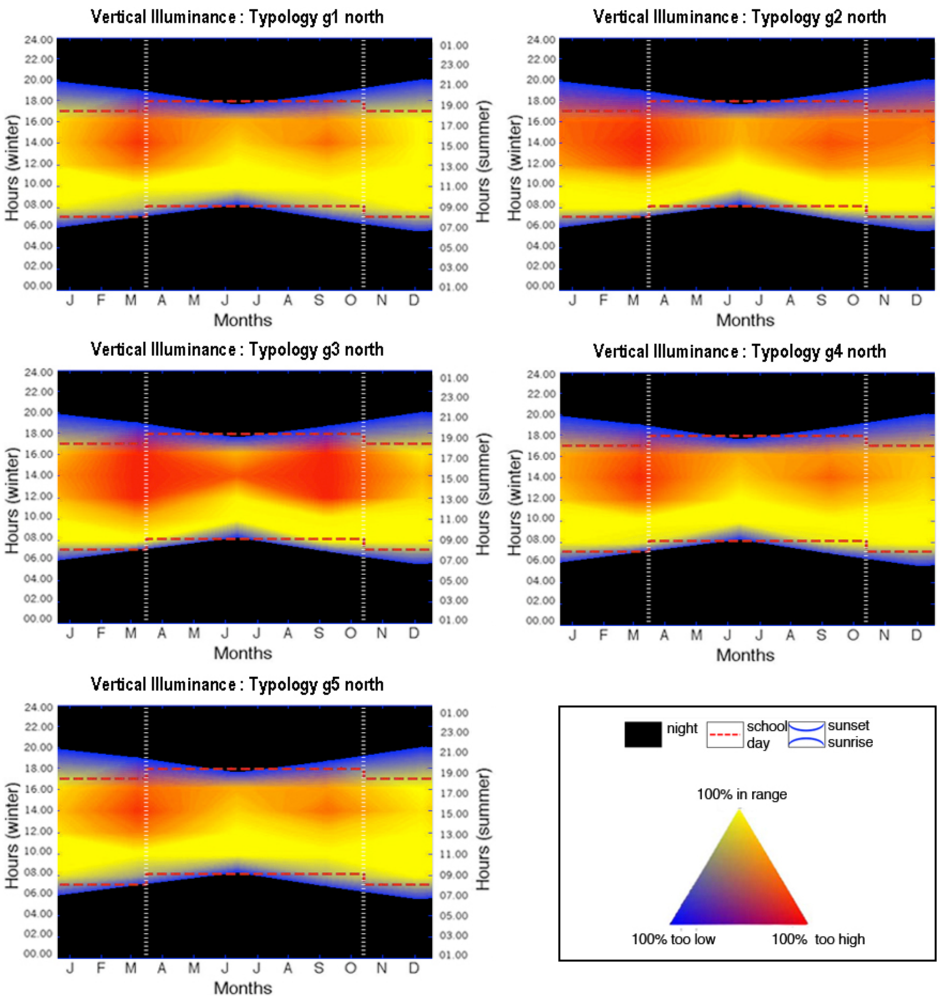
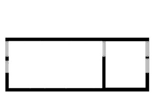
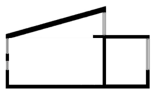
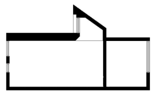
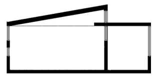
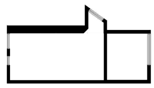


Figure 4.1-3: Vertical Temporal Illuminance maps on the Whiteboard for all the Typologies

Table 4.1-3: Summary of Vertical Temporal Illuminance maps of North-facing classrooms.

North									
TYPOLOGY g1		TYPOLOGY g2		TYPOLOGY g3		TYPOLOGY g4		TYPOLOGY g5	
									
Too Low	33%	Too Low	31%	Too Low	31%	Too Low	32%	Too Low	34%
In range	51%	In range	41%	In range	39%	In range	47%	In range	50%
Too high	16%	Too high	28%	Too high	30%	Too high	21%	Too high	16%

4.1.2 Analysis of Daylight Uniformity for North-facing Classrooms

Criterion 2. Achieving adequate daylight uniformity in the classroom

For the evaluation of this criterion the uniformity, per period and studied skies, was graphed, stating the frequency of these skies in each studied period. The uniformity on the workplane is shown in *Figure 4.1-6* and the uniformity on the whiteboard is shown in *Figure 4.1-7*. The analysis is described below:

- *Uniformity in the workplane area:* when reviewing the daylight uniformity with overcast skies it could be seen that all the typologies achieved uniformity close to 0.5. In a comparative graph of these values, shown in *Figure 4.1-4*, we can confirm that only Typology g3 recorded uniformity greater than 0.5 becoming, comparatively, the most favorable one for an overcast day; however, it did not achieve the uniformity here defined as adequate.

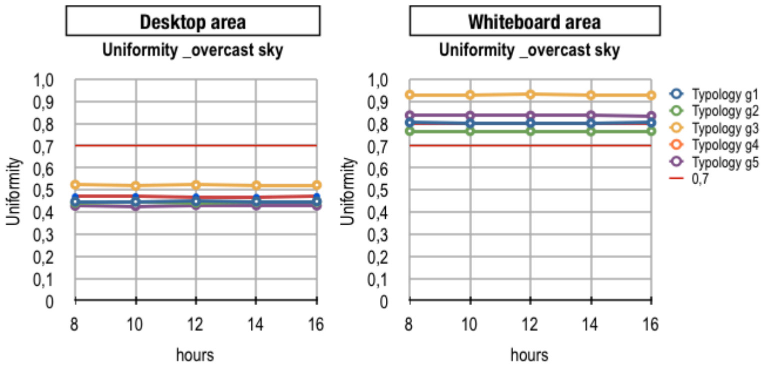


Figure 4.1-4: Daylighting uniformity on the Workplane and on the Whiteboard

The uniformity obtained with clear and clear turbid skies was similar for both. In most part of the day, a great lighting contrast was achieved, starting from 10am, resulting in a great difference between the minimum illuminance (Em) and the average illuminance (Eav), which translates into a high contrast. This is explained in *Figure*

4.1-5, which shows that the uniformity obtained for the five typologies with clear turbid sky varied between 0.1 and 0.25 (between 10am and 4pm). Notwithstanding, in the fourth period (November, December and January) the uniformity was more favorable for all the typologies; all of them achieved a uniformity of around 0.6, verifying that for this period daylight reaches the *adequate uniformity* with clear skies, which can be seen in *Figure 4.1-6*.

For intermediate skies, all the typologies obtained daylighting with variations and contrasts, just as occurred with clear skies. Its uniformity varied between 0.15 and 0.65 and in the three first periods it was found to be well below the recommended levels. In the fourth period, the uniformity improves; only the Typology g3 achieves uniformity greater than 0.65 after 2pm, which corresponds to an *adequate uniformity.*

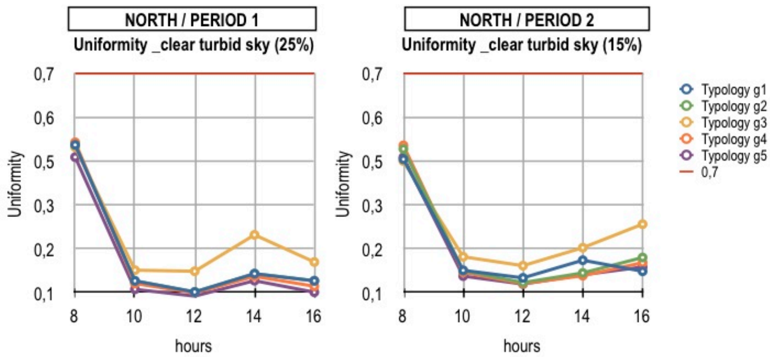


Figure 4.1-5: Daylighting uniformity for clear turbid sky in periods (1) and (2) of the North-facing typologies

- *Uniformity on the whiteboard:* with overcast skies, there was no great difference between the Emin and the Eav on the whiteboard plane. We obtained *optimal levels of uniformity* (> 0.7) in all typologies, as can be seen in *Figure 4.1-4*.

  For clear and clear turbid skies, Typology g3 achieved an *optimal uniformity* in all the study periods.. In the case of the other typologies, an *optimal uniformity* was only achieved during the morning; starting from midday a slight daylight contrast is produced, but stays within the adequate levels (< 0.6), with the exception of the second period where there is a greater contrast, obtaining for some typologies uniformities of 0.2, as can be seen in *Figure 4.1-7*. In the fourth period, they all obtained optimal uniformity for the whiteboard. For the intermediate skies, Typologies g1, g3 and g5 achieved *optimal uniformity*. In the case of Typologies g2 and g4, in the second study period, they presented daylighting contrasts after midday, as can be seen in the graphs of *Figure 4.1-7*.

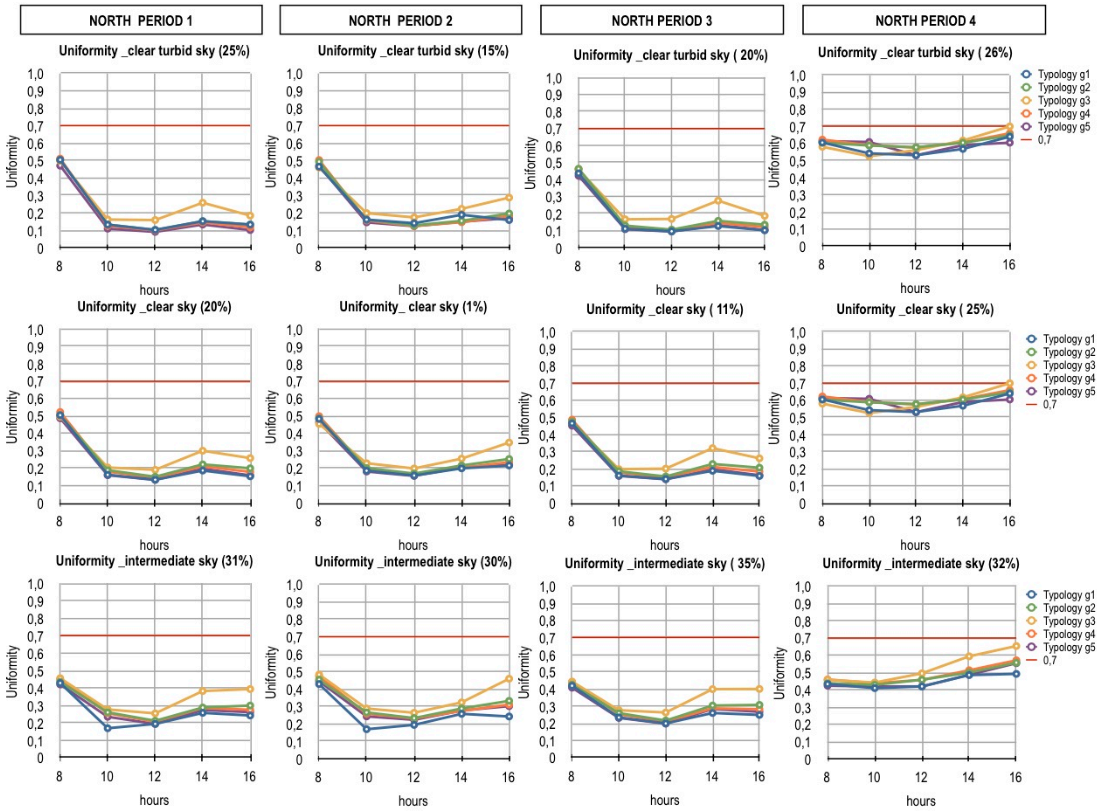


Figure 4.1-6: Uniformity of the daylight on the workplane for the North-facing Typologies

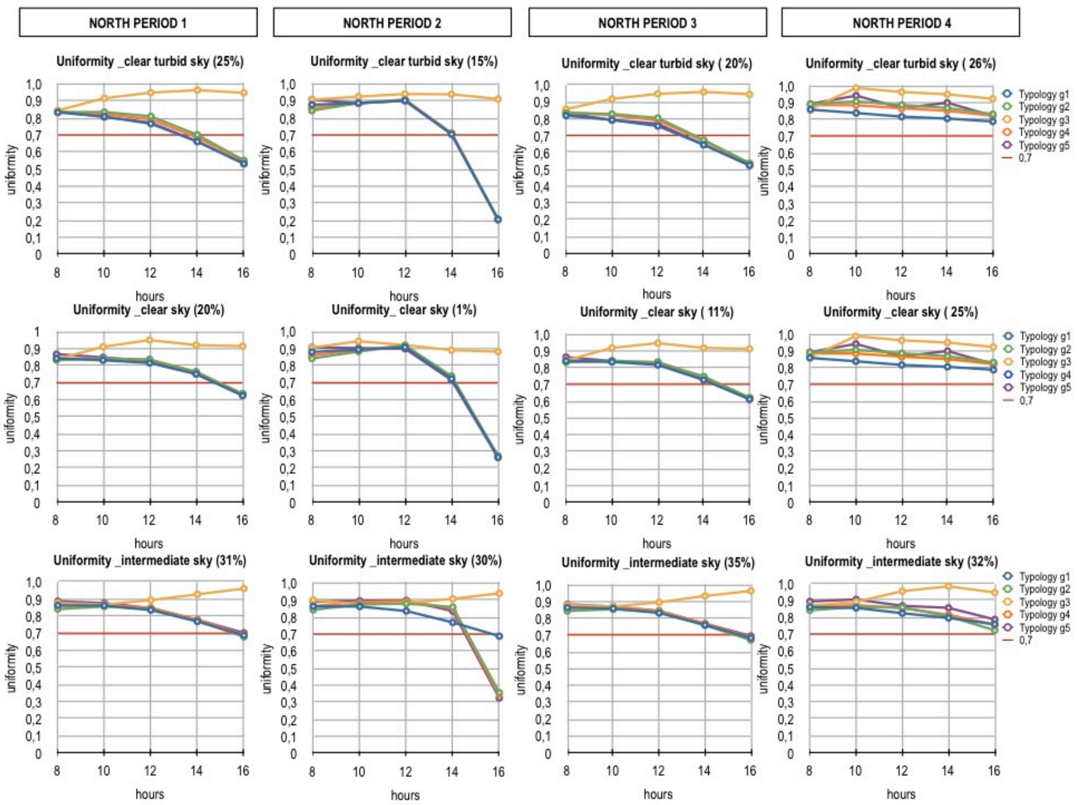


Figure 4.1-7: Daylighting uniformity for the whiteboard for the North-facing Typologies

4.1.3 Glare Analysis for North-facing Classrooms

Criterion 3. Ensuring visual comfort in the field of view of students.

The results are represented in the temporal maps in Figure 4.1-8. For this orientation, all the typologies obtained the same Daylighting Glare Probability (DGP) results. All the typologies presented high glare probabilities, so none can ensure the visual comfort of the students seated in the back of the classroom, next to the window, position that can be seen in section 3.3 of Chapter 3.

- *Temporal DGP maps*: glare probabilities reached their highest point during March, April, May, June and, starting in July, they decrease, though high glare probabilities still exist, maintaining a DGP over 35%.

- *Temporal DGP_{max} maps*: in all the Typologies it could be seen that over 80% of the glare probabilities, for this position, took place in the studied period going from March to October. These high probabilities are reduced as we approach the end of the year; however, a DGP_{max} of over 55% was maintained, which is still unfavorable for visual comfort.

- *Rated DGP:* the perception of the glare sources varied, for the DGP, between imperceptible, disturbing and perceptible. In the case of the DGP_{max}, the perception of the glare source for the most glaring sky was rated as intolerable in all the studied periods.

  In Figure 4.1-9, the rated DGP graphs can be seen, for the four periods of Typology g1. With them, we illustrate the glare probabilities obtained, which were similar for all typologies as was stated at the beginning of this section. It allows us to see the visual discomfort situation that was found.

  The rated DGP graphs for the other typologies are attached in Appendix C

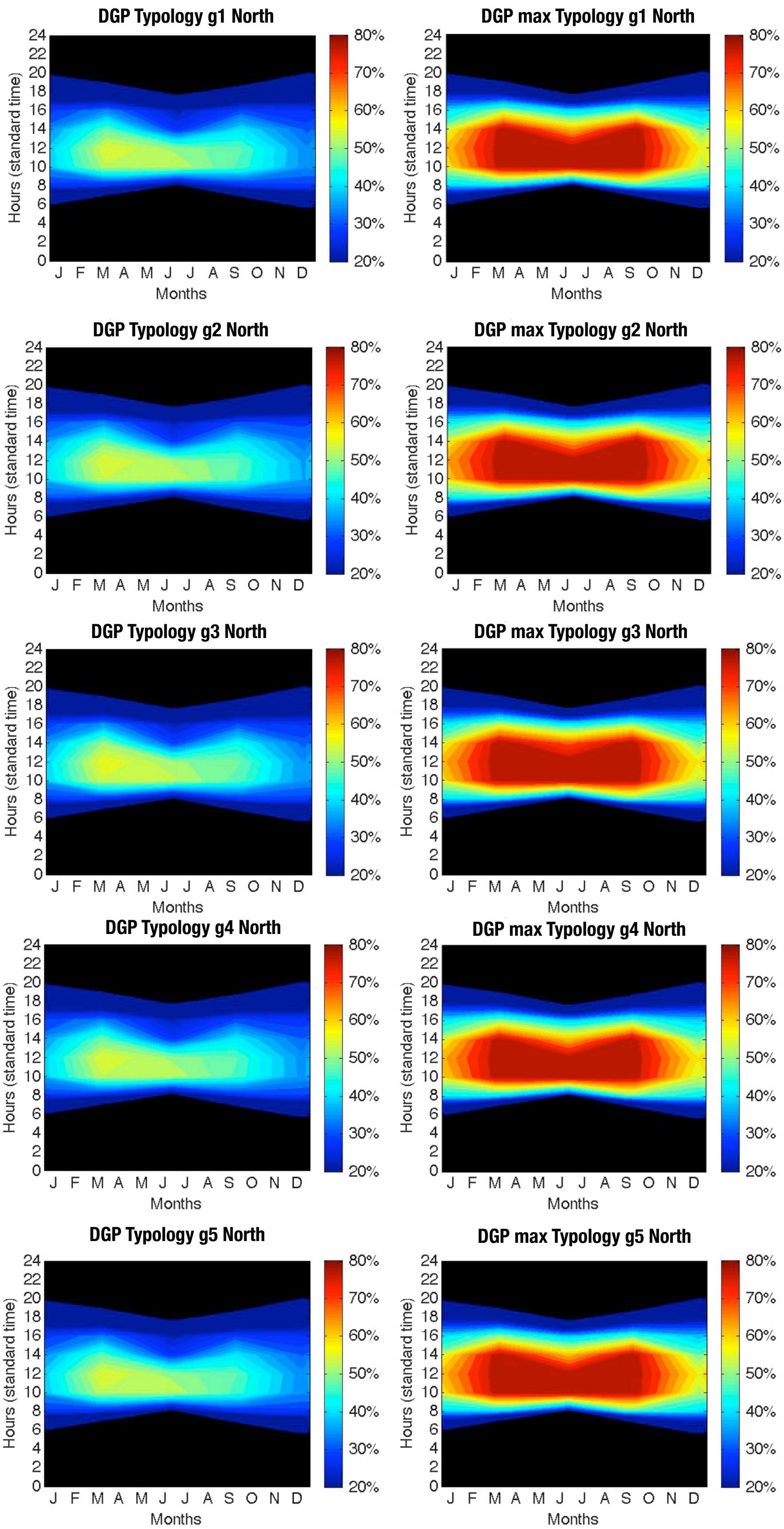


Figure 4.1-8: Temporal DGP y DGP_{max} maps of the North-facing Typologies.

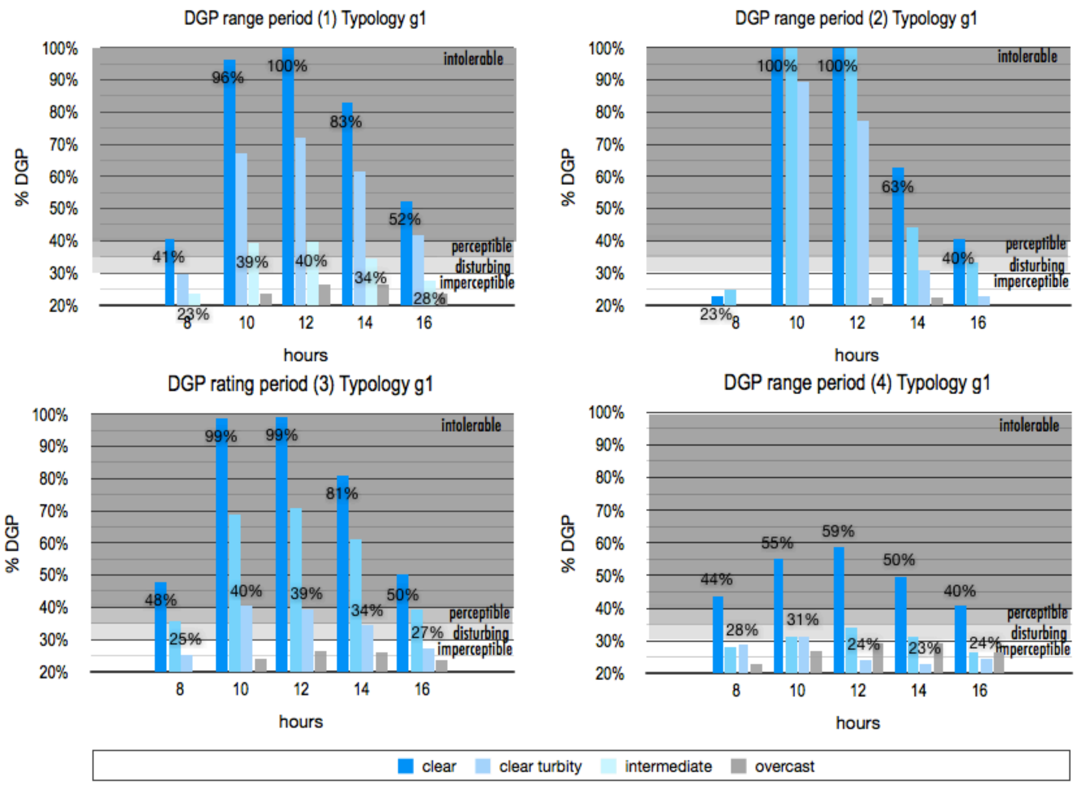


Figure 4.1-9: DGP rated for the typology g1 North-facing in all the evaluated skies.

4.1.4 Analysis of Sunlight Penetration for North-facing Classrooms

Criterion 4. Preventing direct sunlight penetration in the classroom

The images obtained using quick-render in RADIANCE, for the different Typologies, were analyzed. These images can be found in Appendix D for all typologies. Sunlight penetration was seen on the workplane and on the whiteboard, and it is detailed below

Sunlight penetration on the workplane: We see sunlight penetration during the first, second and third period, i.e., during a substantial part of the school year. This affects the students seated next to the northern window. In Figure 4.1-10, the sunlight penetration for Typology g2 is shown.

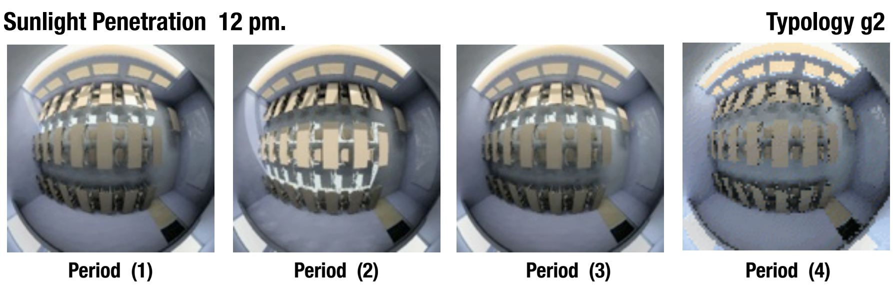


Figure 4.1-10: Sunlight penetration for North-facing Typology g2 during periods of study, at 12pm.

In the fourth period, there was no sunlight penetration in most of the Typologies. Typology g5 has sunlight penetration through the skylight, as can be seen in Figure 4.1-11.

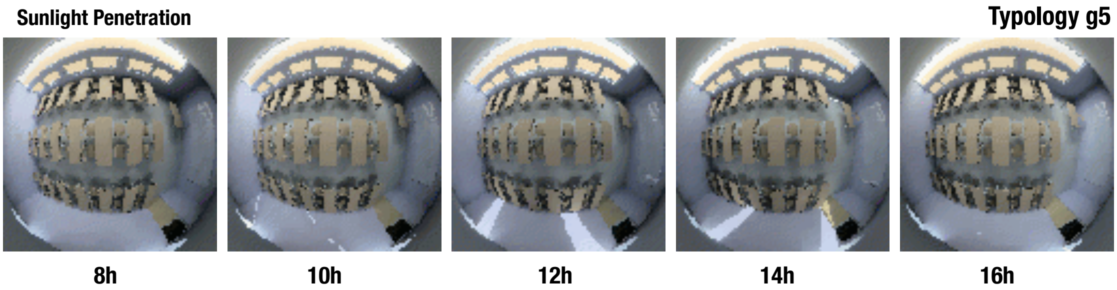


Figure 4.1-11: Sunlight penetration during the fourth studied period, for North-facing Typology g5.

Sunlight penetration on the whiteboard: we have an important sunlight penetration on the second studied period, during the winter. The greatest intensity appeared close to the end of the school day, as seen in Figure 4.1-12.

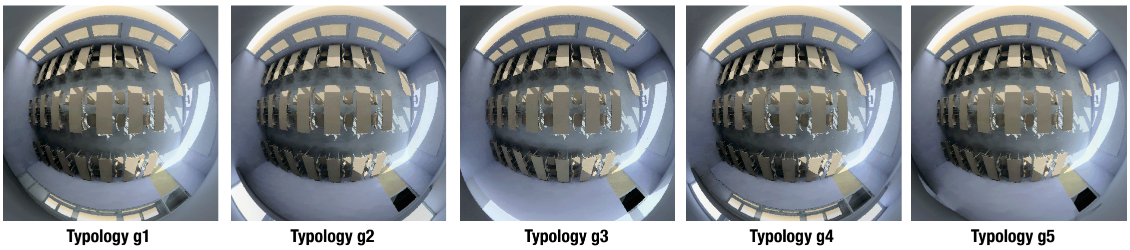


Figure 4.1-12: Sunlight penetration in period (2) at 4pm, for all the North-facing typologies. Patches of light and shadows can be seen on the whiteboard.

4.2 Daylighting Analysis of South-facing Classrooms

4.2.1 Analysis of Daylighting Levels for South-facing Classrooms

Criterion 1. Providing an adequate amount of daylight in the classroom

a. Providing an adequate amount of daylight on the workplane: the Horizontal Temporal Illuminance maps shown in Figure 4.2-1, and the time ranges from Table 4.2-1 were analyzed. Also, the Spatial Illuminance distribution maps shown in Figure 4.2-2 and the space percentages during the year whose "in range" values are shown in Table 4.2-2 were analyzed.

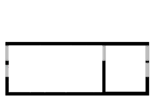
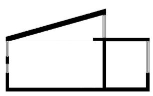
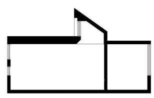
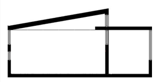
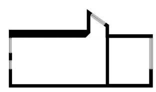
This analysis is described below:

- *Analysis of Horizontal Temporal Illuminance maps:* we proved that Southern orientation is favorable to achieve adequate daylight levels; on the one hand, for Typologies g4 and g5, *adequate daylighting levels* were achieved, keeping 50% and 54% of the time, respectively, with illuminances rated as "in range" throughout the year. These typologies are on the verge of reaching *optimal*, so it can be said that the results can be optimized with some adjustments.

  On the other hand, Typologies g1 and g3 achieved *optimal daylighting levels,* according to the time with "%in range", where Typology g1 obtained 55% and Typology g3, 57% of time throughout the year. Upon observing the temporal maps, they both present a high "%in range" in the classrooms; only in winter time, during the morning and slightly in the afternoon, they present "%too low".

  Typology g2, however, did not achieve an adequate daylight. Its results show that it is below that defined in the criterion. It achieved 33% of the time with illuminances rated as "in range" throughout the year and 36% of the time with illuminances rated as "too high". It could be verified, in the temporal map, that the "%too high" was concentrated on the first, third and fourth studied period.

Table 4.2-1*: Summary of Horizontal Temporal Illuminance Maps of South-facing Classrooms*

South									
TYPOLOGY g1		TYPOLOGY g2		TYPOLOGY g3		TYPOLOGY g4		TYPOLOGY g5	
									
Too Low	38%	Too Low	31%	Too Low	35%	Too Low	32%	Too Low	38%
In range	55%	In range	33%	In range	57%	In range	50%	In range	54%
Too high	7%	Too high	36%	Too high	8%	Too high	18%	Too high	8%

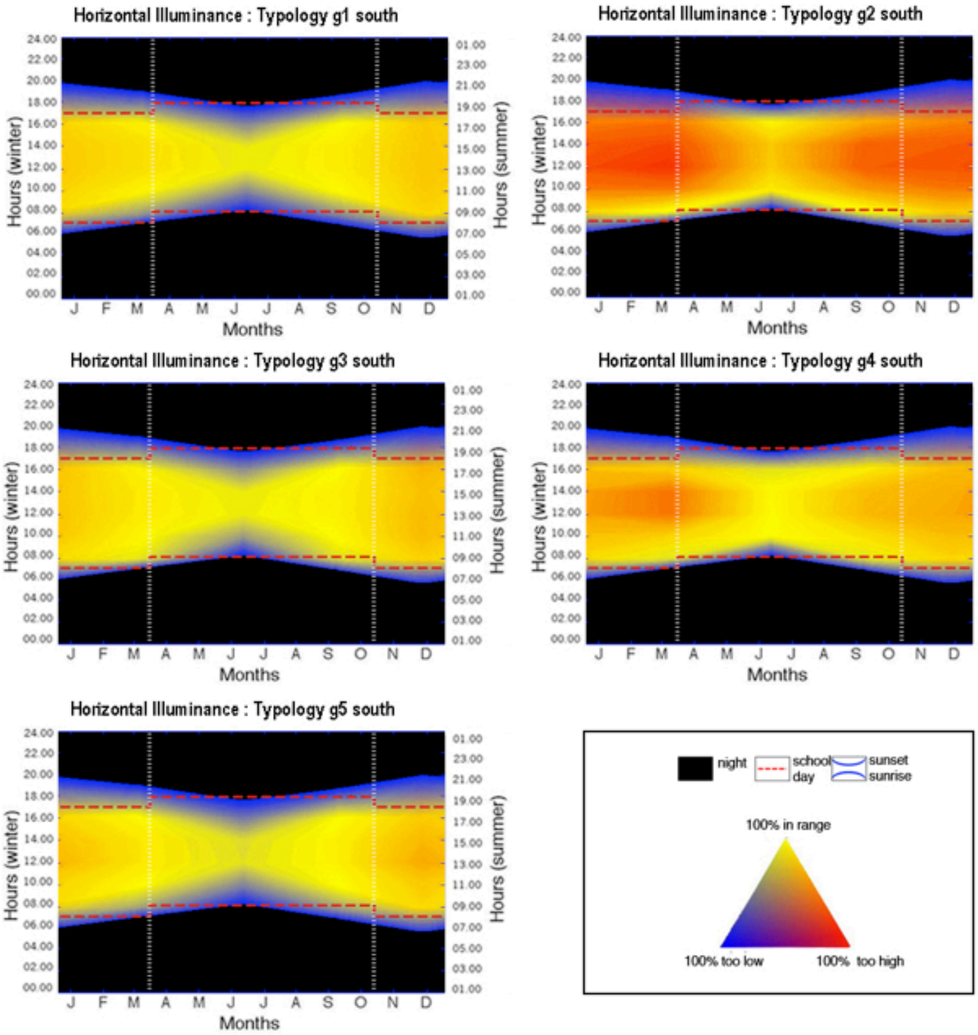
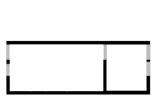
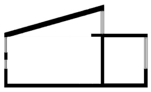
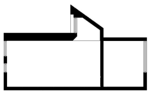
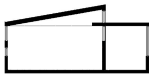
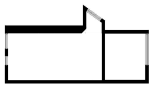


Figure 4.2-1: Horizontal Temporal Illuminance maps for all the South-facing Typologies

- *Analysis of Spatial Illuminance distribution maps:* in the results it could be seen that Typologies g1 and g3 achieved an *optimal spatial distribution* of daylight, obtaining 75% and 78% of the classroom area with illuminances rated as "in range", respectively. Typology g1 allowed for an excellent distribution in the classroom area due to the indirect daylight coming from the corridor that receives Northern light, which feeds daylight to the area next to the corridor. In the case of Typology g3, this distribution was obtained thanks to the use of a bilateral daylighting strategy with Southern orientation. This can be clearly seen on the spatial maps. On the other hand, Typology g5 it at the limit of an *optimal distribution,* since it obtained a 74% of the area with "%in range". Upon observing the temporal maps, it presented illuminances rated as "too low" in the area next to the door, as can be seen in the spatial maps. Typologies g2 and g4 achieved a *regular spatial distribution*. When studying the temporal maps it could be seen that typology g2, even though it achieved a regular distribution, presented a "% too high" in a large part of the workplane surface because of the North-facing clerestory. In Typology g4 something similar occurred, although with a lesser intensity.

Table 4.2-2: Summary of Spatial Illuminance Distribution Maps for South-facing Classrooms

South									
TYPOLOGY g1		TYPOLOGY g2		TYPOLOGY g3		TYPOLOGY g4		TYPOLOGY g5	
									
Too Low	17%	Too Low	5%	Too Low	12%	Too Low	7%	Too Low	17%
In range	75%	In range	50%	In range	78%	In range	71%	In range	74%
Too high	8%	Too high	45%	Too high	9%	Too high	22%	Too high	9%

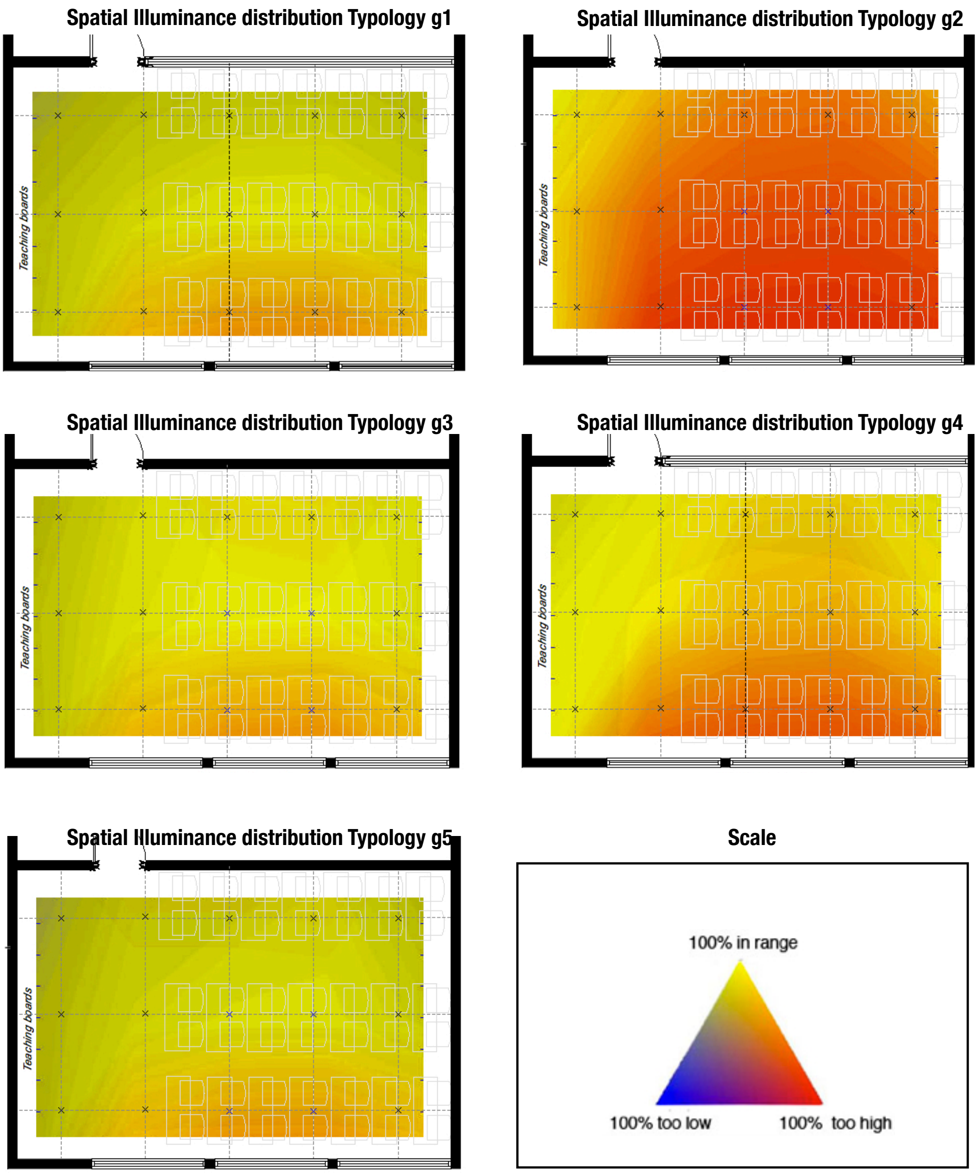


Figure 4.2-2: Spatial Illuminance distribution maps for South-facing Typologies

b. Providing an adequate amount of daylight on the whiteboard: the results obtained are expressed in the temporal maps of Figure 4.2-3 and the percentage of time throughout the year, in each range, is shown in Table 4.2-3. The following can be observed:

Typologies g1, g3, g4 and g5 achieved *optimal daylighting levels* in relation to the percentage of time with illuminances rated as "in range". When examining the temporal maps, it can be seen that the Typologies g1, g3 and g5 presented "%too low" during the second period (May, June and July), in the morning and part of the afternoon, which can be solved by having a lighting system which complements daylight in this period. In the case of Typology g4, "%too low" did not appear during the aforementioned period.

Typology g2 was shown to be the most unfavorable, as it did not achieve adequate daylighting, it was shown as "%too high" in the temporal maps for a large part of the year, this being more noticeable in the first, third and fourth periods.

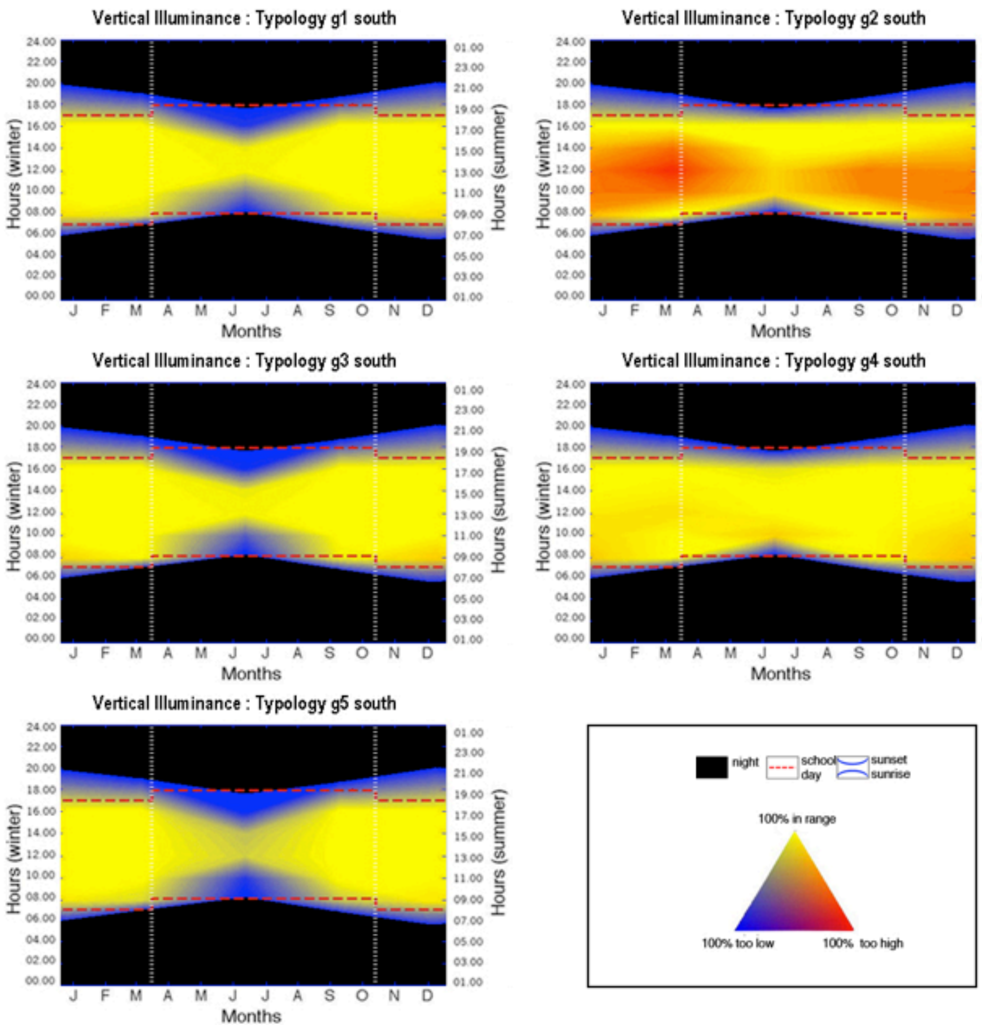
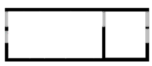
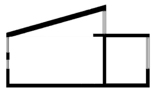
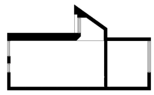
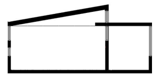
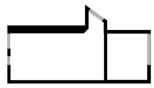


Figure 4.2-3: Vertical Temporal Illuminance maps for South-facing Typologies

Table 4.2-3: Summary of Vertical Temporal Illuminance Maps for South-facing Classrooms

South									
TYPOLOGY g1		TYPOLOGY g2		TYPOLOGY g3		TYPOLOGY g4		TYPOLOGY g5	
									
Too Low	36%	Too Low	31%	Too Low	36%	Too Low	32%	Too Low	38%
In range	63%	In range	45%	In range	63%	In range	64%	In range	61%
Too high	1%	Too high	24%	Too high	1%	Too high	4%	Too high	1%

4.2.2 Analysis of Daylight Uniformity for South-facing Classrooms

Criterion 2. Achieving the adequate daylight uniformity in the classroom

In order to evaluate the fulfillment of this criterion, the uniformity was graphed in the same way as for the North-facing classrooms. Uniformity on the workplane is shown on Figure 4.2-6 and uniformity on the whiteboard in shown on Figure 4.2-7. The analysis is described below:

- *Uniformity on the workplane:* with overcast skies, the uniformity achieved by the different typologies, varied in a range of 0.4 and 0.5, as can be seen in Figure 4.2-4. Typology g3 achieved a uniformity greater than 0.5; therefore this was presented as the most favorable one for a Southern orientation with overcast skies.

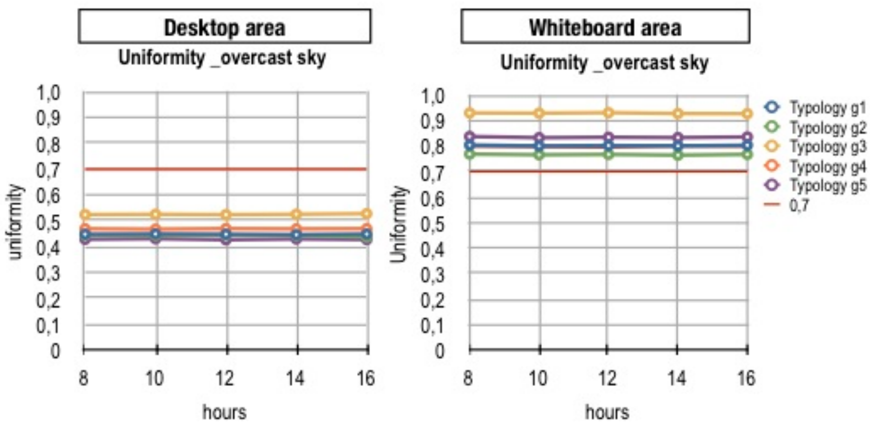


Figure 4.2-4: Uniformity on the workplane and on the whiteboard for South-facing Typologies

In the case of clear and clear turbid skies, the uniformity achieved by all the typologies varied in a range of 0.5 - 0.75. Upon detailed revision, the uniformity obtained under clear turbid skies during the second and third, as shown in Figure 4.2-5, we could prove that, with the exception of Typologies and g4, they all achieved a uniformity between 0.6 and 0.7, which is between an *adequate uniformity* and an *optimal uniformity*.

Only Typology g5, during the fourth studied period, presents greater variations, which generated a very low uniformity as can be seen in the graphs of Figure 4.2-6.

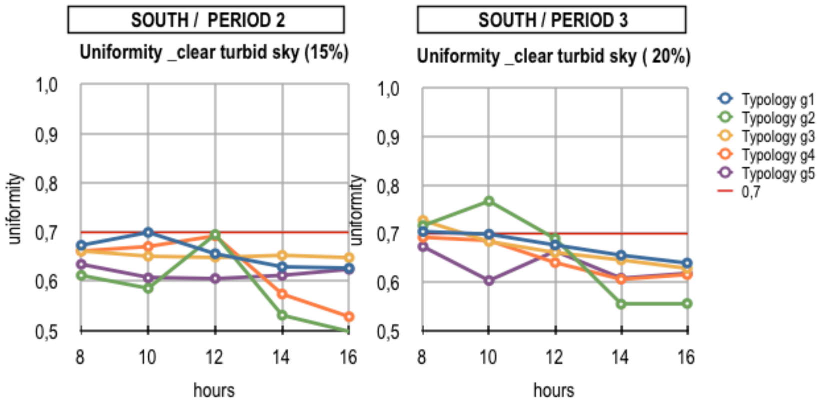


Figure 4.2-5: Uniformity obtained in periods (2) and (3) under clear turbid skies for South-facing Typologies

Under intermediate skies, most of the Typologies showed a very constant uniformity, between 0.4 and 0.6, achieving an *adequate uniformity* during the morning. In the graph of Figure 4.2-6 it can be seen that Typology g3 was the closest one to achieve an *optimal uniformity*. On the other hand, Typology g5 presented variations and contrasts during the fourth studied period, once again.

- *Uniformity on the whiteboard:* when examining the uniformity under overcast skies in Figure 4.2-4 it can be seen that all Typologies achieved an *optimal uniformity,* of over 0.7.

In respect to the uniformity obtained with clear and intermediate skies, Typologies g1, g3 and g5 obtained *optimal uniformity.*

However, Typologies g2 and g4, even though they achieved *optimal uniformity* in the first and fourth studied period, presented moments of great contrast during the morning in the other periods, with their uniformity varying between 0.2 and 0.9 as can be seen in the graph of Figure 4.2-7, produced by sunlight penetration through the clerestory window, as can be seen in Figure 4.2-12 of section 4.2.4.

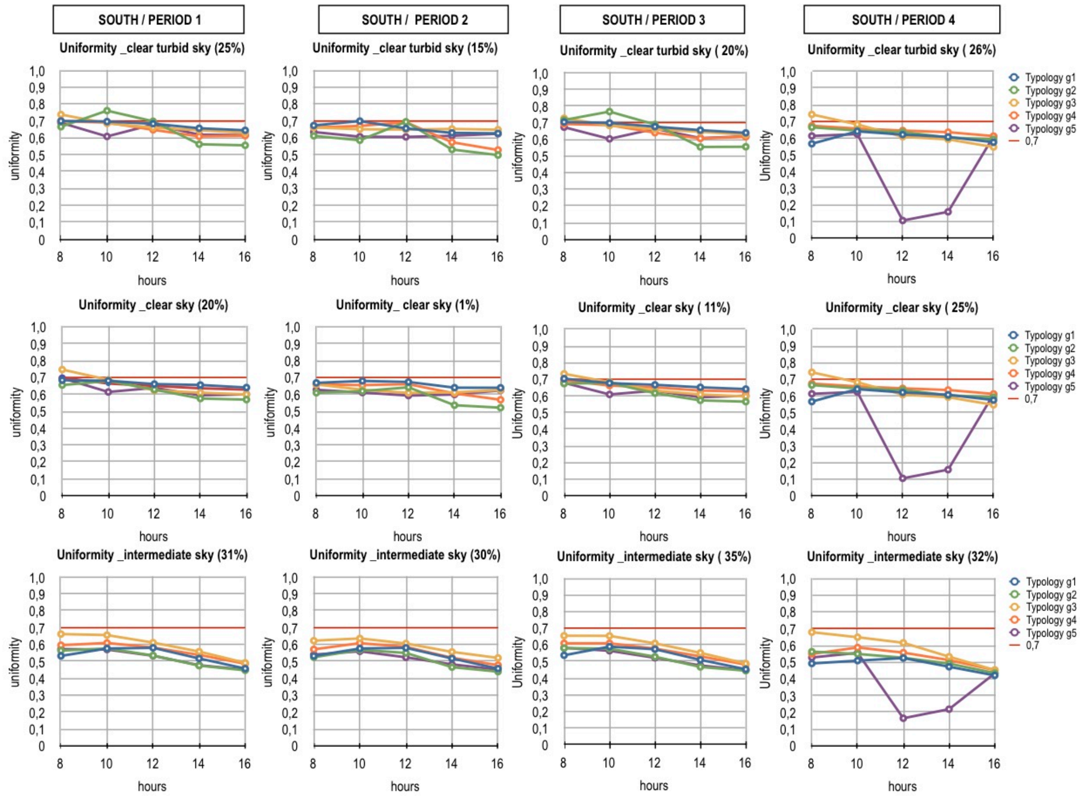


Figure 4.2-6: Daylight Uniformity on the workplanes for South-facing Typologies

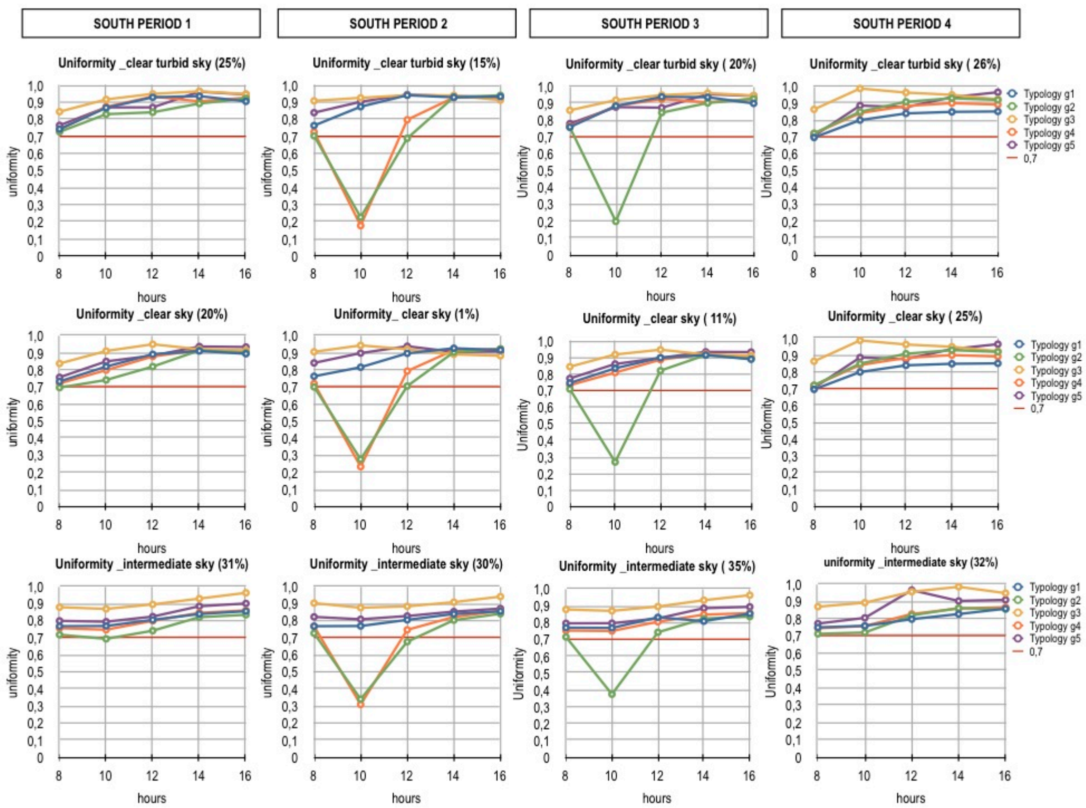


Figure 4.2-7: Daylight Uniformity on the Whiteboard for South-facing Typologies

4.2.3 Analysis of Glare for South-facing Classrooms

Criterion 3. Ensuring visual comfort in the field of view of the students.

Starting from the most unfavorable position, the temporal maps shown in Figure 4.2-8 were analyzed. This analysis is described below:

- *Temporal DGP maps:* we were able to observe that the glare probabilities were low for Typologies g1, g3, g4 and g5, which obtained DGPs under 30%. According to the evaluated position, we can state that these typologies ensure the visual comfort of the students.

  Typology g2, during the second studied period, presented a DGP that was greater than 40%, only for a reduced time interval between 12pm and 2pm. When facing this specific situation, the visual comfort could not be ensured for this typology.

- *Temporal DGP_{max} maps*: with the glare probabilities under the most glaring sky (the clear sky), it was observed that Typologies g1, g3 and g5 had a DGP lower than 40% for the majority of the year. They presented a slight glare risk in the summer months, which does not have a large influence due to the school year. Typology g4 had greater glare probabilities; however, it never exceeded 50%. Typology g2 presented greater glare probabilities during the year, with this being more noticeable during winter, a period which presented daylight penetration through the North-facing window, as can be seen in the analysis of criterion 4.

- *Rated DGP:* we could confirm that the perception of the glare source for the predominant skies was *imperceptible* for all the typologies throughout the year. In the case of Typology g2, which is the most unfavorable one, the perception was *intolerable* for the most glaring sky throughout the whole year, and for the predominant sky it was only *intolerable* during the second studied period; for the rest of the periods it stays as *imperceptible* as can be seen in the graphs of Figure 4.2-9, which shows the rated DGPs for all four periods.

  The rated DGP graphs for the other Typologies are attached in Appendix C.

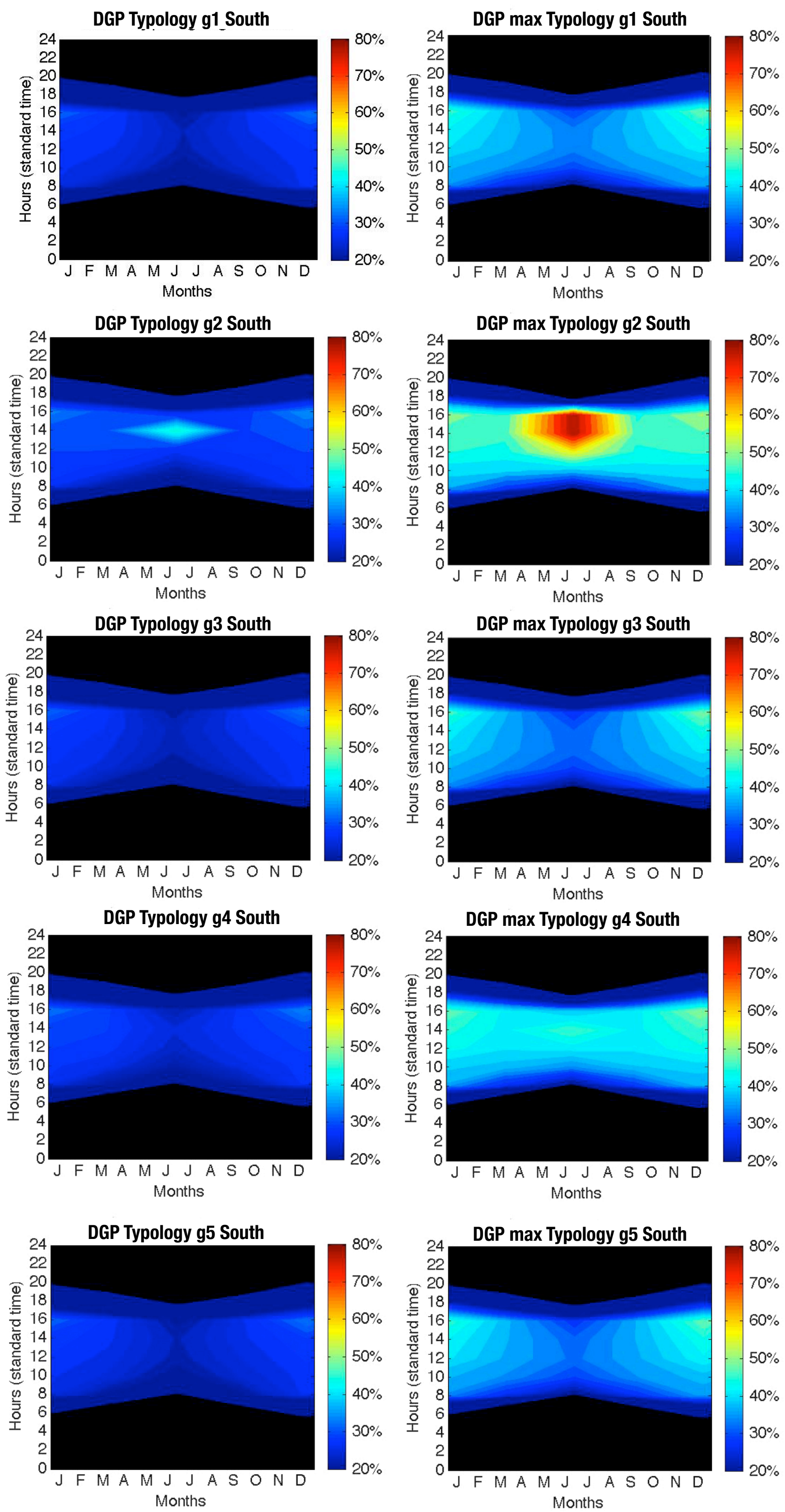


Figure 4.2-8: Temporal DGP and DGP$_{max}$ maps for South-facing Typologies

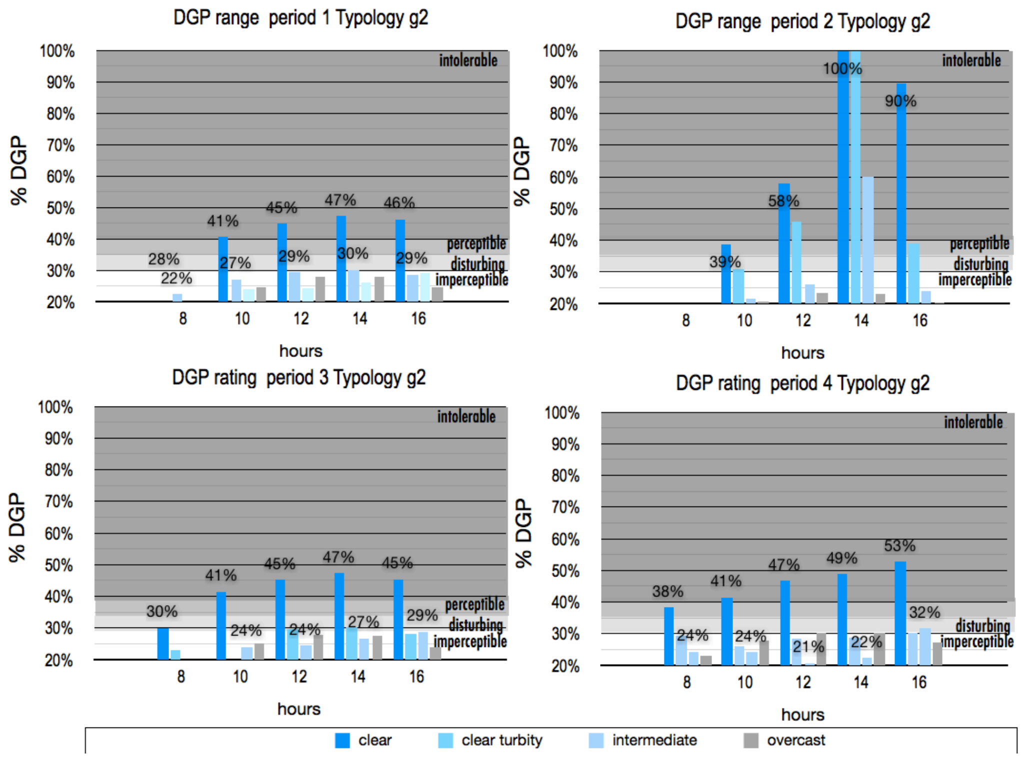


Figure 4.2-9: Graphs of DGP range for Typology g2, Southern Orientation

4.2.4 Analysis of Sunlight Penetration for South-facing Classrooms

Criterion 4. Preventing direct sunlight penetration in the classroom

The images obtained using quick-render in RADIANCE were analyzed, for each of the different typologies, and can be found in Appendix D. The most relevant findings are detailed below:

Sunlight penetration occurred in Typologies g2, g4 and g5. In Typologies g2 and g5, sunlight came in during the first, second and third period. In Typology g2, it entered through the North-facing window as shown in Figure 4.2-10. In Typology g5, sunlight penetrated between 12pm and 2pm through the skylight, as can be seen in Figure 4.2-11, which explains the uniformity variations they presented.

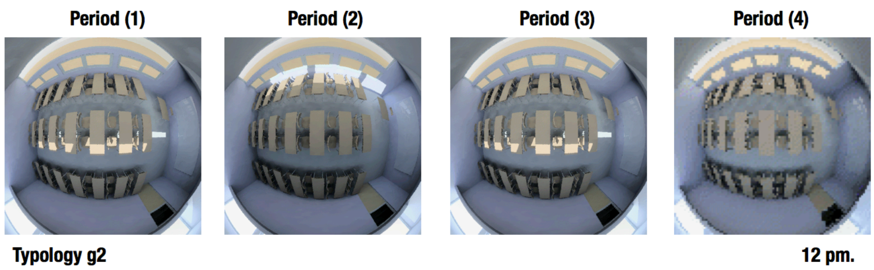


Figure 4.2-10: Sunlight penetration in South-facing Typology g2 at midday in all the studied periods.

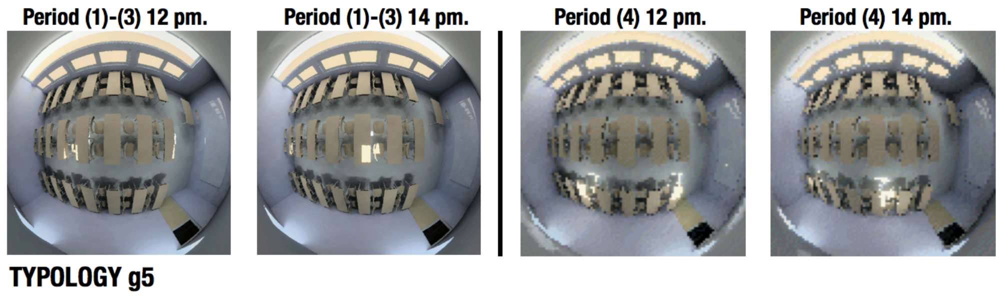


Figure 4.2-11: Sunlight penetration in South-facing Typology g5 at midday and 2pm in studied periods (1), (3) and (4).

In Typology g4, sunlight penetration occurred on the workplane and the whiteboard only during the second studied period. In Figure 4.2-12 it is possible to see the daily trajectory of sunlight during the analyzed hours.

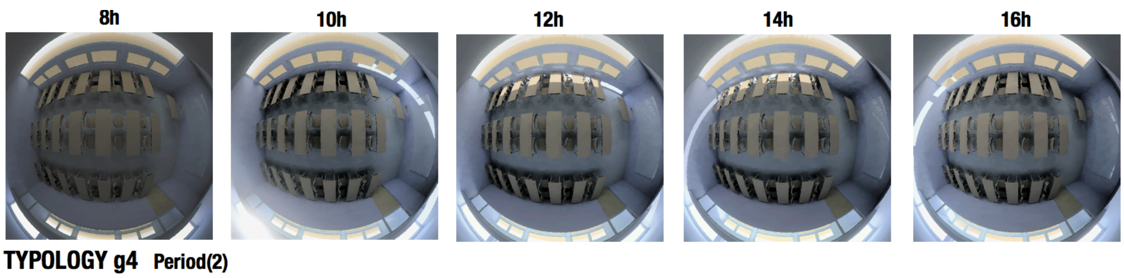


Figure 4.2-12: Sunlight penetration for South-facing Typology g4 on the second studied period at all times.

4.3 Daylighting Analysis of East-facing Classroom Typologies

4.3.1 Analysis of Daylighting levels for East-facing Classrooms

Criterion 1. Providing an adequate amount of daylight in the classroom

a. Providing an adequate amount of daylight on the workplane: The Horizontal Temporal Illuminance Maps indicated in Figure 4.3-1 and in Table 4.3-1 were analyzed; in them we can see the percentage of time of the ranges.

In addition, the Spatial Illuminance Distribution Maps shown in Figure 4.3-2 and in Table 4.3-2 were observed; they indicate the percentages of area within ranges throughout the year. This analysis is described below:

- *Analysis of Horizontal Temporal Illuminance Maps:* we could see that for this orientation none of the Typologies reached the *adequate daylighting levels.*

They all presented a "%too high" during the morning. Typologies g1 and g5 obtained a 41% and 40% of illuminances rated as "in range" throughout the year; however, we could verify in the temporal maps that there is a "%too high" during the morning.

Typology g2 presented a 48% of the time with "%too high" throughout the year; only in June it presented "%in range". Typologies g3 and g4 obtained 33% of illuminances rated as "in range" throughout the year. It can be verified in the temporal maps that they are distributed in a different way, temporally speaking.

Typology g3 presented "%too high" during the morning on the first, third and fourth periods, while Typology g4 presented "%too high" during the morning and part of the afternoon in the aforementioned periods.

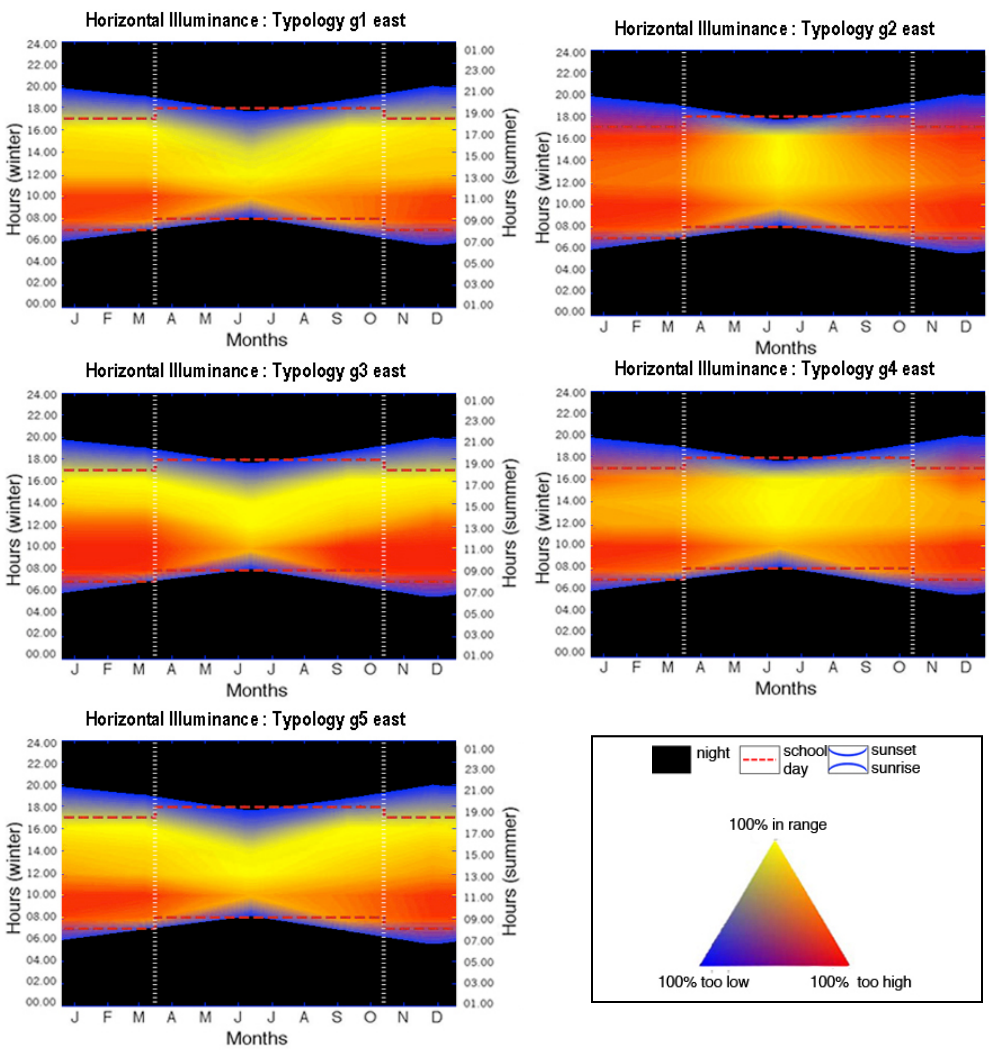
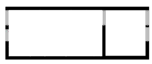
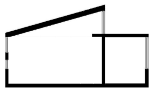
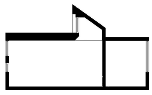
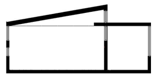
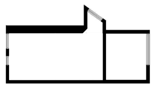


Figure 4.3-1: Horizontal temporal Illuminance maps for all East-facing Typologies.

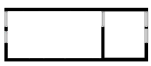
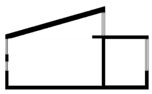
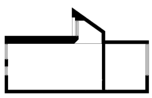
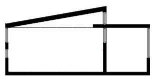
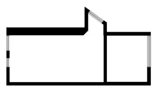
Table 4.3-1: Summary of Horizontal Temporal Illuminance Maps for East-facing Classrooms

East									
TYPOLOGY g1		TYPOLOGY g2		TYPOLOGY g3		TYPOLOGY g4		TYPOLOGY g5	
									
Too Low	33%	Too Low	31%	Too Low	32%	Too Low	33%	Too Low	33%
In range	41%	In range	21%	In range	33%	In range	33%	In range	40%
Too high	26%	Too high	48%	Too high	35%	Too high	36%	Too high	28%

- *Analysis of Spatial Illuminance distribution maps:* When referring to the distribution maps, we can see that Typologies g1, g4 and g5 had a *regular spatial distribution* of daylight throughout the year. They all presented illuminances rated as "too high" next to the window.

  The results obtained for Typologies g3 and g2 were the least favorable, because they obtained an *irregular spatial distribution*, having high illuminances distributed in the whole of the area of the workplane. Typology g2 presented 59% percent of the area with illuminances rated as "too high" during the year, and Typology g3 obtained 44% of the classroom area with an inadequate illuminance range.

Table 4.3-2: Summary of Spatial Illuminance distribution maps for East-facing Classrooms.

East									
TYPOLOGY g1		TYPOLOGY g2		TYPOLOGY g3		TYPOLOGY g4		TYPOLOGY g5	
									
Too Low	9%	Too Low	5%	Too Low	8%	Too Low	5%	Too Low	9%
In range	59%	In range	36%	In range	48%	In range	51%	In range	52%
Too high	32%	Too high	59%	Too high	44%	Too high	43%	Too high	34%

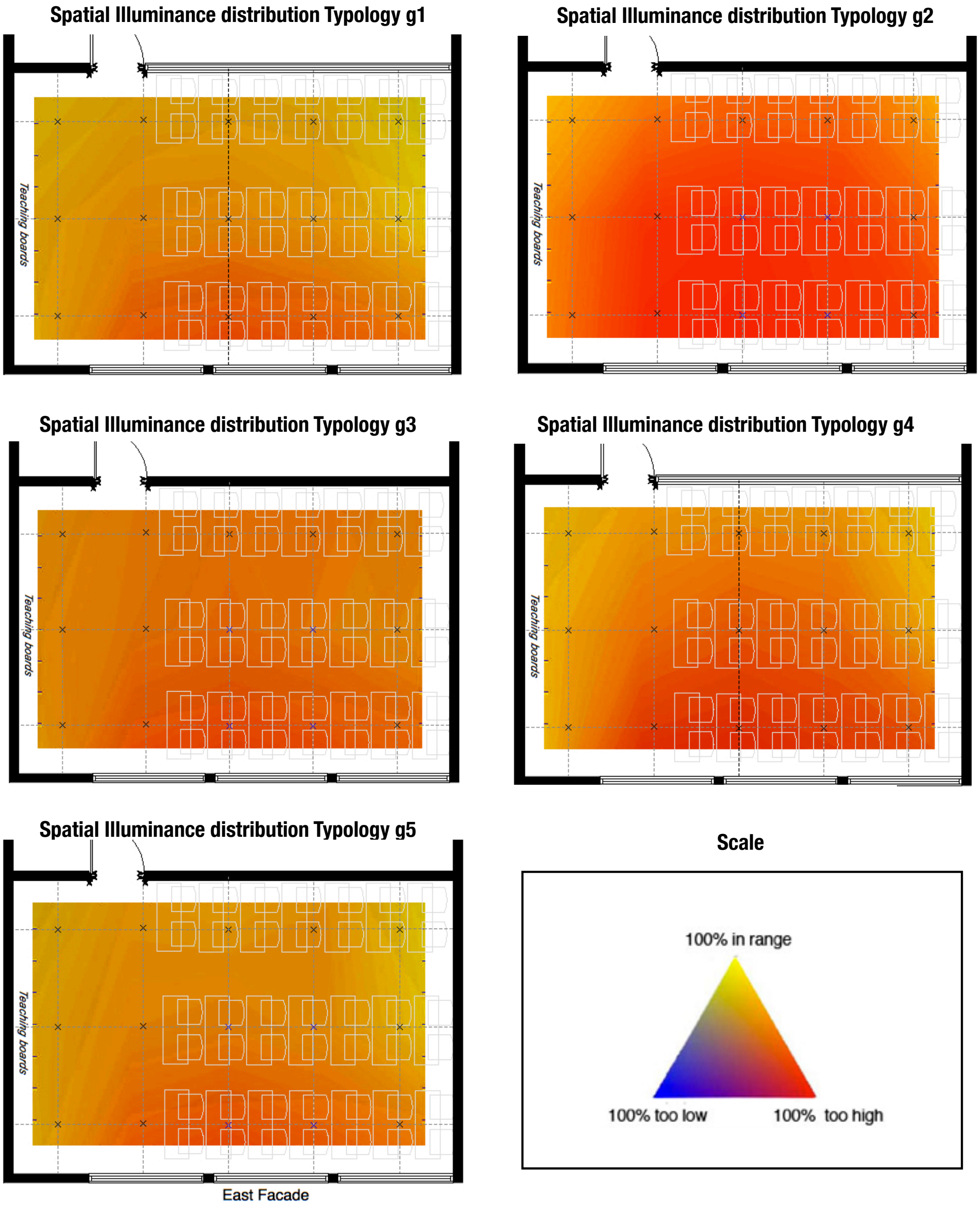


Figure 4.3-2: Spatial Illuminance distribution maps for the East-facing Typologies.

b. Providing an adequate amount of daylight on the whiteboard: the results expressed in the temporal maps shown in Figure 4.3-3, and the time percentages "in range" are shown in Table 4.3-3. These allowed us to observe that:

In the temporal maps, it can be observed that Typologies g1, g3 and g5 presented "%too high" during the mornings on the first, third and fourth period. These presented, also, "%too low" during the afternoons of the second period. Typology g4 did not present "%too low" on the second period, and can be seen in its temporal maps.

Typology g2 presented a "%too high" in the majority of the year; "% in range" was limited and focused on the second period, during the winter. It can be verified that in 45% of the time it presents illuminances rated as "too high" on the whiteboard.

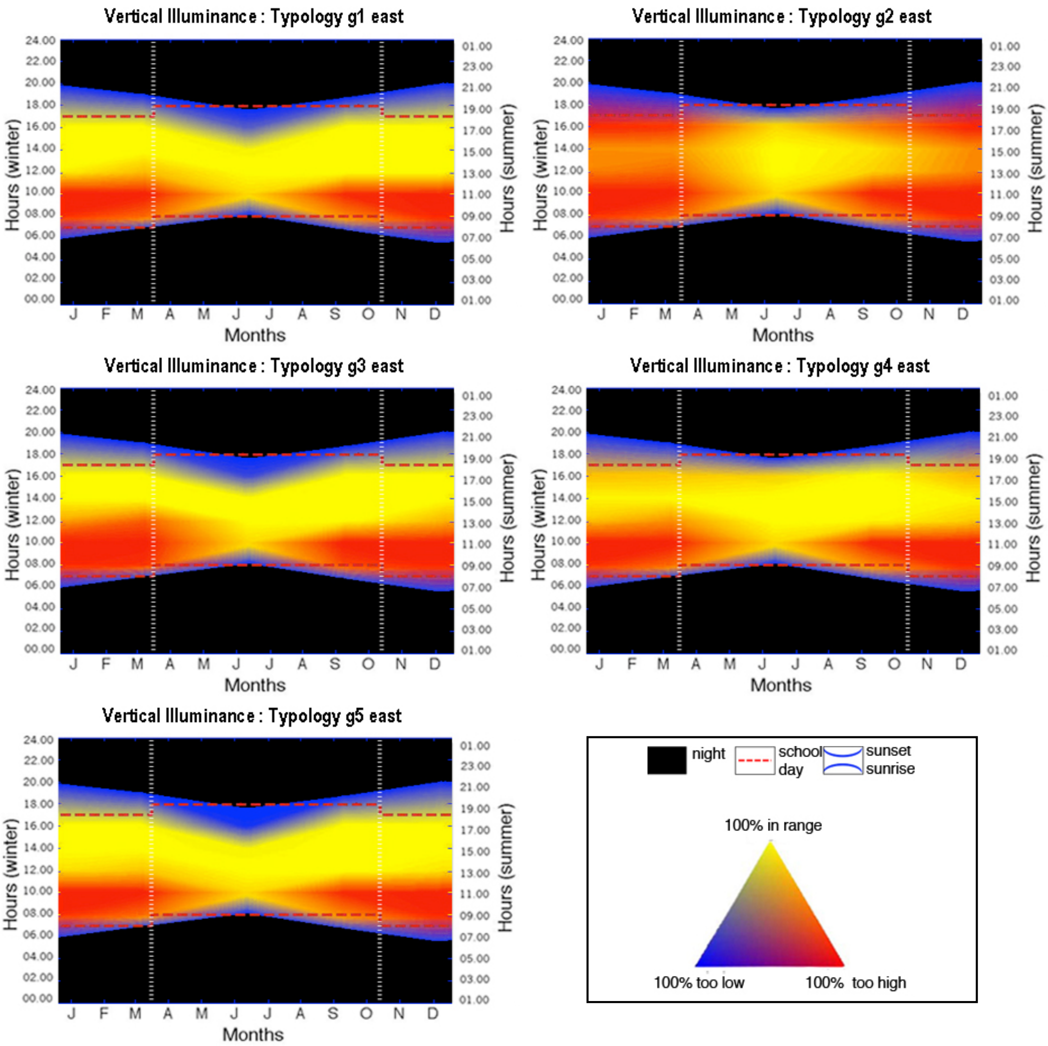
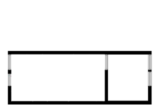
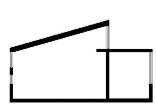
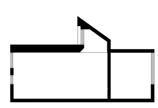
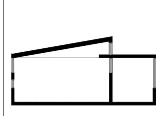
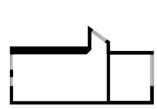


Figure 4.3-3: Vertical temporal illuminance maps for East-facing Typologies

Table 4.3-3: Summary of Vertical Temporal Illuminance Maps for East-facing Classrooms

East									
TYPOLOGY g1		TYPOLOGY g2		TYPOLOGY g3		TYPOLOGY g4		TYPOLOGY g5	
									
Too Low	33%	Too Low	31%	Too Low	33%	Too Low	31%	Too Low	33%
In range	44%	In range	24%	In range	38%	In range	40%	In range	43%
Too high	23%	Too high	45%	Too high	29%	Too high	29%	Too high	24%

4.3.2 Analysis of Daylight Uniformity for East-facing Classrooms

Criterion 2. Achieving an adequate daylight uniformity in the classroom

The uniformity graphs on the workplane shown in *Figure 4.3-6* and the uniformity on the whiteboard shown in *Figure 4.3-7* were observed. The analysis is described below.

- *Daylight uniformity on the workplane:* the uniformity under overcast skies shown in Figure 4.3-4 varied between 0.4 and 0.5. In Typology g3 a uniformity slightly greater than 0.5 was achieved, while the other typologies obtained a uniformity slightly greater than 0.4.

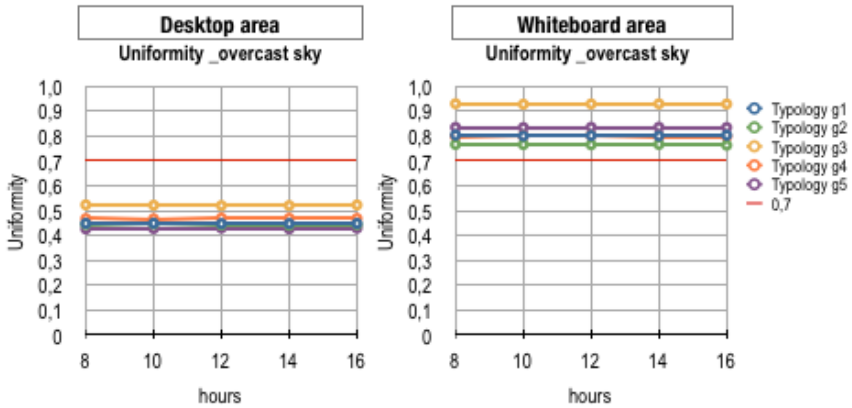


Figure 4.3-4: Uniformity on the workplane and on the whiteboard for East-facing Typologies.

With clear and clear turbid skies, the uniformity obtained by the typologies presented important variations. A critical moment of great daylight contrast was observed between 8am and 12pm during the first and second studied periods.

When seeing the graph in detail, shown in Figure 4.3-5, it can be verified that they all had a hour of greatest contrast which corresponds to 10am in the first and second period, a uniformity which varied between 0.2 and 0.6. It can also be seen that on the third period, Typology g2 obtained uniformity variations also in the afternoon.

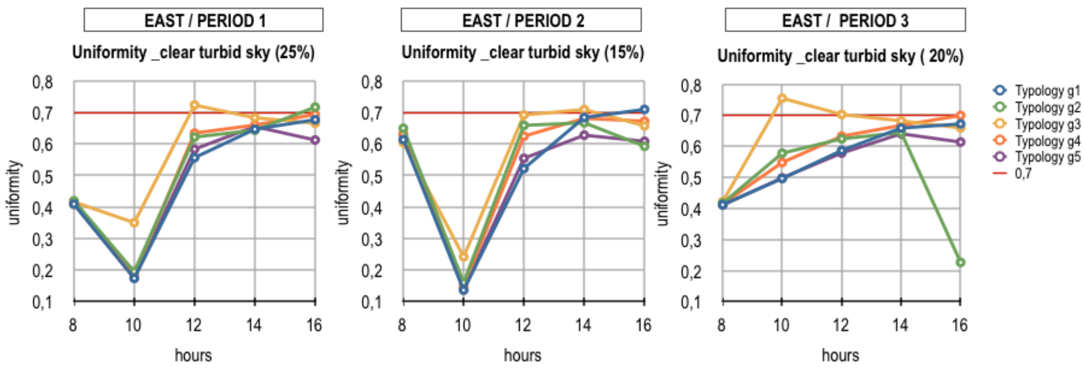


Figure 4.3-5: Uniformity obtained in periods (1), (2) and (3) with clear turbid skies for East-facing Typologies.

For intermediate skies, the uniformity varied between 0.3 and 0.7; the contrast situation for the illuminance in the morning persisted. Typology g3 obtained uniformities between *adequate* and *optimum* starting from 10am throughout the year. Typology g2, during the fourth studied period, presented great uniformity variations both in the morning and the afternoon, as can be seen in Figure 4.3-6.

- *Uniformity on the whiteboard:* with overcast skies, an *optimal uniformity* was achieved in all the Typologies, as can be seen in Figure 4.3-4. In the case of Typology g3, when observing the graph it can be seen that its uniformity is close to 1; to be more accurate it was of 0.93. Also, there is a slight difference between the average illuminance (Eav) and the minimum illuminance (Emin).

  With clear, clear turbid and intermediate skies, the daylight's uniformity varied between 0.65 and 0.95. In the first, third and fourth studied periods, the uniformity for all the Typologies fluctuates between *adequate* and *optimal.* In the second studied period, great variations occurred in the morning, becoming stable later in the day.

  In the case of Typologies g2 and g4, when observing the graph we can see that contrasts situations occur in the afternoon, because of the West-facing clerestory window, which allows sunlight penetration as can be seen in Appendix D.

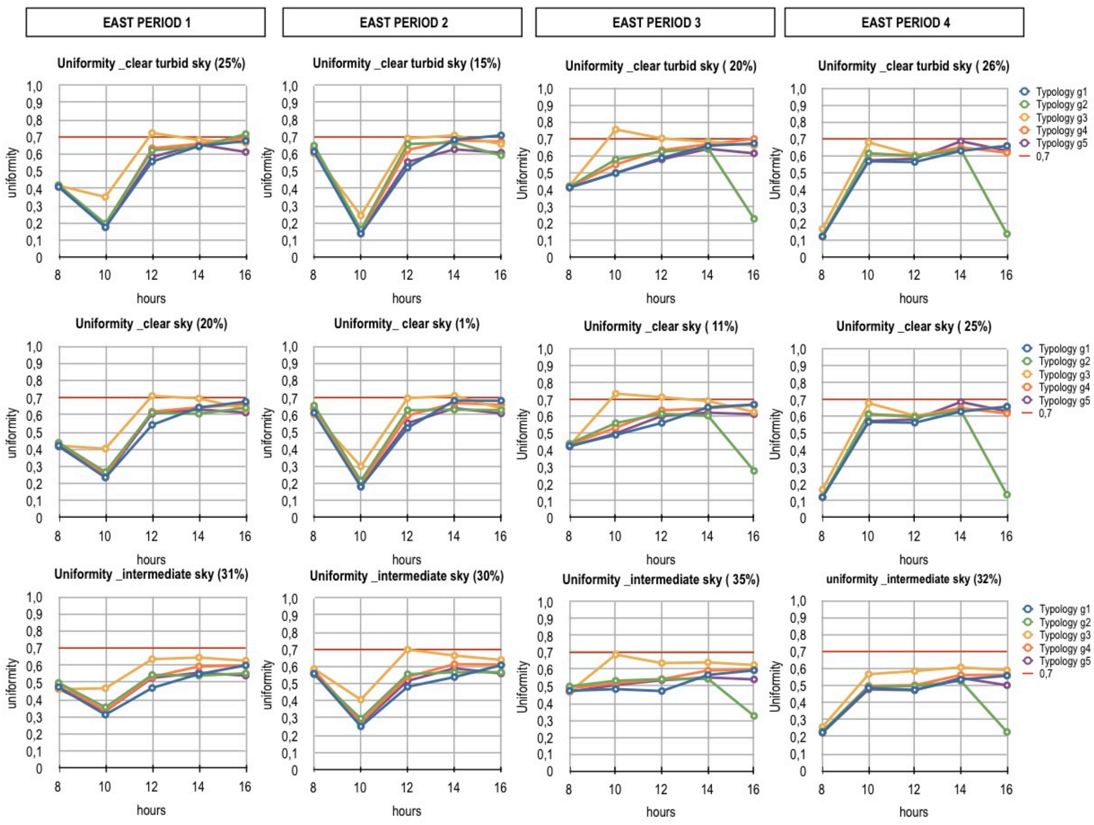


Figure 4.3-6: Graph for uniformity on the workplane for all the Typologies with all the studied skies

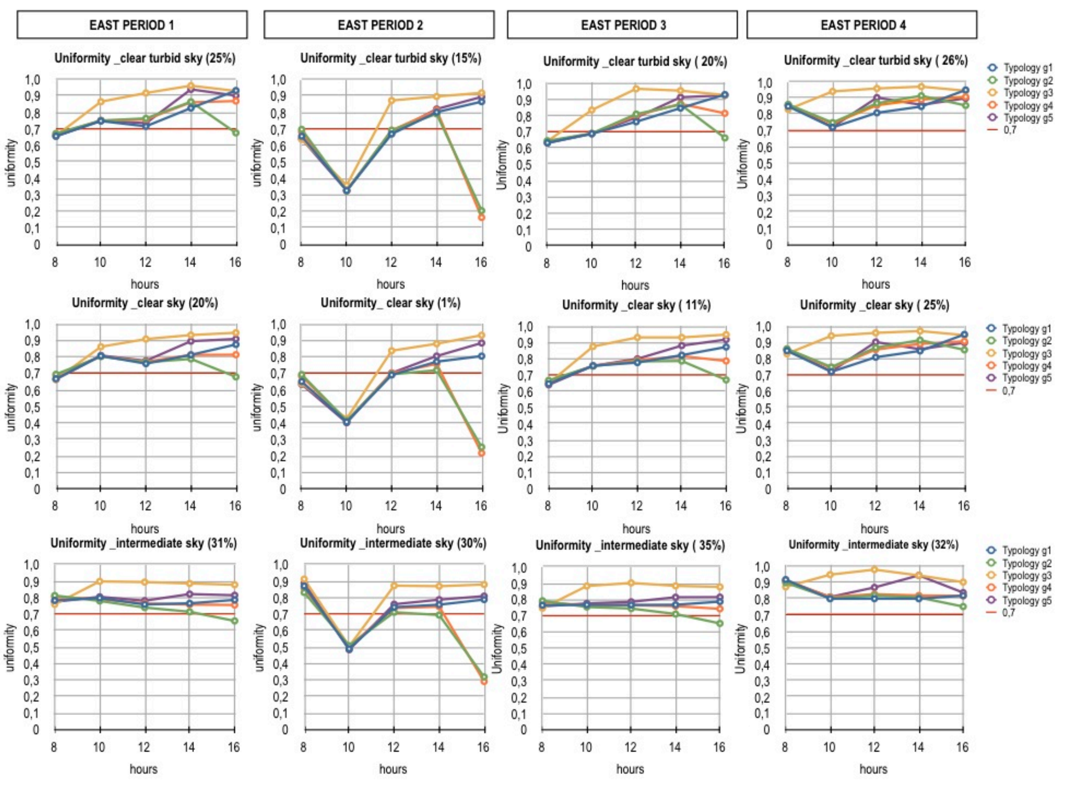


Figure 4.3-7: Graph of the uniformity on the whiteboard of all the Typologies and studied skies.

4.3.3 Analysis of Glare for East-facing classrooms

Criterion 3. Ensuring visual comfort in the field of view of the students.

The temporal maps shown in Figure 4.3-8 are analyzed.

Their analysis is described below:

- *Temporal DGP maps*: Upon examining them it can be seen that all Typologies present the same probability. There is a greater glare probability for the months from January to May and September to December, only during the morning, where it can be verified on the graphs that the DGP was over 40%; in the rest of the year the glare probabilities were under 30%.

- *Temporal DGP_{max} maps*: Greater glare probabilities were found in these for all the Typologies. From what was seen in the temporal maps, Typologies g1, g3 and g5 obtained similar results; they presented greater probabilities during the morning, with the probabilities later falling considerably.

  In the cases of Typologies g2 and g4, they presented high glare probabilities with the majority of the year having DGPs greater than 40%; only in the winter, during the afternoon, did they present a DGP under than 40%.

- *Rated DGP* according to the glare source perception rating for the predominant sky, this fell between *intolerable* and *disturbing* for a large part of the day; only in the afternoon did it reach *imperceptible.*

  With respect to the most glaring sky, the glare source perception fell also between *intolerable* and *perceptible* during the afternoon. In the case of Typologies g2 and g4, the glare perception remained as *intolerable* during the whole day. In Figure 4.3-9 se we can see the DGP obtained for Typology g2 in all the studied periods.

  The rated DGP graphs for the other Typologies are attached in Appendix C.

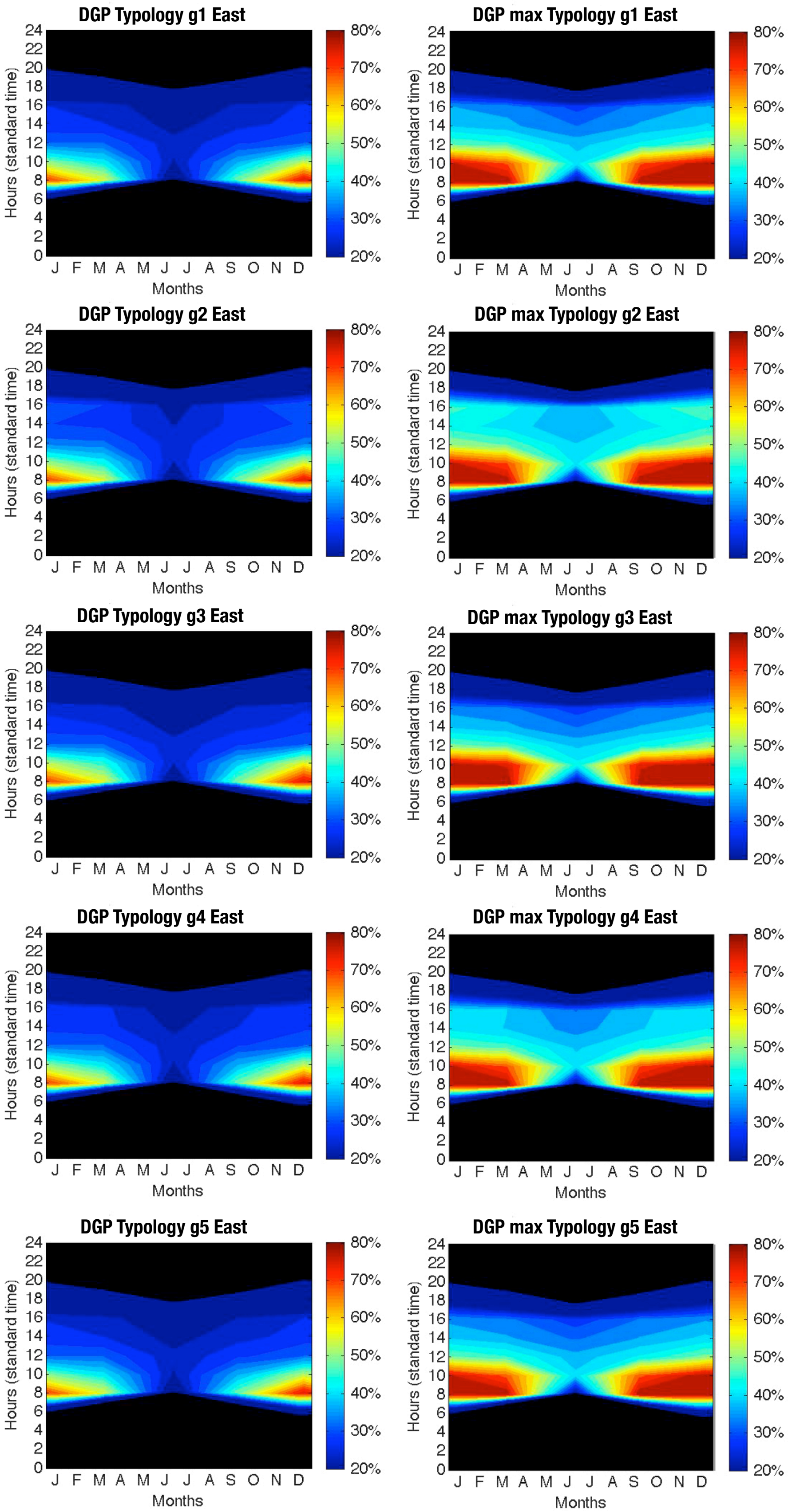


Figure 4.3-8: Temporal DGP y DGP_{max} maps for East-facing Typologies

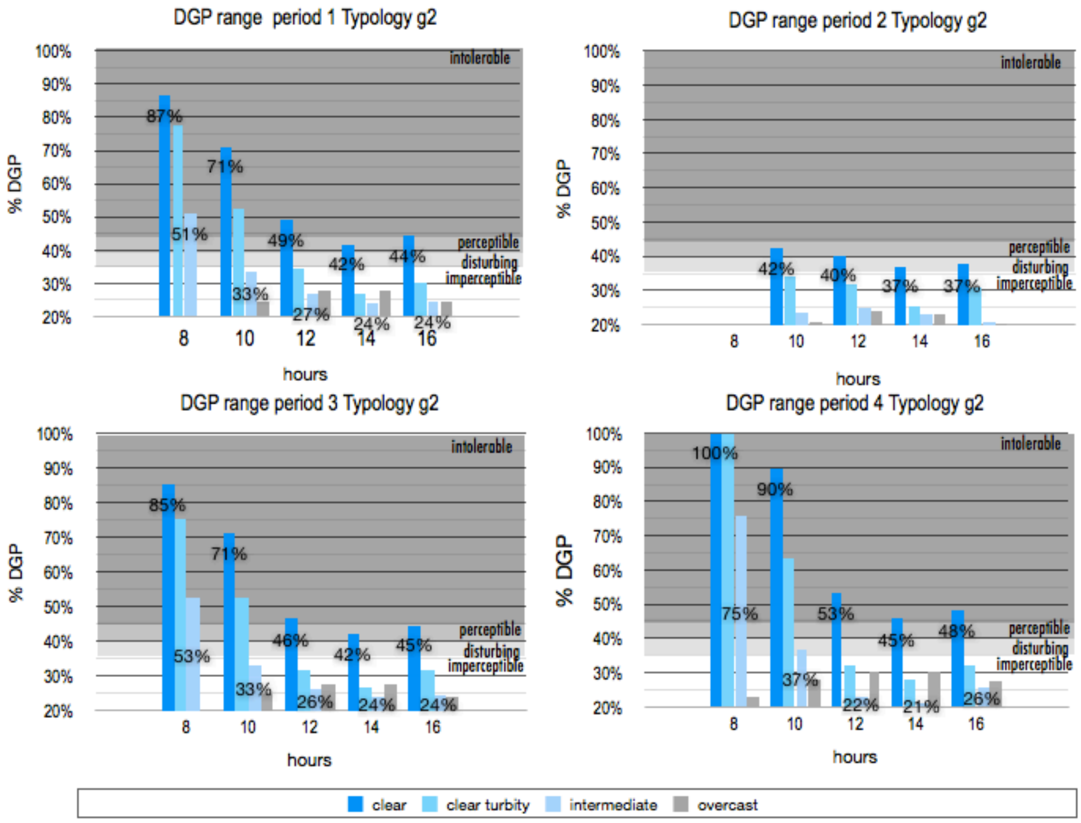


Figure 4.3-9: Graphs for East-facing Typology g2

4.3.4 Analysis of Sunlight Penetration for East-facing Classrooms

Criterion 4. Preventing direct sunlight penetration in the classroom

The images are generated using quick-render in RADIANCE for all the Typologies were analyzed, and can be found, for all the Typologies, in Appendix D. Their relevant aspects are described below:

Upon reviewing the images obtained, the problems caused by the high illuminance described before for the workplane, can be seen; the unreached uniformity and glare risk are produced in those moments where there is some light penetration.

All Typologies presented sunlight penetration in the morning, indistinctive from the studied period of the year. In Figure 4.3-10 sunlight penetration for Typology g1, at 8am, in all the studied periods can be observed.

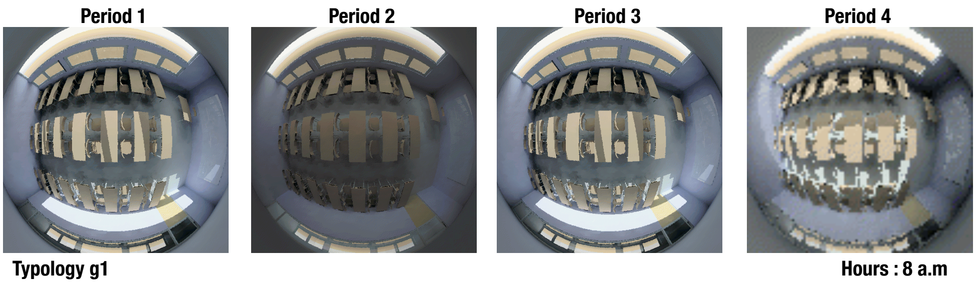


Figure 4.3-10: Sunlight penetration for East-facing Typology g1 at 8am, for all the studied periods.

Typologies with a daylight strategy including a West-facing light entrance, such as Typologies g2 and g4, presented sunlight penetration in the morning and the afternoon. In Figure 4.3-11 the images obtained for these Typologies, at 4pm, in all the studied periods are shown.

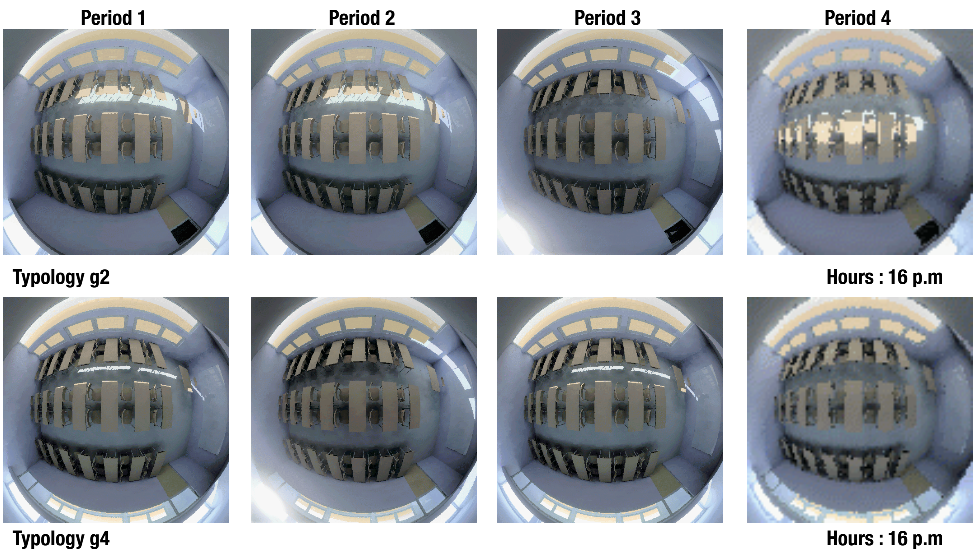


Figure 4.3-11: Sunlight penetration for East-facing Typologies g2 and g4 at 4pm.

4.4 Daylighting Analysis for West-facing Classroom Typologies

4.4.1 Analysis of Daylighting levels for West-facing Classrooms

Criterion 1. Providing an adequate amount of daylight in the classroom

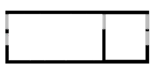
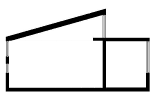
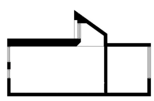
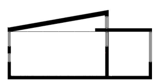
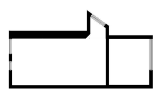
a. Providing an adequate amount of daylight on the workplane: The Horizontal Temporal Illuminance maps indicated in Figure 4.4-1 and in Table 4.4-1, where the percentage of time “in range” during the year is seen, were analyzed. In addition, the Spatial Illuminance distribution maps shown in Figure 4.4-2 and Table 4.4-2, where the percentages of the classroom area “in range” are shown, were observed. Their analysis is described below:

- *Analysis of the Horizontal Temporal Illuminance maps:* we could prove that this orientation was unfavorable for all the studied typologies, because it did not obtain adequate daylighting levels throughout the year.

  It can be seen that Typologies g1 and g5 did not achieve adequate daylight levels with respect to the time with “%in range”; however, in their temporal maps it can be seen that they presented “%in range” on a great portion of the day, from March to October, and only in the second period they presented “%too low” in the morning.

  Typologies g3 and g4 obtained 40% of illuminances “in range”. Typology g3 presented “%too high” in the afternoons of the first, third and fourth studied periods, keeping “%in range” the rest of the time. Typology g4, during the same periods, presented “%too high” in the mornings and the afternoons. Typology g2 obtained illuminances “too high”, 41% of the time. In the temporal maps, it was observed that it presented “%too high” for a large part of the year, mainly in the first and fourth period.

Table 4.4-1: Summary of Horizontal Temporal Illuminance maps for West-facing Classrooms

West									
TYPOLOGY g1		TYPOLOGY g2		TYPOLOGY g3		TYPOLOGY g4		TYPOLOGY g5	
									
Too Low	34%	Too Low	31%	Too Low	35%	Too Low	32%	Too Low	36%
In range	49%	In range	28%	In range	40%	In range	40%	In range	45%
Too high	17%	Too high	41%	Too high	25%	Too high	29%	Too high	18%

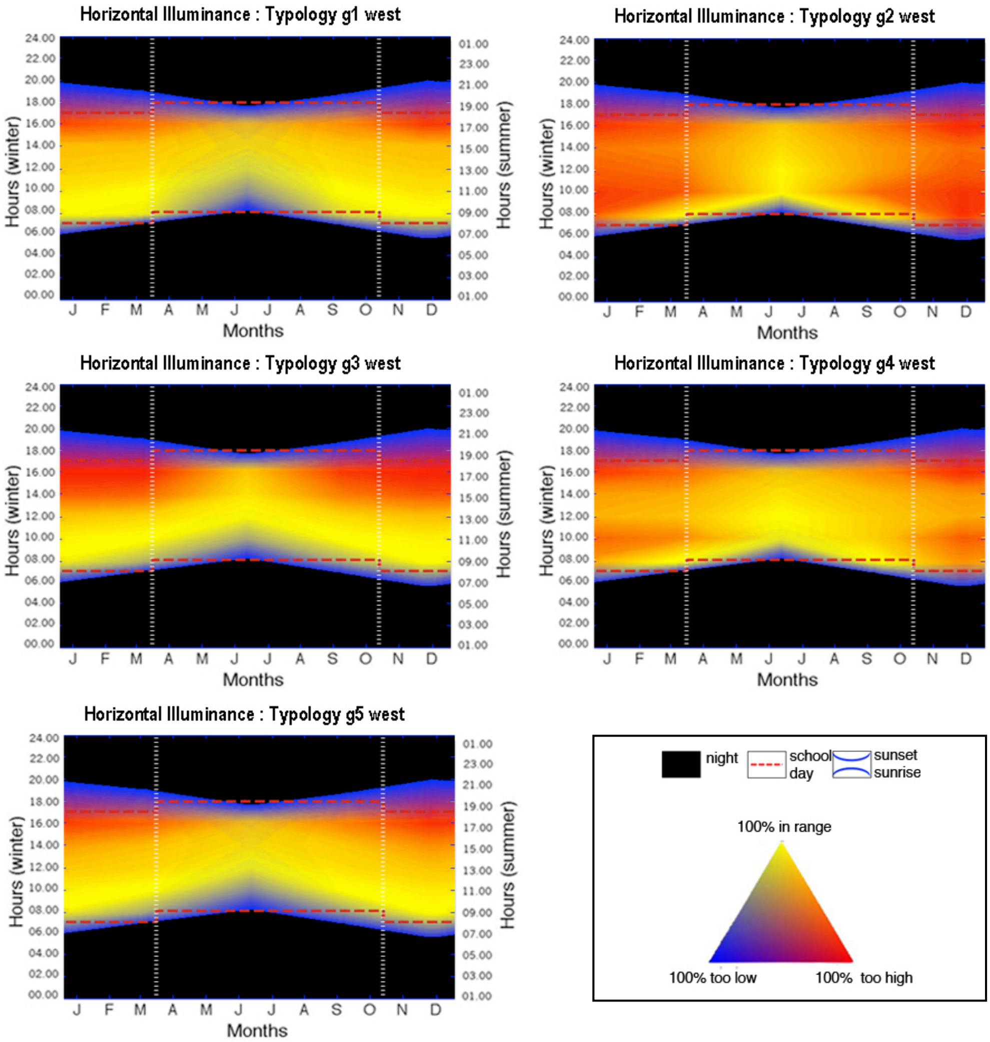


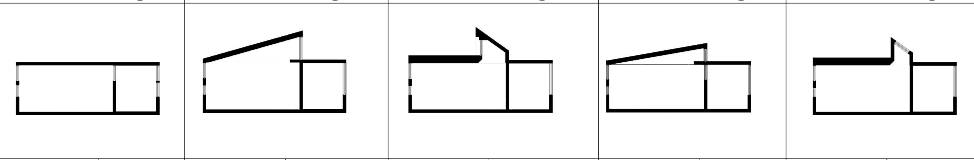
Figure 4.4-1: Horizontal temporal Illuminance maps for all West-facing Typologies

- *Analysis of Spatial Illuminance distribution maps:* it can be seen that Typologies g1, g3, g4 and g5 obtained a *regular spatial distribution* throughout the year.

  Typology g1 obtained 68% of the space and Typology g5 a 63% of the space with illuminances rated as "in range". Upon observing the spatial maps we can see that, only next to the window, illuminances rated as "too high" are present in both cases.

  Typologies g3 and g4, despite achieving a *regular distribution,* upon observing the spatial maps it can be seen that they have illuminances rated as "too high" in a large part of the space. In particular, Typology g4 obtained 35% of the area with illuminances rated as "too high" throughout the year. However, the most unfavorable one was Typology g2, which obtained an *irregular spatial distribution,* with 45% of the area with illuminances rated as "in range" and 50% of the area with illuminances rated as "too high".

Table 4.4-2: Summary of Spatial Illuminance distribution maps for West-facing classrooms

West									
TYPOLOGY g1		TYPOLOGY g2		TYPOLOGY g3		TYPOLOGY g4		TYPOLOGY g5	
									
Too Low	11%	Too Low	5%	Too Low	11%	Too Low	6%	Too Low	14%
In range	68%	In range	45%	In range	57%	In range	59%	In range	63%
Too high	21%	Too high	50%	Too high	32%	Too high	35%	Too high	23%

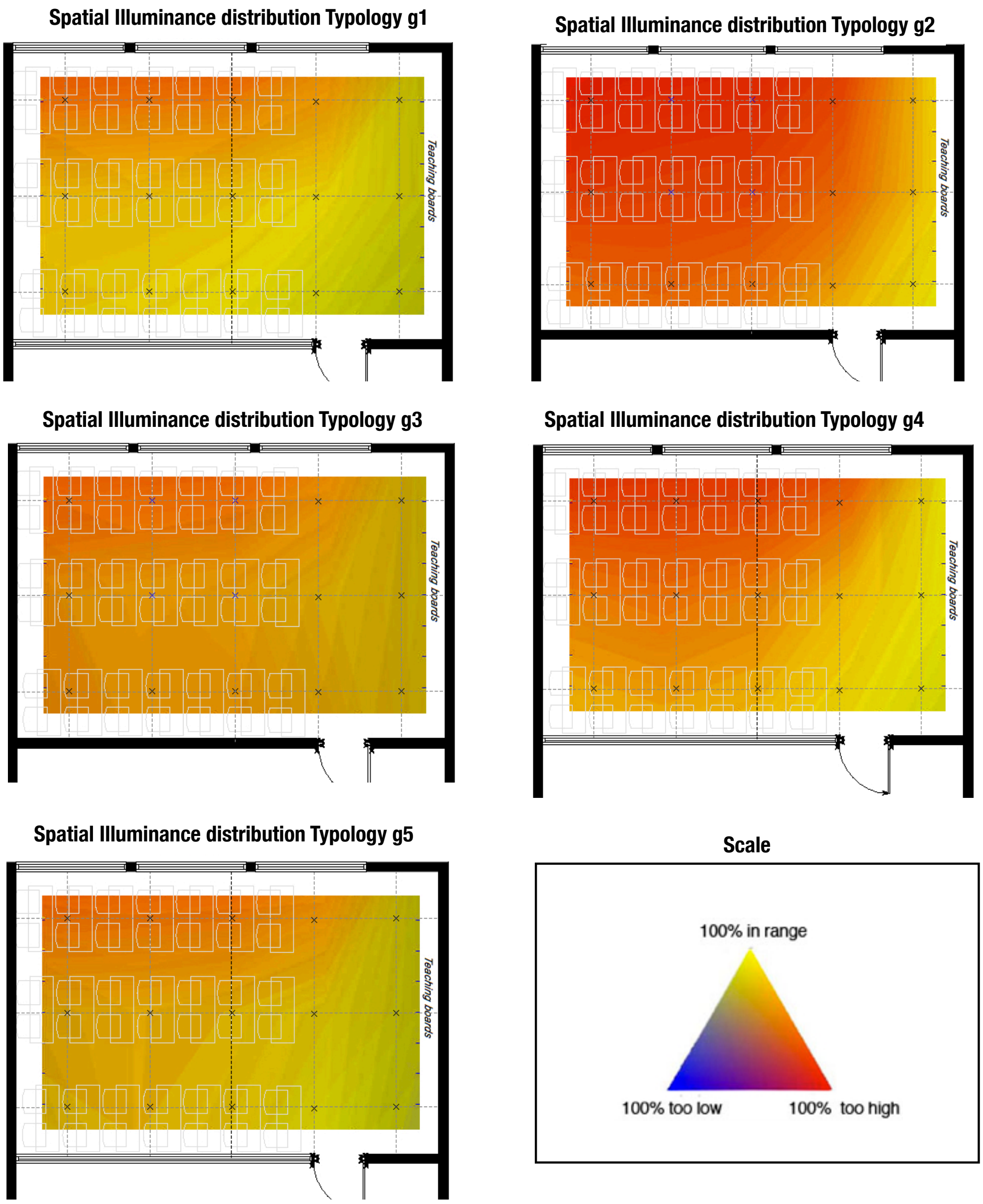


Figure 4.4-2: Spatial Illuminance distribution maps for West-facing Typologies

b. Providing an adequate amount of daylight on the whiteboard: the results expressed in the Vertical Temporal Illuminance maps shown in Figure 4.4-3 and the % of time “in range” are shown in Table 4.4-3. The analysis is described below:

In relation to the time with illuminances rated as “in range”, within the year, Typology g1 obtained 58%; Typology g4, 56%; and Typology g5, 53%, reaching *adequate daylighting levels.* In particular, it what refers to Typologies g1 and g5, upon observing their temporal maps it can be seen that during the winter, the mornings presented “%too low”. Typology g4 resulted as the most favorable one among them, since it did not present “%too low” in the winter. Typology g3 obtained percentages “in range”, 49% of the time, almost reaching adequate daylight. In the temporal maps, it can be seen that it obtained “%too high” in the afternoons, concentrated on the first, third and fourth studied periods. At the same time, it obtained “%too low” in the second studied period. Typology g2 obtained a “%too high” in the first and fourth studied period, both in the morning and afternoon, while during the winter months (May, June, July and August), it obtained “%in range” on the whiteboard.

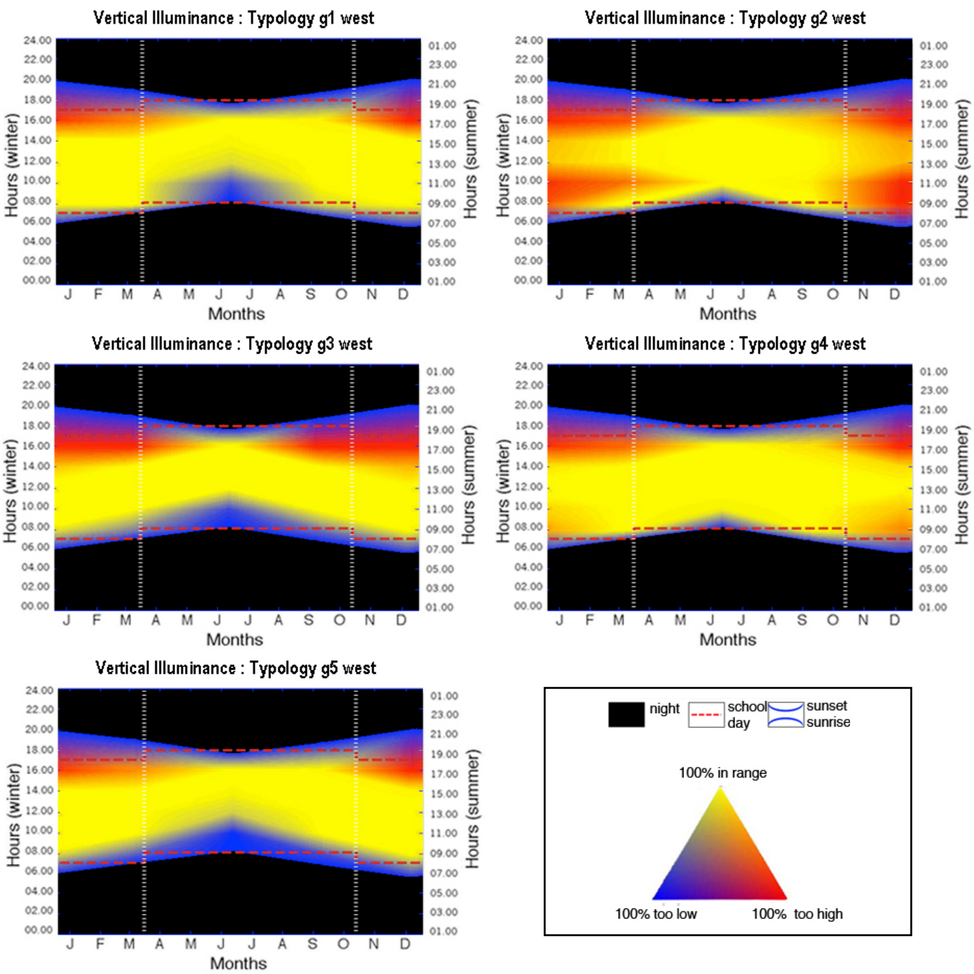
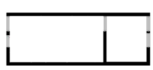
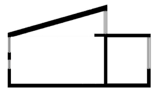
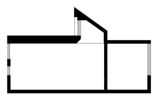
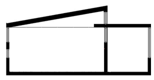
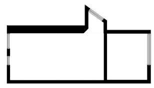


Figure 4.4-3: Vertical temporal illuminance maps for West-facing Typologies

Table 4.4-3: Summary of Vertical Temporal Illuminance Maps for West-facing Classrooms

West									
TYPOLOGY g1		TYPOLOGY g2		TYPOLOGY g3		TYPOLOGY g4		TYPOLOGY g5	
									
Too Low	34%	Too Low	31%	Too Low	37%	Too Low	31%	Too Low	39%
In range	58%	In range	43%	In range	49%	In range	56%	In range	53%
Too high	8%	Too high	26%	Too high	14%	Too high	13%	Too high	8%

4.4.2 Analysis of Daylight Uniformity for West-facing Classrooms

Criterion 2. Achieving an adequate daylight uniformity in the classroom

The uniformity on the workplane is shown in Figure 4.4-6 and the uniformity on the whiteboard, in Figure 4.4-7. The analysis is described below:

- *Uniformity on the workplane:* in Figure 4.4-4, the graph for the uniformity obtained with overcast skies, is shown. It can be observed that all Typologies obtained a uniformity varying between 0.4 and 0.5, meaning that they did not reach an adequate uniformity.

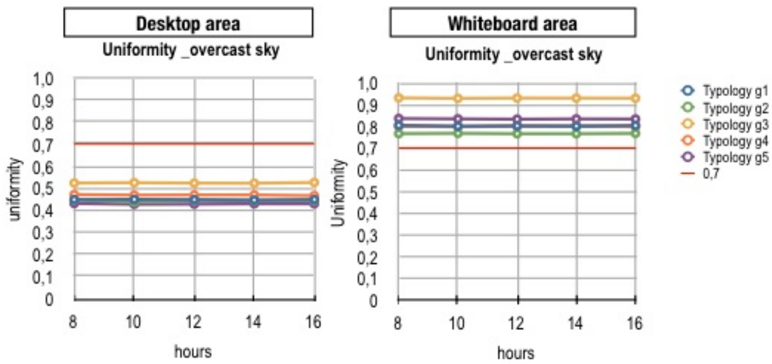


Figure 4.4-4: Uniformity on the workplane and on the whiteboard for the West-facing Typologies

The uniformity achieved with clear and clear turbid skies varied in a considerably larger range of between 0.15 and 0.7, which is the proportion between the average illuminance (Eav) and the minimum illuminance (Em), having moments during the day where the uniformity falls between an adequate and optimal uniformity. It can be seen in the graph in Figure 4.4-5 that Typologies g1 and g3 obtained an *adequate uniformity* during the morning, while in the afternoon they presented large variations in the daylight. All the typologies in the fourth studied period obtained uniformity between 0.5 and 0.6, being around an *adequate uniformity.*

The uniformity obtained with intermediate skies was similar in all the typologies; in the morning an *adequate uniformity* was obtained, later presenting variations up to 0.2 during the first and third period.

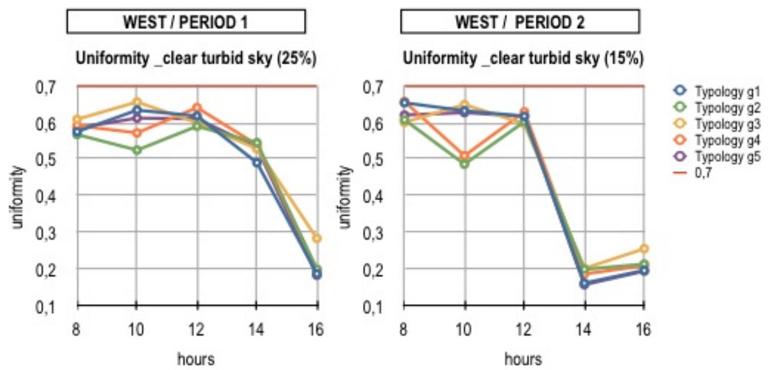


Figure 4.4-5: Uniformity obtained in periods (1) and (2) under clear turbid skies for West-facing Typologies

- *Uniformity on the whiteboard area:* for the uniformity under overcast skies shown in Figure 4.4-4, and with clear and intermediate skies, it can be seen that all typologies reached an *adequate uniformity.* Following these results it is possible to state that the West orientation was favorable to achieve the *uniformity* on the whiteboard. This was constant for all the studied periods and skies.

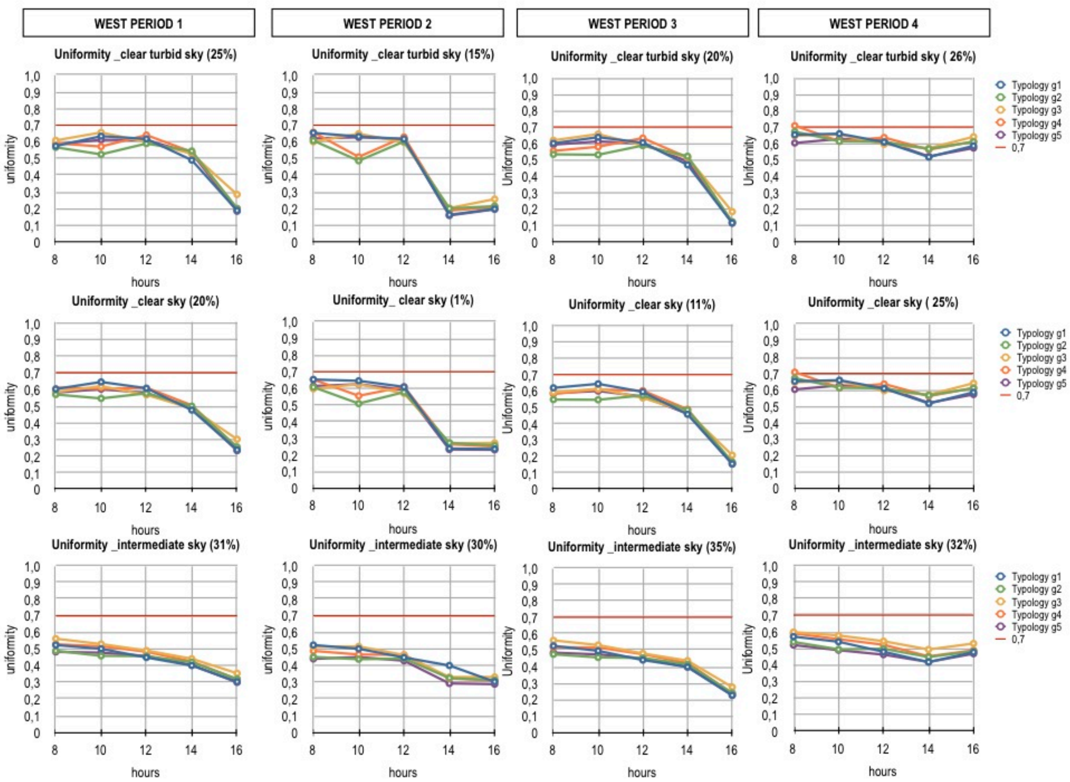


Figure 4.4-6: Graph for daylight uniformity on the workplane for West-facing Typologies

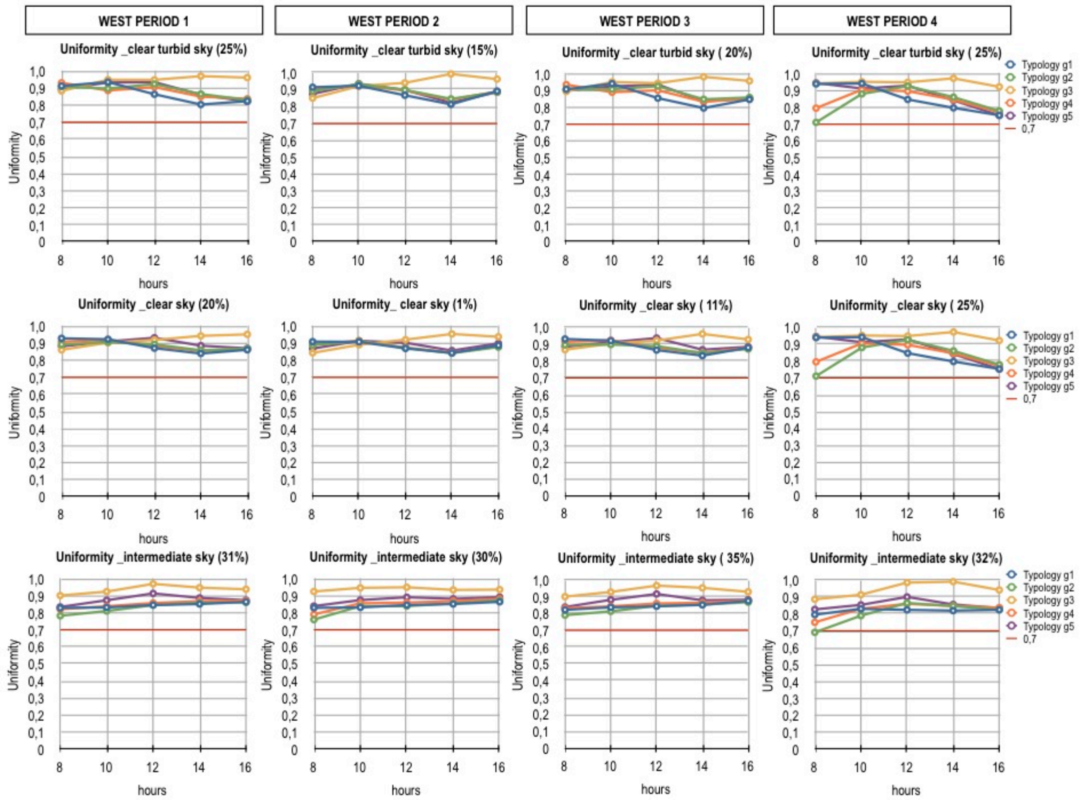


Figure 4.4-7: Graph for daylight uniformity on the whiteboard for West-facing Typologies

4.4.3 Analysis of Glare Sources for West-facing Classrooms

Criterion 3. Ensuring visual comfort in the field of view of the students.

The temporal maps shown in Figure 4.4-10 were analyzed. This analysis is described below:

- *Temporal DGP maps*: it can be seen that all Typologies presented high glare probabilities in the first and third studied periods, during the afternoons. Therefore, these studied periods may cause visual discomfort situations. Typologies g2 and g4 presented, besides the aforementioned situation, less glare probabilities in the second studied period. These obtained DGP values between 40% and 45%.

- *Temporal DGP_{max} maps*: it can be seen that Typologies g1, g3 and g5 do not present glare probabilities during the morning. However, these and other typologies presented high glare probabilities during the afternoon, of over 60%. For the situation found in Typologies g2 and g4, they also presented high glare probabilities in the mornings.

- *Rated DGP*: as for the DGPs in predominant skies, the glare perception for Typologies g1, g3 and g5 was *imperceptible* in the mornings for all studied periods and *intolerable* during the afternoons of the first and third studied periods. In Figure

4.4-10 the graphs obtained by Typology g1 are shown, to illustrate the aforementioned situation.

In relation to the DGP_{max} perception, Typologies g2 and g4 present an *intolerable* situation throughout the year. . In Figure 4.4-9 the graphs for rated DGP for Typlogy g2 are shown, seeing that for clear skies (DGP_{max}), the DGP will become *intolerable* from 10am, during period 1.

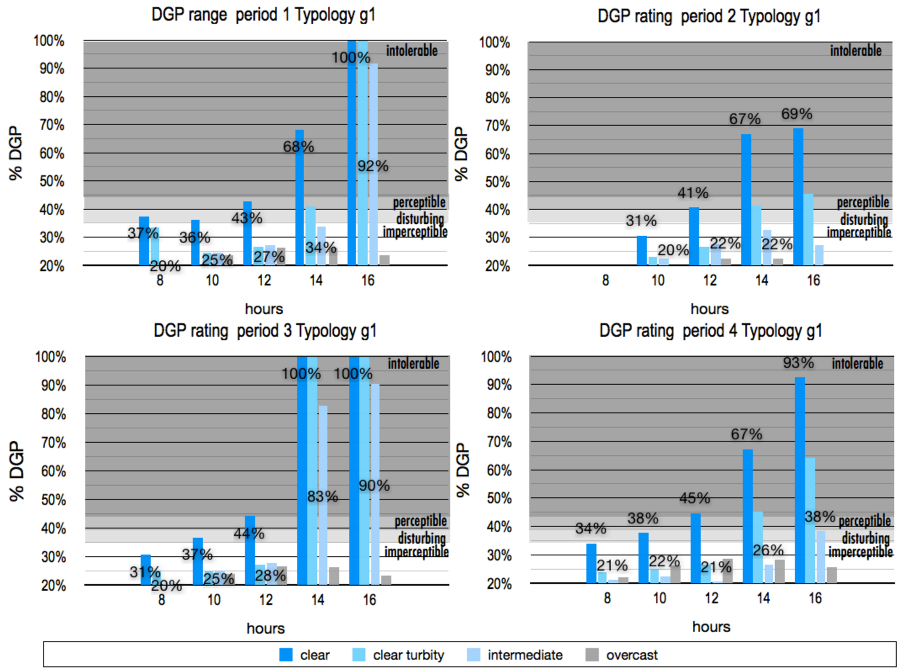


Figure 4.4-8: Graphs for DGP range for West-facing Typologies g1 .

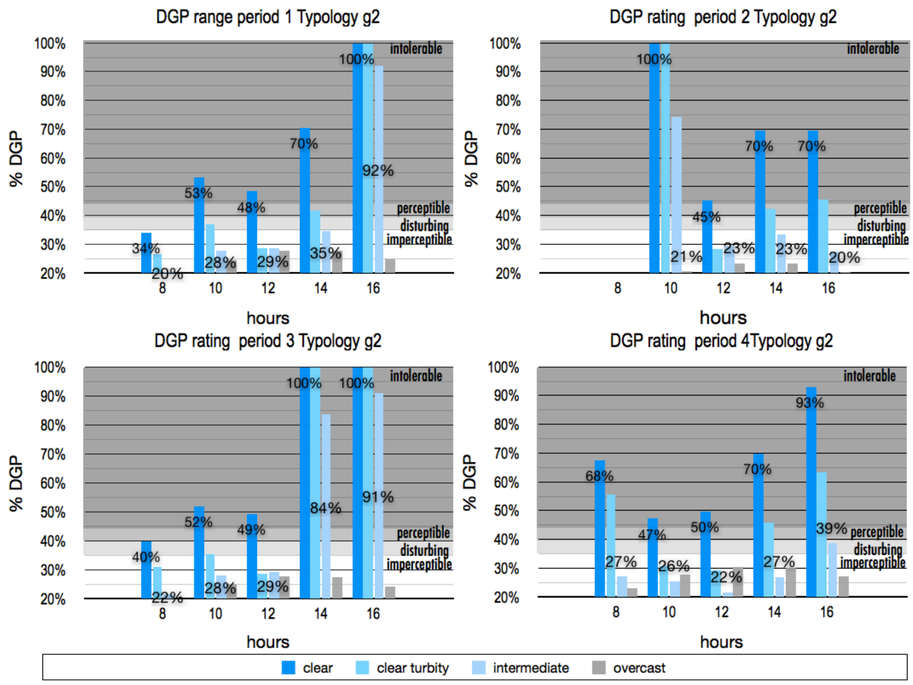


Figure 4.4-9: Graphs for DGP range for West-facing Typology g2

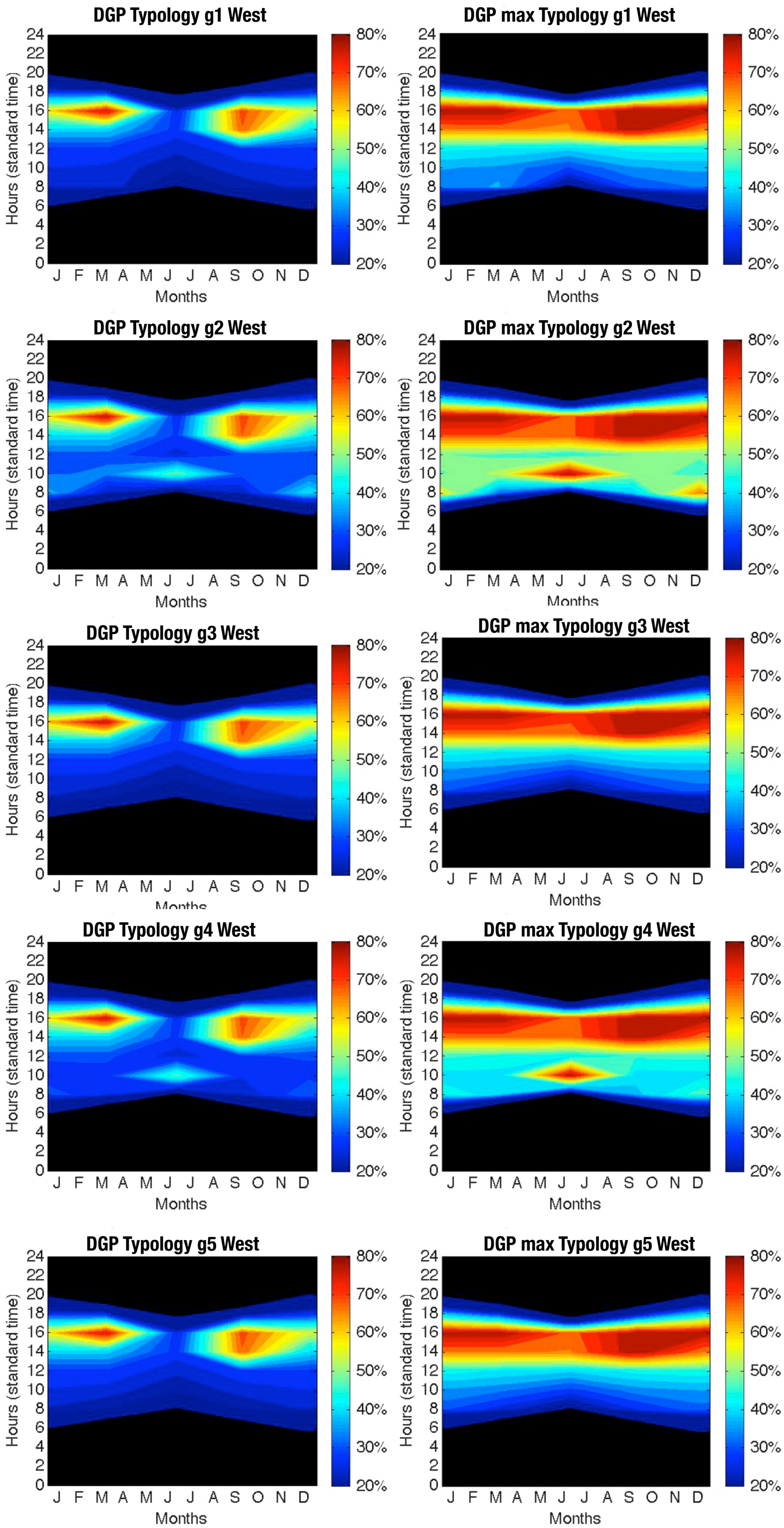


Figure 4.4-10: Temporal DGP and DGP_{max} maps for West-facing Typologies

4.4.4 Analysis of Sunlight Penetration for West-facing Classrooms

Criterion 4. Preventing direct sunlight penetration in the classroom

The images generated using quick-render in RADIANCE for the different Typologies were analyzed and can be found, for all Typologies, in Appendix D. All relevant information is detailed below:

It can be seen that all Typologies presented the same situation due to sunlight penetration in the afternoons of the studied periods. Figure 4.4-11 shows the situation with Typology g3, where from 2pm sunlight penetration occurs only on the workplane area.

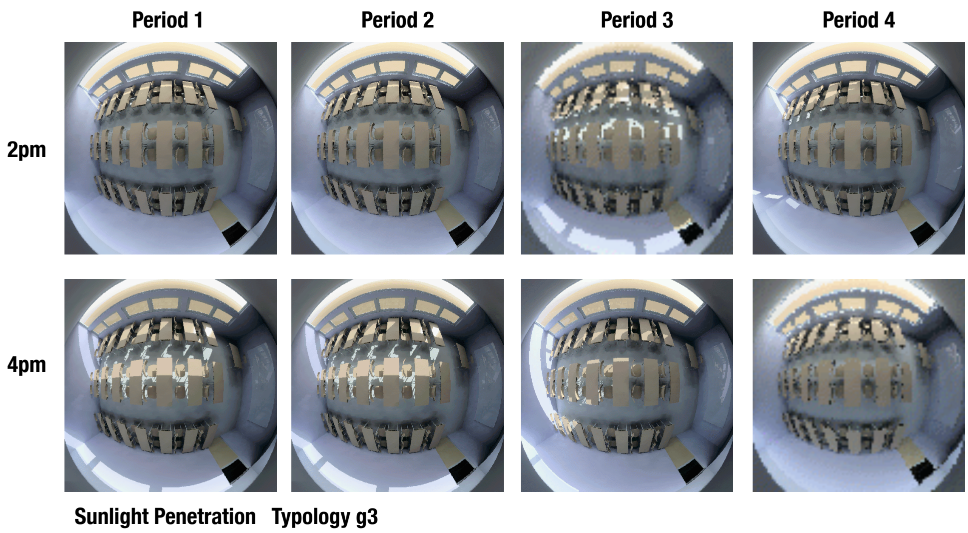


Figure 4.4-11: Sunlight Penetration West-facing Typology g3 between 2pm – 4pm

Typologies with double-orientation daylight systems, i.e. Typologies g2 and g4, showed that sunlight penetration is produced also in the mornings. In Figure 4.4-12 the situation found for Typology g2 is shown.

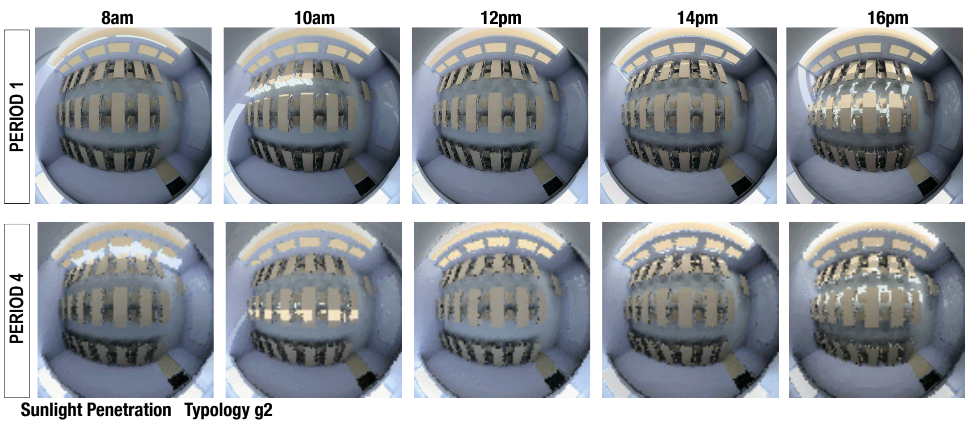


Figure 4.4-12: Sunlight Penetration for periods (1) and (4) for West-facing Typology g2.

4.5 Conclusions of Classroom Daylighting Analysis

The analysis of the typologies in relation to the four stated criteria aimed to make a diagnosis of the *adequate* and/or *optimal* classroom solutions that would allow the improvement of daylighting and visual comfort conditions for the students. The conclusions of this analysis are based on these criteria, and are described below:

Criterion 1. Providing an adequate amount of daylight in the classroom

With respect to the analysis of daylight levels in their temporal distribution on the workplane we verify that all the North, East and West facing classrooms will present "%too high" in the first (February, March, April), third (August, September, October) and fourth (November, December, January) studied periods, so they will be defined as *"critical periods"*.

In the South-facing classrooms, a situation opposite from the aforementioned was generated, because in these unilaterally oriented typologies (Typologies g1 and g3), even though they reach target illuminances for a considerable amount of the year, they still generate "%too low" in the second studied period (May, June, July). This is the *"critical period"* for South-facing classrooms for the typologies evaluated for Concepción.

The analysis of spatial daylight distribution in the *North, East and West-facing* classrooms, showed that, despite achieving a *regular spatial distribution,* still presents areas with illuminance "%too high" for all studied typologies, this being the area next to the window. We conclude that this is presented as the *"critical area",* being defined as *the area within the classroom that is exposed to great daylight variations and to direct sunlight penetration.*

We verify that from all the evaluated typologies, South-facing Typologies g1 and g3 are the only ones that achieved an *optimal spatial distribution* in relation to the area of the classroom with illuminances rated as "in range" throughout the year. We conclude that the daylight strategies used and the orientation favorably contributed to these results. Typology g1 (basic daylighting) obtained important indirect daylight contributions coming from the corridor (Northern light) and Typology g3 (unilateral clerestory window) obtained important Southern light contributions through the clerestory window, which lights the wall resulting in indirect daylight in the area of the wall next to the corridor.

Typology g2 (bilateral clerestory window) resulted to be the least favorable one in terms of the illuminance spatial distribution for all the studied typologies, presenting an *irregular spatial distribution* in all the orientations. The double-orientations of the unprotected sunlight openings do not favor the spatial distribution of daylight.

The daylight levels on the whiteboard's temporal distribution depend strongly on the penetration of sunlight on it. We conclude that the whiteboard area should be differentiated as a *"protected area",* being defined as *such area that is protected from direct sunlight penetration, without luminosity variations.* We anticipate that the daylight strategy applied to this area should be independent from the daylight strategy applied in the workplane area.

- We conclude that the distance between the North and East-facing classroom window and the whiteboard wall was not efficient enough to avoid the penetration of sunlight on it, because of the lack of sunlight penetration control from the unprotected window, generating "%too high" and uniformity variations during the aforementioned *critical periods.*

- The daylighting levels on the whiteboard for West-facing classrooms with unilateral orientation (Typology g1), even though many of the typologies achieve an adequate daylighting level, still present "%too low" between 8am and 10am on the second period (May, June, July), being defined as the *critical period* for the whiteboard.

- The South-facing classrooms with Typologies g1, g3, g4 and g4 obtained *optimal daylighting levels;* however, a "%too low" is kept for Typologies g1, g3, and g5 during the *critical period* for the South-facing classroom's workplane. We conclude that it is important to contemplate daylighting with an artificial lighting system for this period, in order to ensure an *optimal* daylighting in the *protected area.*

Criterion 2. Achieving an adequate daylight uniformity in the classroom

- The uniformity proposed as *adequate* and *optimal* in this criterion was impossible to achieve for the *North, East and West*-facing classroom's workplane in a constant way. Their daylight uniformity presented great variations during the analyzed days due to sunlight penetration.

- With the results obtained for daylight uniformity on the workplane of South-facing classrooms, we discovered that those typologies, which obtained *optimal* levels in criterion 1 had a uniformity constantly between 0.5 and 0.7. We conclude that for an *exclusively daylit classroom, the workplane uniformity should refer to a range that would allow the daylight's own variations.* We propose that, for the optimization stage developed in chapter 5, this uniformity criterion with this range between 0.5 - 0.7 is considered as an *adequate* and > 0.7 is considered as an *optimal* uniformity.

- The daylighting uniformity on the whiteboard was most favorable in the majority of the typologies, which obtained adequate daylight levels. These typologies achieved a uniformity defined as *optimal,* for which we conclude that it is possible to confirm that an *optimal daylighting uniformity* should be equal or greater than 0.7, even more so if it is considered as a *protected area*.

Criterion 3. Ensuring visual comfort in the field of view of the students.

- The North-facing classrooms presented high glare probabilities in all the analyzed typologies, concluding that if the daylight strategy used does not consider sunlight protection, it will always produce visual discomfort situations for the students in the whole of the critical area.

- The South-facing classrooms with Typologies g1 and g3, defined as *optimal* in terms of daylighting levels and daylighting uniformity, presented low glare probabilities and, thus, they do not present visual discomfort situations for the students. This is why we conclude that South-facing classrooms ensure the visual comfort of the students, becoming an *optimal solution* for daylighting in classrooms.

- East-facing classrooms present glare risk, according to their DGP, limited to the fourth period, between 8am and 10am and for the DGP_{max} it extends from January to March and from September to December between 8am and 2pm for unilateral daylight strategies.

- In West-facing classrooms, the unilateral daylight strategies present glare risks according to the DGP, on the first, third and fourth periods, between 4pm and 6pm and, for the DGP_{max}, it extends to almost the whole of the school day.

Criterion 4. Preventing direct sunlight penetration in the classroom

From this criterion, we conclude that sunlight penetration is crucial for the fulfilment of criteria 1, 2 and 3. Daylight uniformity is not achieved because of the entry of sunlight on the workplane and whiteboard areas, creating light spots, which generate contrast and bad visual conditions. Sunlight is the main glare source in all the cases. The favourable results obtained by the South-facing classrooms were benefited due to the lack of sunlight penetration in the classroom.

From all Typologies resulting in an *optimal solution*, we proved that there is a correspondence between the daylight levels, distribution and uniformity (within the redefined range), with low glare probabilities being found. Therefore, we conclude that the visual comfort for the students will be achieved if we develop a *solution for daylight strategies that integrate the aforementioned conclusions and achieve that stated as optimal for each of the criteria*.

From the daylight strategies for classrooms we conclude that a daylight strategy should consider, in its design, a *critical area, a protected area (whiteboard area)* and should evaluate these strategies as a minimum in the *critical periods* for each orientation and for each Typology.

5 Optimization of Daylighting in Classroom Design

In Chapter 4, the analysis for all the classrooms in the different orientations was stated. Two classrooms are defined as those providing an optimal solution, ensuring the visual comfort of the students. It is suitable for the objectives of this thesis to provide continuity to the daylighting analysis of the classrooms that did not provide the right results, in order to find an optimal solution that suits each orientation. In this chapter, we explain how the optimized classrooms were selected and the results were achieved by the optimizations carried out and finalized. We define the optimal solutions for each orientation and, finally, we state design recommendations for daylit classrooms to ensure the visual comfort of the students. These recommendations link all that found in the initial analysis with that found in the optimization stage.

5.1 Principles for Daylight Optimization

The daylighting analysis in the classrooms, developed in chapter 4, presented the foundations to propose more efficient architectural solutions, i.e. optimal solutions to be applied to a daylit classroom design. Continuity was provided through the redesigning and reevaluation of the typologies that have already been studied. The typologies that presented the greatest differences among the five proposed typologies, in each orientation, were selected.

5.1.1 Selection of Classrooms

For the selection of the typologies to be optimized, the results of the temporal illuminance maps and of the spatial maps were observed. The differences produced between them, in some cases, were not evident, becoming necessary to define a way to establish the differences quantitatively. These differences were found by using a *"Completely Random Block Design"* method, which allowed to state if there were significant differences between the typologies. Once we defined the existence of these differences, a multiple comparison procedure was carried out. This consisted of a measurement comparison test developed by Tukey, the mathematician, called the *"Honestly Significant Difference"* (HSD).

The measurement comparison was carried out using a sample of the illuminance values obtained from the simulations carried out in RADIANCE. The samples taken correspond to the illuminance values obtained with intermediate skies on March 21st, on June 21st, on September 21st and on December 21st, at 12pm.

From the fifteen sensors measured inside the classroom, three were selected that were located transversal to the façade, in the middle of the horizontal grid. The three sensors had the following order: in Zone 1, next to the window, the main sensor 13; in Zone 2, which corresponds to the central part of the classroom, sensor 8; in Zone 3, area far from the façade, sensor 3. This order is shown in Figure 5.1-1.

The comparison method applied is detailed in Appendix E, and from it we conclude the following:

- The highly significant differences are marked by Typologies g1, g2 and g3;
- We proved that there are no highly significant differences between Typologies g2 and g4, and between Typologies g1 and g5;

- With respect to the differences in the different areas, we proved that in Area 1 of Typology g2 we had the greatest differences with Typologies g1 and g5, respectively. In Area 2, the highly significant differences were produced between Typology g2 and Typologies g1 and g3, respectively. In Zone 3, Typology g3 obtained highly significant differences with all the Typologies, because its illuminance values were twice those obtained by the other Typologies.

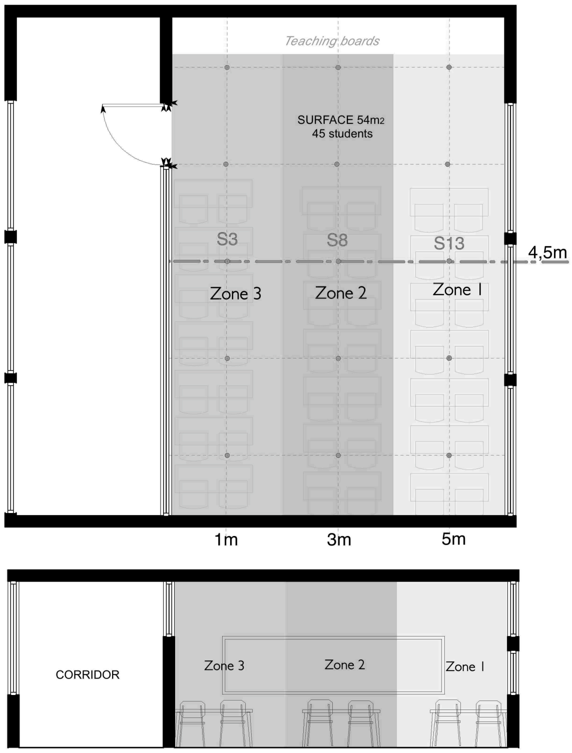


Figure 5.1-1: Schematic Cut of Typology g1, indicating the position of the sensors

From the conclusions derived from the differences found, we decided to optimize the North, East and West-facing classroom Typologies g1, g2 and g3.

In the case of the Southern orientation, the selection of the classroom was not based on this differentiation method. We proved in the previous evaluation that this orientation was favorable to obtain a positive result, deciding to optimize those typologies that did not provide an optimal solution for the stated criteria as a result. We considered the optimization of Typologies g2, g4 and g5.

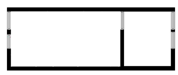
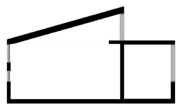
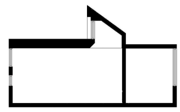
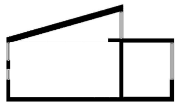
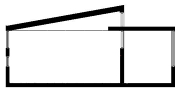
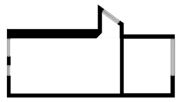
Classroom North - East - West		
TYPOLOGY g1	TYPOLOGY g2	TYPOLOGY g3
		
Classroom South		
TYPOLOGY g2	TYPOLOGY g4	TYPOLOGY g5
		

Table 5.1-1: Schematic cut of the optimized Typologies

5.1.2 Design Goal

The following design goals were stated.

1. Prove the effectiveness of the proposed architectural elements to protect the incidence of direct sunlight in the critical periods.

2. Confirm if, upon obtaining *optimal daylight level* and *optimal spatial distribution,* the uniformity values fit within the 0.5 - 0.7 range, verifying that concluded with the South-facing classrooms.

3. Verify if upon obtaining a daylight level in the classroom that fulfills the optimal objectives defined for Criterion 1 and Criterion 2, we were able to obtain the environmental conditions that favor the visual comfort of the students, by reducing the glare probabilities in the critical periods, ensuring that the official discomfort problems are limited to the first and third period, i.e., for the wintertime.

In the reevaluation of the typologies, the criteria proposed for daylit classrooms were applied as follows:

- *Criterion 1. Providing an adequate amount of daylight in the classroom:* obtaining solutions that achieve the *optimal daylighting levels on the workplane and on the whiteboard of the classroom throughout the year,* and also obtaining an *optimal distribution* in the classroom.

- *Criterion 2. Achieving the adequate daylight uniformity in the workplane:* the uniformity analysis is applied to the workplane because this is the area that presented the most difficulties when trying to achieve the proposed uniformity. The vertical uniformity was applied only to verify the existence of significant changes in some cases.

- *Criterion 3. Ensuring visual comfort in the field of view of the students:* the glare probabilities are analyzed only in some of the typologies to be optimized because of the simulation time involved. The DGP was evaluated in the same position as that considered in chapter 4.

- *Criterion 4. Preventing direct sunlight penetration in the workplane:* it is applied to verify some results. We begin by the premise that, by considering sunlight protections, we will be preventing a direct sunlight penetration at least in the critical periods.

All the simulations carried out to verify the optimized typologies were executed in RADIANCE. The same environmental parameters as those used for the calculation of the illuminance values through "*rtrace*" were used. We used the same analysis grid detailed in section 3.5 , i.e. the 15-sensor horizontal grid for the workplane and the 5-sensor vertical grid for the whiteboard.

The method and metrics explained in detail in section 3.2 of chapter 3, for the analysis of vertical and horizontal illuminance, expressed on the temporal maps, are applied. We graphed the illuminance uniformity obtained for the 20 calculated moments of the year, portraying the uniformity under each type of sky separately for each period of analysis.

5.1.3 Design strategies

Architectural solutions that are feasible in any project were considered for the optimization proposals. In the selected typologies, the redesign of their daylighting strategy was carried out so that it does not block the view to the outside through the viewing window and the sunlight protection elements were considered as fixed. For this study, the use of mobile sunlight protections was not considered. Below, the strategies used for each orientation are described:

- *Optimization for North-facing Classrooms:* Typologies g1, g2, and g3 are intervened in order to control and protect it from direct sunlight penetration, with the purpose of reducing the high illuminances produced in the *critical area.* The solution stated for the façade window was the same for the three optimized typologies. The typologies are intervened as follows:

  a) The high window is protected in a bid to reduce the illuminances and luminances coming from the sky through it, placing an external element on its top, i.e. an external overhang. The proposed dimension of it is 0.5 meters wide, placed along the length of the high window;

  b) The viewing window is protected during the critical periods, by placing an external overhang over it. This is 0.8 meters wide similar to the height of the window, placed along the length of the viewing window;

  c) We aimed at blocking the direct sunlight penetration coming from the high window, protecting the students seated right under it, by placing a 0.5 meter wide internal lightshelf, placed along the length of the window.

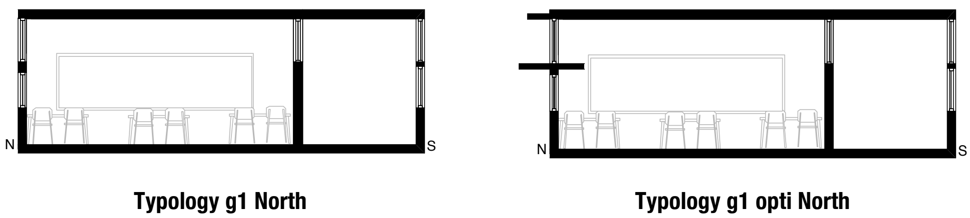


Figure 5.1-2: Sectional cut of North-facing Typology g1 - original and optimized (opti).

  d) For Typology g1 seen in Figure 5.1-2, the aforementioned window solution was applied and the same materials used in the previous simulation are kept, remembering that we used a simple glass with 90% luminous transmission.

  e) In Typology g2, seen in Figure 5.1-3 and Typology g3, shown in Figure 5.1-4, we modified the type of glass in order to reduce the "%too high" produced on them. We considered a glass with a lower luminous transmission, proposing a double-glazed clear glass with a visible light transmitted that is equal to 70%.

f) In Typology g3, we increased the width of the overhang protecting the clerestory window in order to control the direct sunlight falling on the wall located right under it; the proposed width for the overhang is 0.6 meters.

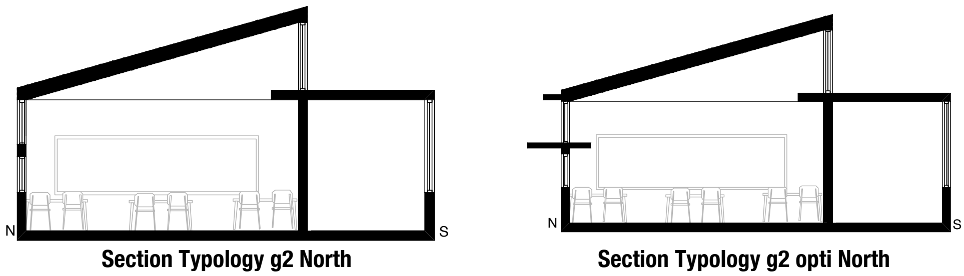


Figure 5.1-3: Sectional Cut of North-facing Typology g2 - original and optimized (opti).

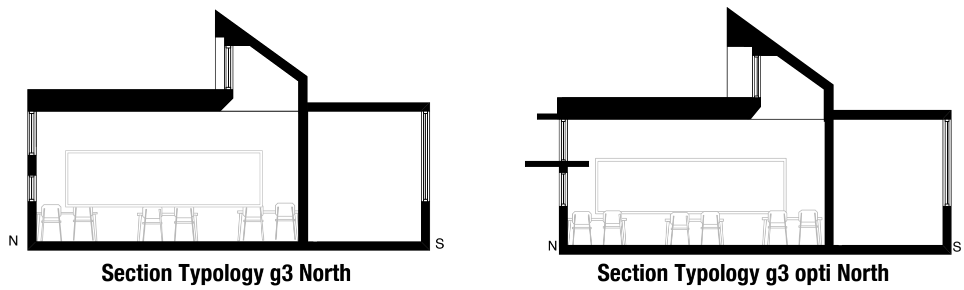


Figure 5.1-4: Sectional cut of North-facing Typology g3 - original and optimized (opti).

- *Optimization of South-facing Classrooms:* the proposed typologies were adjusted in order to achieve an optimal solution. These typologies were intervened as follows:

a) In Typologies g2 and g4, we propose to protect the Northern window to reduce the "%too high" in the critical area and in the central area of the classroom. The elements that make up the clerestory window were protected with a 0.6m external projection, as shown in Figure 5.1-5 for Typology g2 and in Figure 5.1-6 for Typology g4.

b) In Typology g2, the type of glass of the Northern clerestory window was modified, proposing a diffuse glass with a visible light transmitted (VT) equal to 50%.

c) In Typology g5, we increased the skylight area by 50%, meaning it went from $1m^2$ to $1.5m^2$. We considered the use of a diffuse glass with VT=50% to protect the area under the skylight, which is shown in Figure 5.1-7.

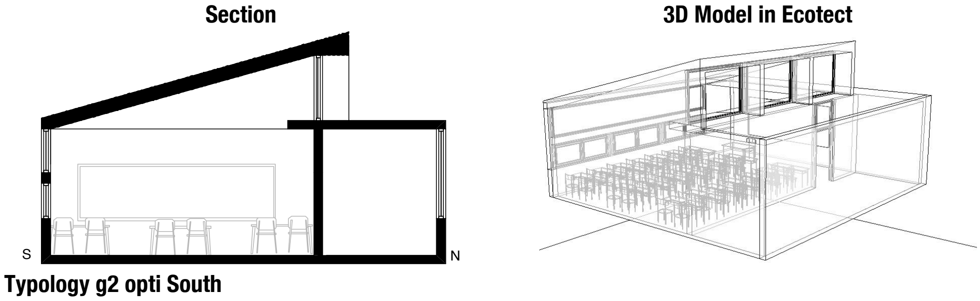


Figure 5.1-5: Sectional cut of South-facing Typology g2, optimized (opti), and its 3D model.

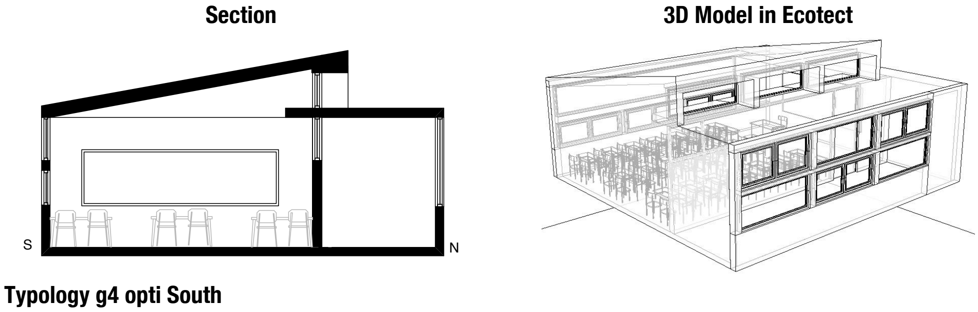


Figure 5.1-6: Sectional cut of South-facing Typology g4, optimized (opti), and its 3D model.

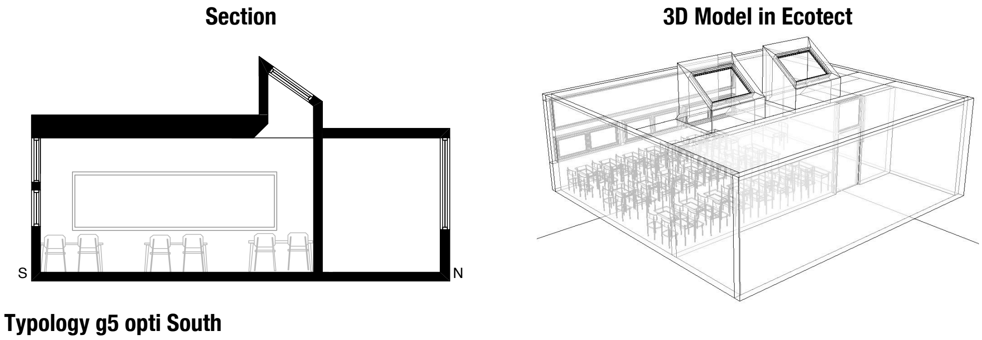


Figure 5.1-7: Sectional cut of South-facing Typology g5,optimized (opti), and its 3D model.

- *Optimization for East and West-facing classrooms:* in the typologies to be optimized, the architectural interventions proposed are the same for both of them. We searched for the *adequate daylighting levels* because none of the verified Typologies achieved them, according to the analysis in Chapter 4. In the East-facing typologies, we aimed to reduce the "%too high" which occured during the mornings of the critical periods.

In the West-facing Typologies, we aimed to reduce these high illuminances obtained during the afternoons of the same periods.

Typologies g1, g2 and g3 are intervened as follows:

a) In Typology g1, the high window was protected with a 0.8m overhang. The view window was protected with a 0.8m external overhang and with vertical elements of the same dimensions, located as shown in Figure 5.1-8. These acted as elements that reflect and diffuse the light towards the inside.

b) In Typologies g2 and g3, we used an external overhang and vertical elements to protect the low window. For the high facade window and the clerestory window, we used a diffuse glass, with visible light transmitted (VT) equal to 50%. The purpose of this glass is to diffuse the light towards the inside and, in this way, avoid sunlight penetration. This solution is shown, for Typology g2, in Figure 5.1-9 and for Typology g3, in Figure 5.1-10.

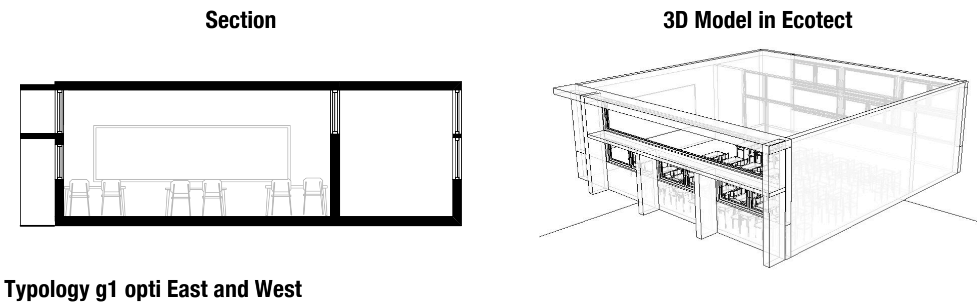


Figure 5.1-8: Sectional cut of East and West-facing Typology g1, optimized (opti), and its 3D model. .

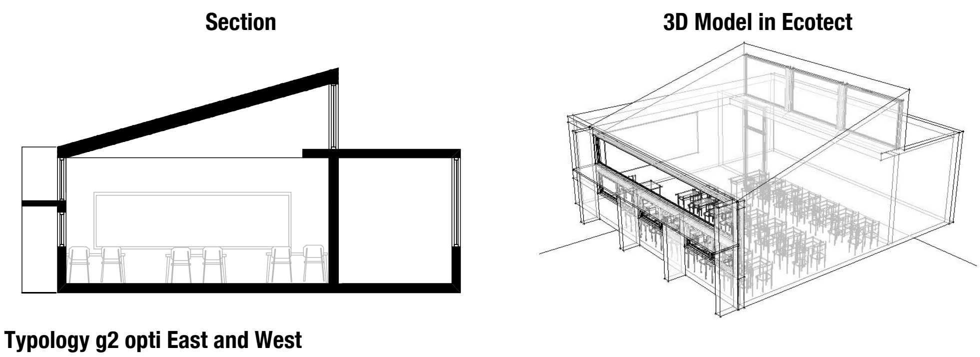


Figure 5.1-9: Sectional cut of East and West-facing Typology g2, optimized (opti) and its 3D model.

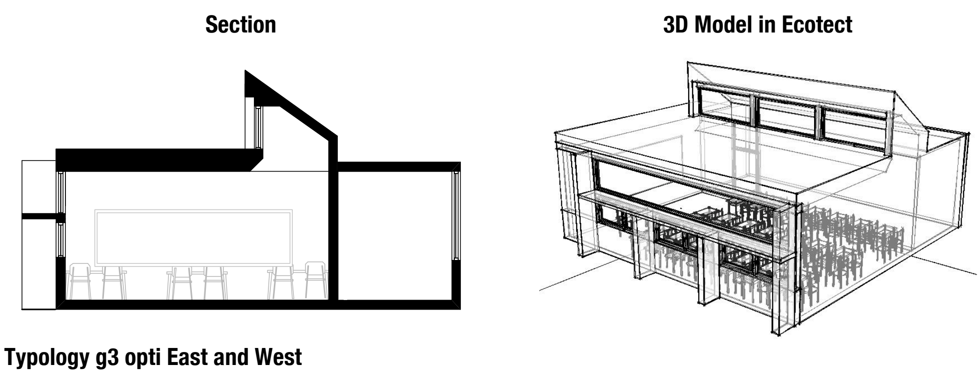


Figure 5.1-10: Sectional cut of East and West-facing Typology g3, optimized (opti), and its 3D model.

5.2 Analysis Classroom Optimizations

5.2.1 Optimization of North-facing Classrooms

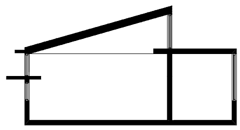
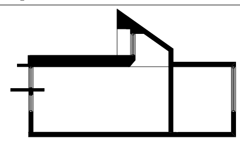
Criterion 1. Providing an adequate amount of daylight in the classroom.

a. *Providing an adequate amount of daylight on the workplane*: the simulations of the optimized typologies have demonstrated that, by placing horizontal elements to protect the high and view windows, we significantly improve the daylight in the classroom throughout the year while providing, in addition, the necessary protection for the critical periods.

Upon revising the time with "%in range", shown in

Table 5.2-1, we could verify that the solution proposed for the Northern window increased the "%in range" by 13%. This increase allows us to state that this Typology ensures more than 55% of the year with "%in range" (500 – 1500 lux) in the area of the classroom. Likewise, Typologies g2 and g3 showed an increase of 27% of the time with illuminances rated as in range throughout the year. In these Typologies, the type of glass was modified and the window protection strategy was applied; the combination of these two elements contributed to the reduction of the time with "%too high", in a significant amount. In Typology g2, it was reduced by 31% and in Typology g3, by 36%, according to the "%too high" throughout the year.

Table 5.2-1: Comparison of percentages, summarizing the Horizontal Temporal Illuminance maps of the original and optimized North-facing Typologies.

Horizontal Illuminace temporal maps-North Optimized								
								
TYPOLOGY g1		OPTI	TYPOLOGY g2		OPTI	TYPOLOGY g3		OPTI
Too Low	34%	36%	Too Low	32%	35%	Too Low	32%	35%
In range	42%	55%	In range	32%	59%	In range	25%	55%
Too high	24%	9%	Too high	37%	6%	Too high	44%	8%

In the temporal maps we could observe that, in the three Typologies, the space percentage with "%in range" was broadened in terms of time, increasing significantly throughout the year. We could observe an important reduction of the % of space with "%too high", as shown in Figure 5.2-1, and with the results obtained for Typology g2, which went from being a Typology that provided a great % of space "%too high" to a Typology that is favorable for achieving target illuminances in the workplane.

Typologies g2 and g3 keep a "%too high" only in winter (which refers to period 2), for a short time period, between 12pm and 2pm. This can be seen in the corresponding temporal maps of Appendix F.

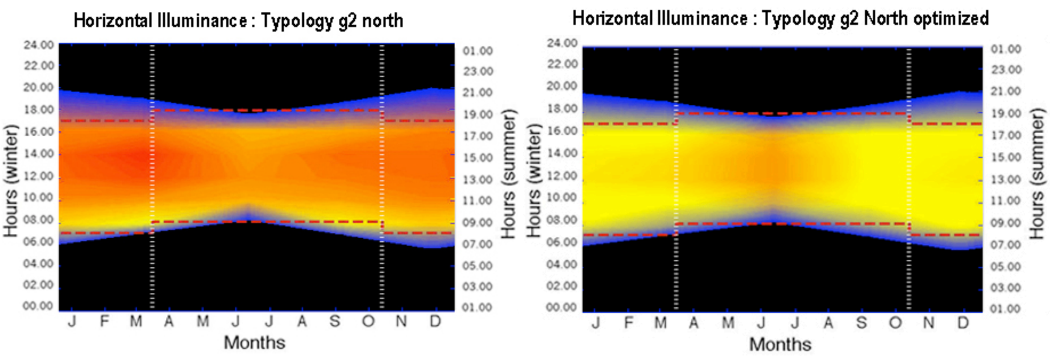


Figure 5.2-1: Comparison of the Horizontal Temporal Illuminance maps of original and optimized Typology g2.

The *Spatial Illuminance distribution maps* were verified, confirming that all the typologies achieved an *optimal spatial distribution.* Typology g1 increased the area by 18%, achieving 75% of the area with "%in range". Typology g2 increased the space by 34%, achieving 79% of the space with "%in range" values throughout the year. Typology g3 increased it by 43%, achieving 77% of the space with "%in range" values, reducing by 48% the area with "%too high".

Table 5.2-2: Comparison of percentages, summarizing the Spatial Illuminance maps of the original and optimized North-facing classroom Typologies.

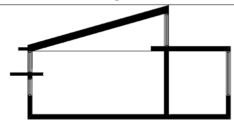
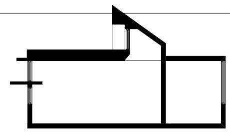
North Optimized								
								
TYPOLOGY g1 Original		OPTI	TYPOLOGY g2 Original		OPTI	TYPOLOGY g3 Original		OPTI
Too Low	9%	12%	Too Low	6%	11%	Too Low	6%	11%
In range	57%	75%	In range	45%	79%	In range	34%	77%
Too high	34%	13%	Too high	49%	10%	Too high	60%	12%

Figure 5.2-2 shows the Spatial Illuminance maps for Typology g3, where we can see the effectiveness of the overhang placed on the clerestory window, combined with the protection of the facade window, which resulted on having the whole of the workplane area with "%in range", becoming a favorable solution for the North-facing classrooms.

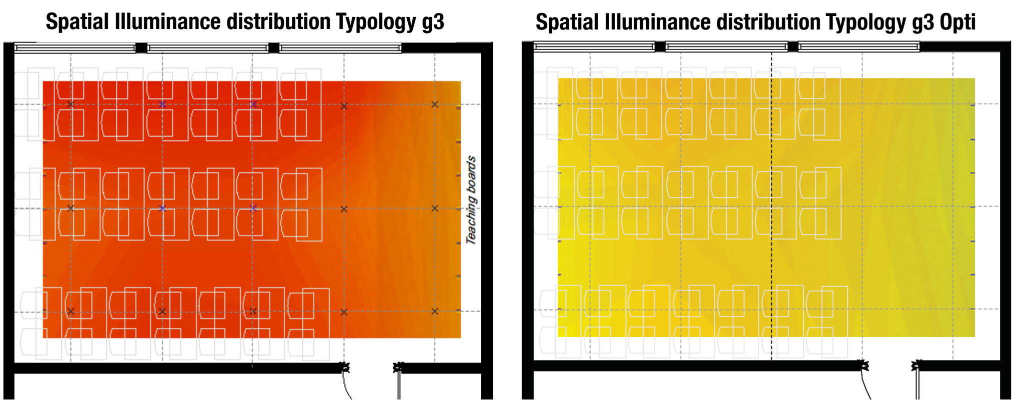
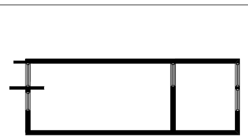
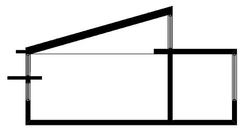
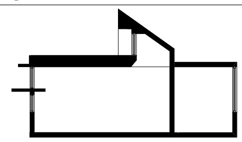


Figure 5.2-2: Comparison of the Spatial Illuminance maps of the original and optimized North-facing classroom Typologies.

The three-optimized typologies for this orientation were favorable to obtain an optimal solution in terms of the levels and distribution of the target illuminances in the classroom.

b. *Providing an adequate amount of daylight on the whiteboard:* we could verify that all the Typologies achieve *optimal daylight levels,* with target values in more than 55% of the time throughout the year. The proposed solutions were able to optimize the daylight on the whiteboard. The horizontal elements on the window combined with the proposed architectural solution, with the purpose of keeping this area protected from direct sunlight were, in fact, effective.

Table 5.2-3: Comparison of percentages summarizing the Vertical Temporal Illuminance maps of the original and optimized North-facing classroom Typologies.

Vertical Illuminance temporal maps-North Optimized								
								
TYPOLOGY g1		OPTI	TYPOLOGY g2		OPTI	TYPOLOGY g3		OPTI
Too Low	33%	37%	Too Low	31%	37%	Too Low	31%	38%
In range	51%	62%	In range	41%	62%	In range	39%	61%
Too high	16%	1%	Too high	28%	1%	Too high	30%	1%

As can be seen in Table 5.2-3, Typology g1 presented an 11% increase on its "%in range"; Typology g2 presented a 21% increase; and Typology g3, a 22%. For the last two, the increase was twice that of typology g1. This was achieved due to the type of glass used, which has a lesser luminous transmission coefficient.

In Figure 5.2-3, the temporal maps comparing the results of the two architectural solutions for Typology g3 are shown. We can see how the percentage of the whiteboard with "%too high" was reduced in the critical periods.

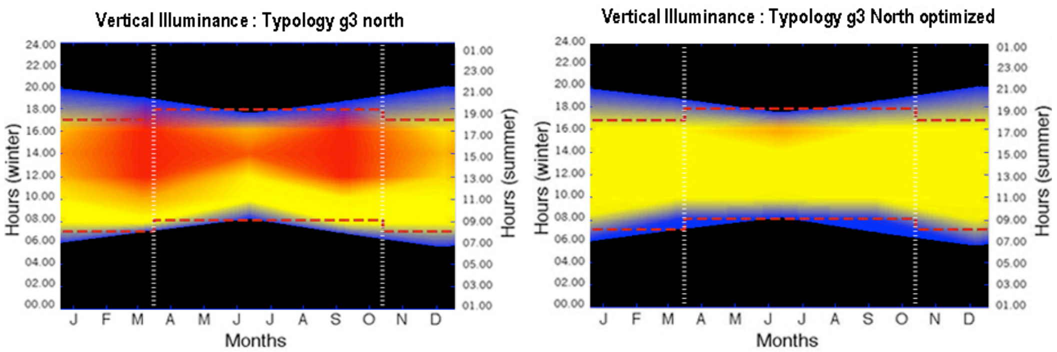


Figure 5.2-3: Comparison of the Vertical Temporal Illuminance maps of the original and optimized classroom Typology g3.

Criteria 2. Achieving an adequate daylight uniformity in the classroom.

Uniformity on the workplane: upon revising the Typologies' daylight uniformity with overcast skies, comparatively shown in Figure 5.2-4, we could confirm that they all obtained uniformities that were within the 0.5 – 0.7 range.

In relation to the illuminance values obtained with clear and intermediate skies, we could verify that the uniformity in all the Typologies, during the first, third and fourth studied periods, was maintained within the same range. The proposed uniformity could not be reached only during the second period, and in consequence it was not the optimal one. In Figure 5.2-5, the results for Typology g2 are shown, where we can verify all that occurred in the three optimized Typologies.

In spite of the aforementioned, if we verify the frequency of the skies during this period we can prove that the overcast skies have a frequency of 54%, that is to say, the proposed uniformity is not achieved only in 46% of the period.

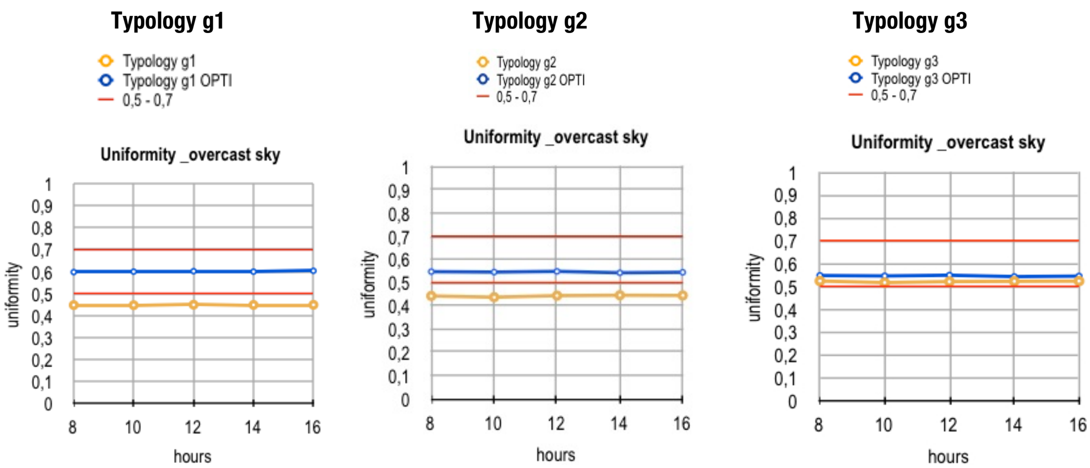


Figure 5.2-4: Daylight uniformity on the workplane of the optimized, North-facing Typologies.

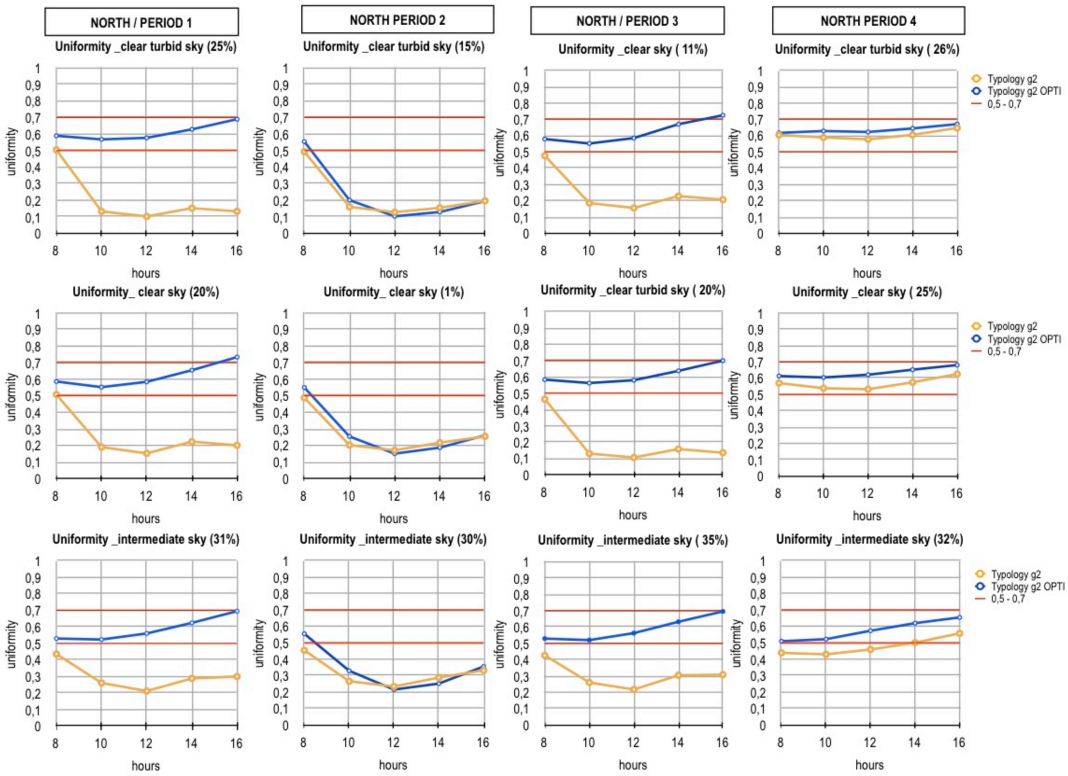


Figure 5.2-5: Daylight uniformity on the workplane of the optimized, North-facing Typology g2

Criterion 3. Ensuring visual comfort in the field of view of the students.

We determined the DGP for Typologies g1 and g2, verifying that the proposed architectural solutions are able to reduce the glare probabilities in the studied position in both cases. Upon observing the temporal maps, we can see how the visual discomfort risk is reduced during the critical periods. In Figure 5.2-6, we can see the results for Typology g1, which resulted to be the maps for Typology g2 shown in Appendix F. The temporal DGP maps show that the glare risk was limited to the second studied period, between 8am and 2pm. This risk varied from 40% to 50%, rated as intolerable according to the human subject rates proposed by Wienold (Wienold J. , 2009). For the rest of the year, a small glare risk was observed in the visual field of the students (with values under 30%), which was rated as imperceptible.

With respect to the DGP_{max}, we could observe that the visual discomfort risk for the most glaring sky was significantly reduced; however, a glare risk persists throughout the year, especially in the winter, as can be seen in the figure. For this orientation and sky, the stated architectural solutions were not satisfying. With them it was possible to reduce and limit, but not eliminate the glare probabilities.

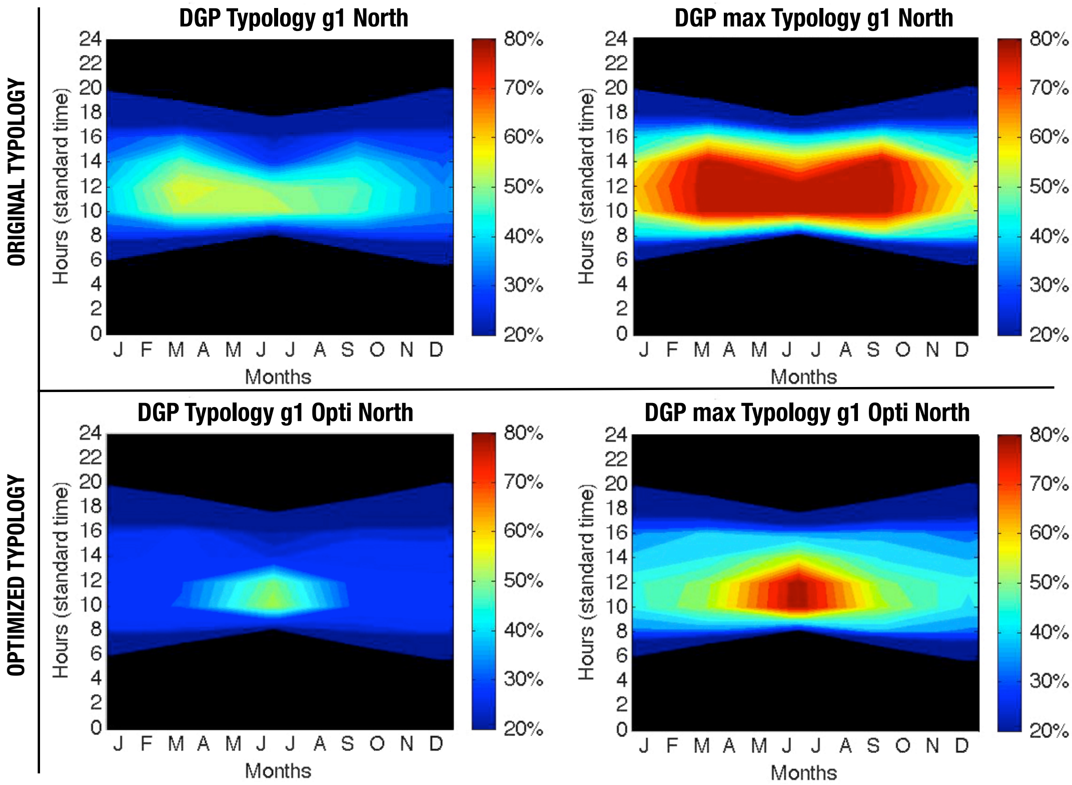


Figure 5.2-6: Temporal DGP and DGP $_{max}$ maps of the original and optimized North-facing Typology g1.

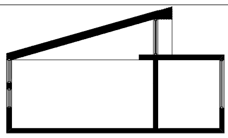
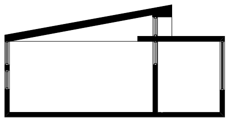
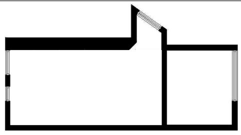
5.2.2 Optimization of South-facing Classrooms

Criterion 1. Providing an adequate amount of daylight in the classroom

a. *Providing an adequate amount of daylight on the workplane:* upon revising the % of time with "%in range" shown in Table 5.2-5, we could verify that the solution proposed for Typology g2 was not completely efficient. We only achieved *adequate daylight levels* for the proposed solution. The time with "%in range" increased by 19% verifying, then, a 52% of "%in range". Upon observing its temporal maps, we could prove that the goal of reducing the percentage of the classroom presenting "%too high" was achieved, especially for the critical periods (third and fourth periods). We could confirm that the time with "%too high" was reduced by 22% throughout the year, which is shown in Figure 5.2-7.

Typologies g4 and g5 achieved *optimal daylighting levels,* verifying an increase of the % of time with "%in range". In Typology g5, we propose to reduce the percentage of time with "%too low", verifying a slight reduction of this during the wintertime in the temporal maps, enough to fall within the "% in range".

Table 5.2-4: Comparison of percentages summarizing the Horizontal Temporal Illuminance maps of the original and optimized South-facing classroom Typologies.

Horizontal Illuminance temporal maps - South Optimized								
								
TYPOLOGY g2 Original		OPTI	TYPOLOGY g4 Original		OPTI	TYPOLOGY g5 Original		OPTI
Too Low	31%	34%	Too Low	32%	34%	Too Low	38%	36%
In range	33%	52%	In range	50%	55%	In range	54%	55%
Too high	36%	14%	Too high	18%	11%	Too high	8%	9%

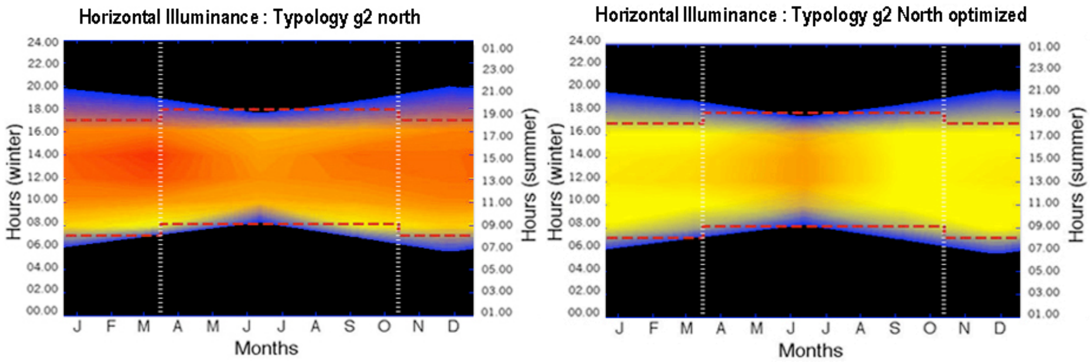
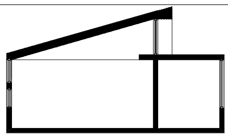
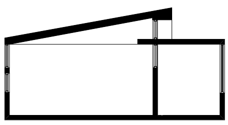
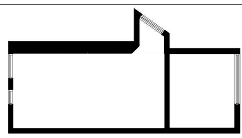


Figure 5.2-7: Comparison of the Horizontal Temporal Illuminance maps of the original and optimized South-facing Typology g2.

We examined the *Spatial Illuminance distribution maps,* confirming that Typologies g4 and g5 obtained an *optimal spatial distribution* of "%in range" in the classroom area. For Typology g2, the area of the classroom with "%in range" was increased by 24%. It is possible to see, in the temporal maps shown in the Figure 5.2-8, that the area near the window maintains high illuminance values, but the distribution of illuminance levels is kept within good levels, obtaining an *adequate spatial distribution*.

Table 5.2-5: Comparison of percentages summarizing the Spatial Illuminance maps of the original and optimized South-facing classroom typologies.

Spatial Illuminance maps - South Optimized								
								
TYPOLOGY g2 Original		OPTI	TYPOLOGY g4 Original		OPTI	TYPOLOGY g5 Original		OPTI
Too Low	5%	10%	Too Low	7%	10%	Too Low	17%	14%
In range	50%	74%	In range	71%	77%	In range	74%	75%
Too high	45%	16%	Too high	22%	13%	Too high	9%	11%

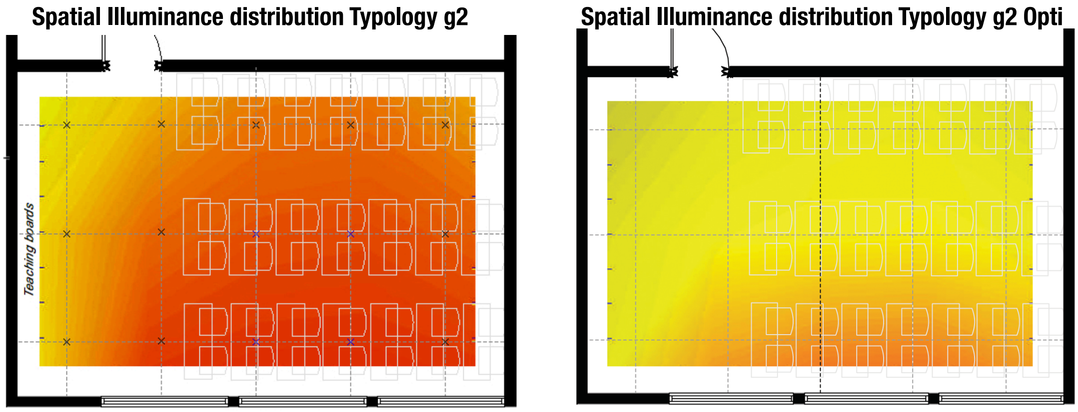
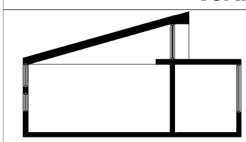
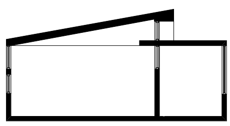
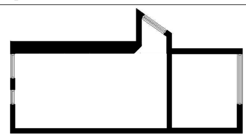


Figure 5.2-8: Comparison of the Spatial Illuminance maps of the original and optimized South-facing Typology g2.

b. *Providing an adequate amount of daylight on the whiteboard:* we could verify that all Typologies obtained *optimal daylight levels* with a "%in range" throughout the year. This was achieved with a slight increase of the % of "%in range" in Typologies g4 and g5. In Typology g2, this increase was greater than 22%, being able to reduce the "%too high" in the first and second periods, as shown Table 5.2-6.

In the temporal maps of Typology g5, shown in Figure 5.2-10, we could confirm that it was possible to reduce the "%too low" during the winter on the whiteboard.

Table 5.2-6: Comparison of percentages summarizing the Vertical temporal Illuminance maps of the original and optimized South-facing classroom typologies.

Vertical Illuminance temporal maps - South Optimized								
								
TYPOLOGY g2 Original		OPTI	TYPOLOGY g4 Original		OPTI	TYPOLOGY g5 Original		OPTI
Too Low	31%	33%	Too Low	32%	33%	Too Low	38%	38%
In range	45%	66%	In range	64%	65%	In range	61%	62%
Too high	24%	1%	Too high	4%	2%	Too high	1%	0%

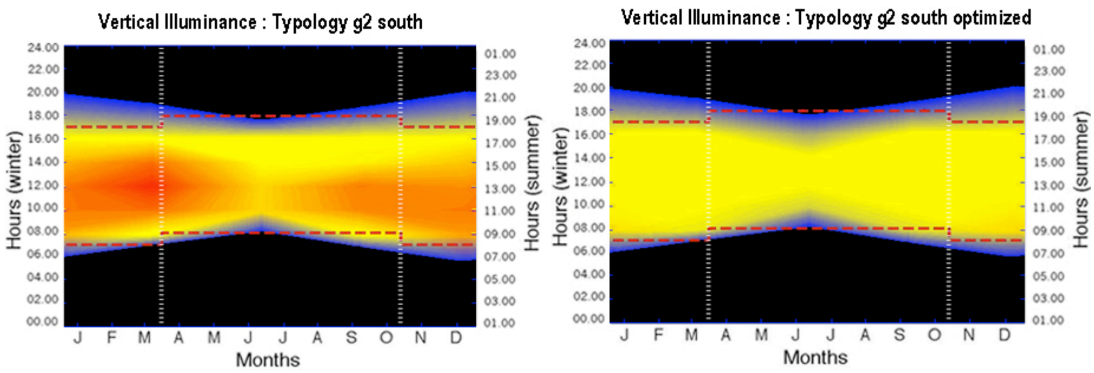


Figure 5.2-9: Comparison of the Vertical temporal Illuminance maps of the original and optimized South-facing Typology g2.

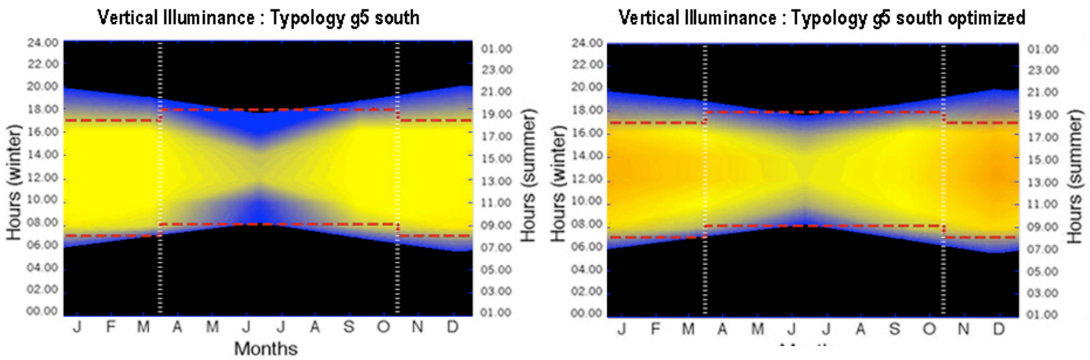


Figure 5.2-10: Comparison of the Vertical temporal Illuminance maps of the original and optimized South facing Typology g5.

Criterion 2. Achieving the adequate daylight uniformity in the classroom

Uniformity on the workplane: from the results obtained, we could confirm that the uniformity did not present variation with overcast skies. It was maintained as that previously evaluated, i.e., under 0.5.

For clear skies (clear and clear turbid), we could observe that they all maintain uniformity within the 0.5 – 0.7 range. In Typology g5, the uniformity was optimized for the fourth period; the diffuse glass helps prevent the contrast problems found, as can be confirmed in the graph in Figure 5.2-12. In Typology g2, we achieved a more constant uniformity during the day, always within a 0.5 – 0.7 range (see *Figure 5.2-11*).

For the intermediate sky, the uniformity is maintained for all cases and in all the periods, falling within the aforementioned range in the mornings while, in the afternoon, it is reduced, being under 0.5.

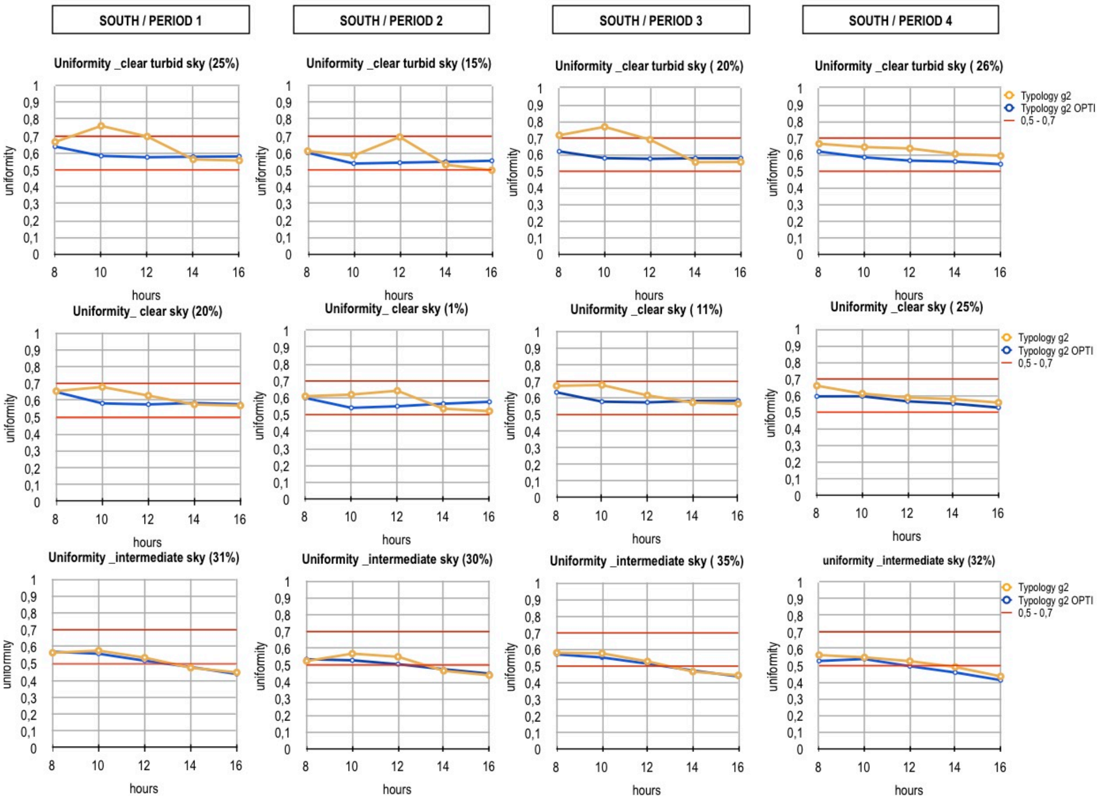


Figure 5.2-11: Daylight uniformity on the workplane, for optimized South-facing Typology g2.

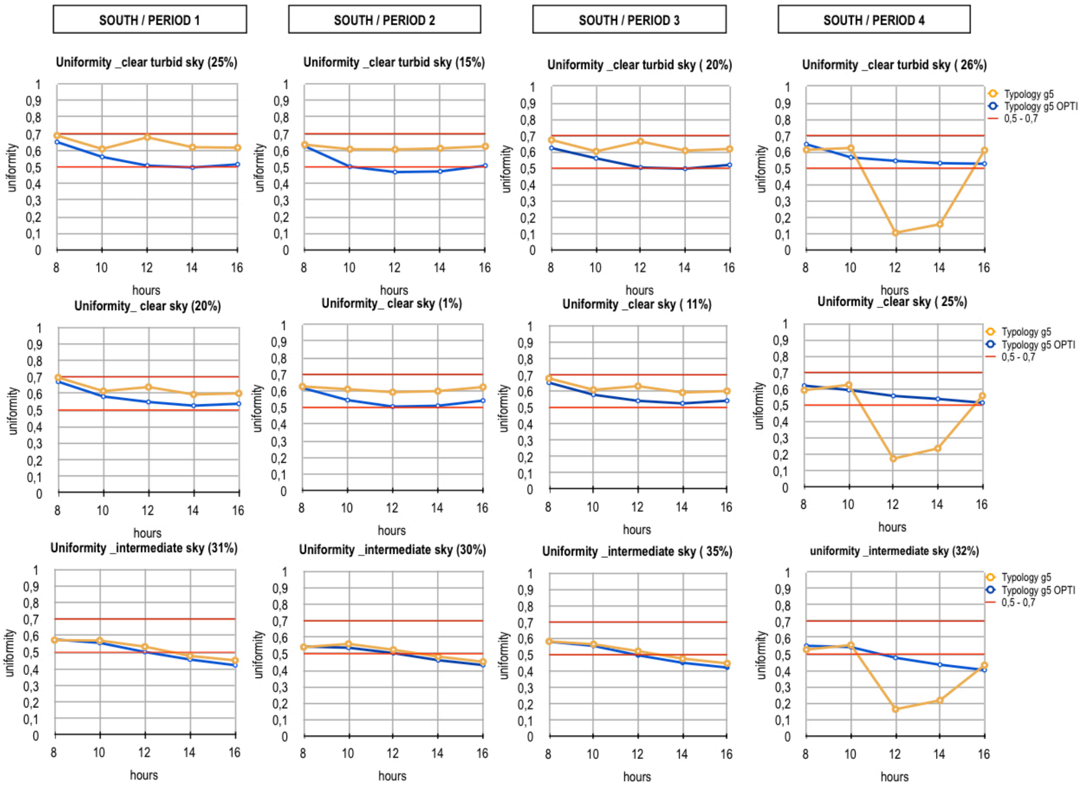


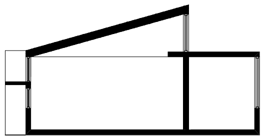
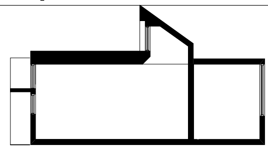
Figure 5.2-12: Daylight uniformity on the workplane, for optimized South-facing Typology g5.

5.2.3 Optimization of East-facing Classrooms

***Criterion 1. Providing an adequate amount of daylight in the classroom*.**

a. *Providing an adequate amount of daylight in the classroom:* the percentage of time with "%in range" was improved in the three Typologies. The results expressed in *Table 5.2-7* confirm that *adequate daylighting levels* for Typology g1, which increased by 9% its "%in range" throughout the year. The results for Typologies g2 and g3 demonstrate that they did not achieve enough time with "%in range", having daylighting under the adequate levels during a major part of the year. Upon observing the temporal maps detailed in appendix D, we could observe a greater "%in range" in Typology g2, now covering the months from April to October. In Typology g3, although an increase of the "% in range" by 8% was proved, in its temporal maps we could observe an increase of the "%too low" during the afternoons in wintertime, having a slight reduction of the "%too high" in the critical periods, because the number of hours in this interval is reduced, as can be seen in *Figure 5.2-13*.

Table 5.2-7: Comparison of percentages summarizing the Horizontal Temporal Illuminance maps of the original and optimized East-facing classroom typologies.

Horizontal Illuminance temporal maps - East Optimized								
								
TYPOLOGY g1 Original		OPTI	TYPOLOGY g2 Original		OPTI	TYPOLOGY g3 Original		OPTI
Too Low	33%	35%	Too Low	31%	32%	Too Low	32%	37%
In range	41%	50%	In range	21%	42%	In range	33%	41%
Too high	26%	15%	Too high	48%	26%	Too high	35%	22%

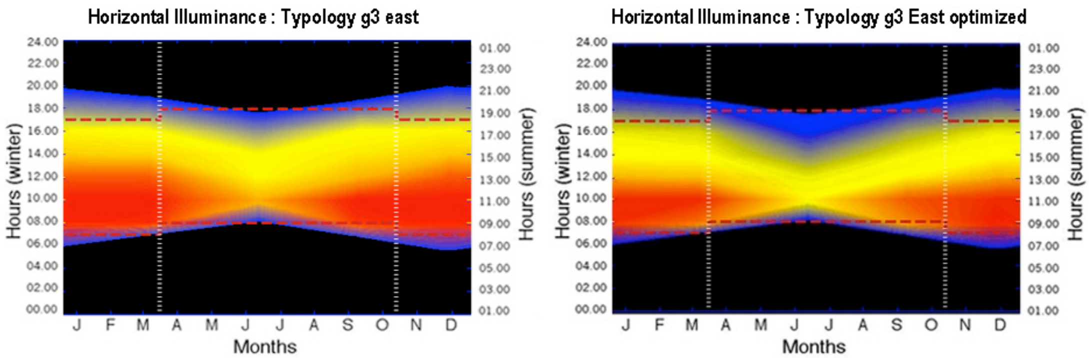
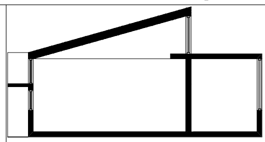
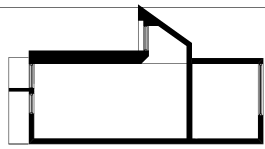


Figure 5.2-13: Comparison of the Horizontal Temporal Illuminance maps of the original and optimized East-facing Typology g2.

The *Spatial Illuminance distribution maps* were reviewed, confirming that all Typologies obtained a *regular spatial distribution.* The percentages shown in Table 5.2-8 confirm that the daylight spatial distribution in Typology g1 increased the area with "%in range" by 18%, while Typology g3 increased it by 9%. The latter also obtained an 8% increase of the area with "%too low" right in the area next to the whiteboard. In Typology g2, the area with "%in range" was increased, going from 36% to 62% of the classroom, becoming the most efficient solution since it presented a 26% increase. Despite the aforementioned, upon observing the spatial map we can see that it maintains an area with "%too high" next to the window, which is the critical area. That described for Typologies g2 and g3 is shown in Figure 5.2-14. In the temporal maps, we could confirm that none of them achieves an *optimal spatial distribution*, since there are areas with high illuminances.

Table 5.2-8: Comparison of percentages summarizing the Spatial Illuminance maps of the original and optimized East-facing classroom typologies.

Spatial Illuminance maps - East Optimized								
								
TYPOLOGY g1 Original		OPTI	TYPOLOGY g2 Original		OPTI	TYPOLOGY g3 Original		OPTI
Too Low	9%	14%	Too Low	5%	8%	Too Low	8%	16%
In range	59%	69%	In range	36%	62%	In range	48%	57%
Too high	32%	17%	Too high	59%	30%	Too high	44%	27%

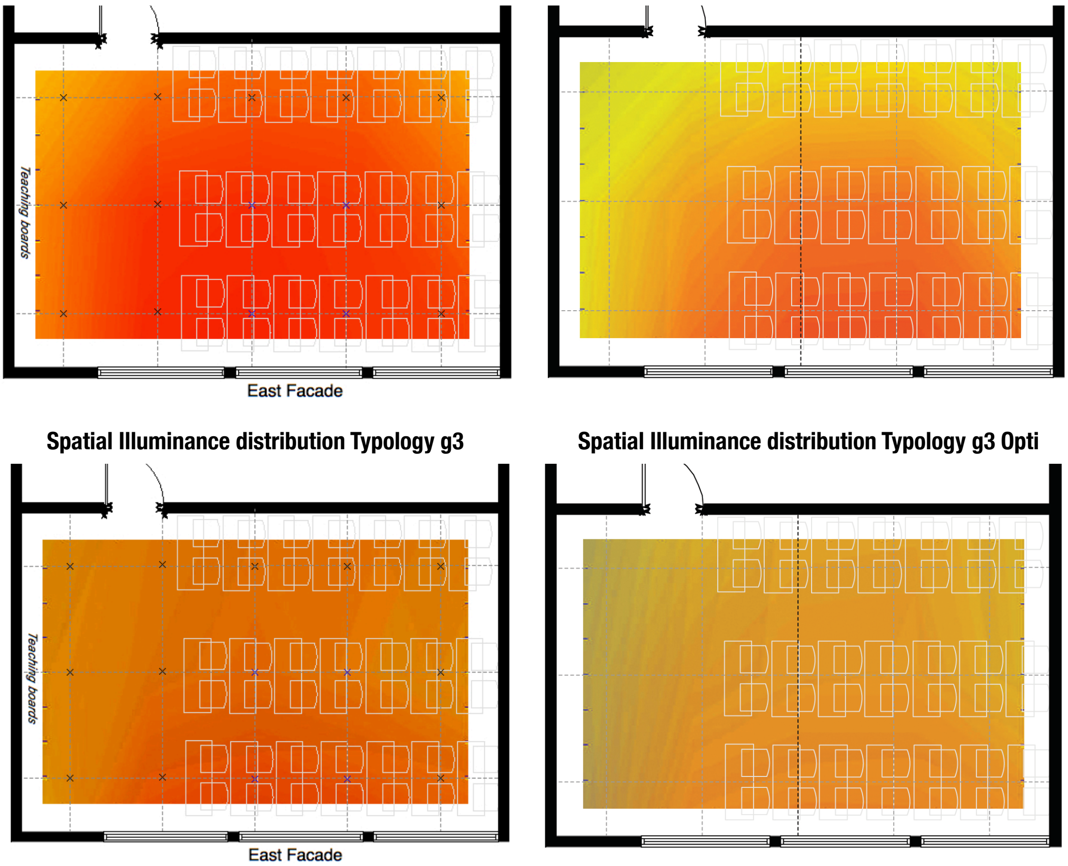
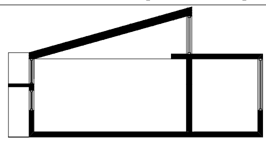
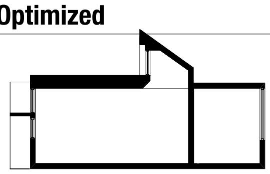


Figure 5.2-14: Comparison of the Spatial Illuminance maps of the original and optimized East-facing Typologies g1 and g2

b. *Providing an adequate amount of daylight on the whiteboard*: the results show that Typology g1 achieved *adequate daylighting levels*. Typology g2 was the most efficient, because it increased its time by 32%, obtaining 56% of the time with "%in range", this resulting in *optimal daylighting levels* throughout the year. Typology g3 is the most unfavorable for this orientation, because it presented a slight increase of the "%in range" by 1%, but remains below what is considered as adequate. Upon observing the temporal maps, we can see that Typologies g1 and g3, in the afternoons during winter, present "%too low", which indicates that, if it is decided to implement one of these strategies we should, also, consider an artificial lighting system to complement daylight on the whiteboard.

Table 5.2-9: Comparison of percentages summarizing the Vertical Temporal Illuminance maps of the original and optimized East-facing classroom Typologies

Vertical Illuminance temporal maps - East Optimized								
								
TYPOLOGY g1 Original		OPTI	TYPOLOGY g2 Original		OPTI	TYPOLOGY g3 Original		OPTI
Too Low	33%	34%	Too Low	31%	33%	Too Low	33%	39%
In range	44%	53%	In range	24%	56%	In range	38%	46%
Too high	23%	13%	Too high	45%	11%	Too high	29%	15%

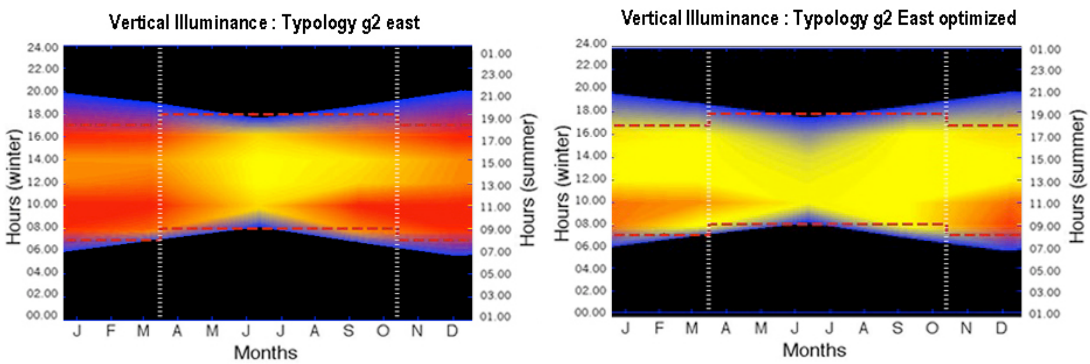


Figure 5.2-15: Comparison of the Vertical Temporal Illuminance maps of the original and optimized East-facing Typology g2.

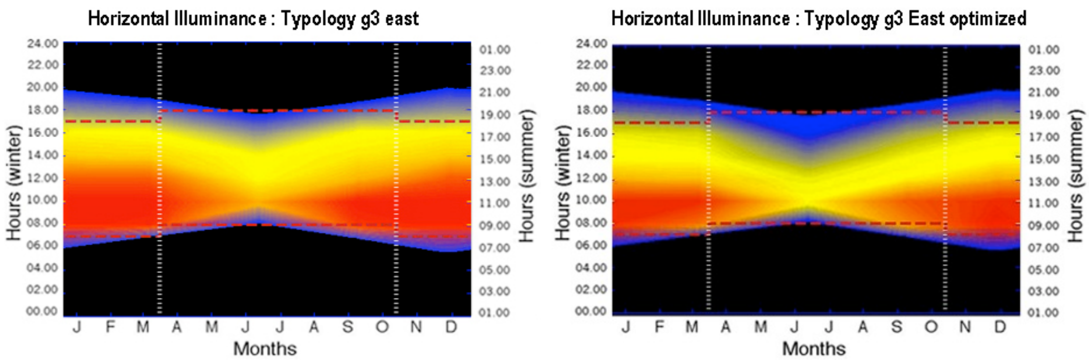


Figure 5.2-16: Comparison of the Horizontal Temporal Illuminance maps of the original and optimized East-facing Typology g2.

***Criterion 2. Achieving an** adequate daylight uniformity in the classroom.*

Uniformity on the workplane: Upon observing the uniformity graph shown in Figure 5.2-17, with overcast skies, it was possible to see that the uniformity was optimized in all the Typologies, becoming an *adequate uniformity* for Typologies g1 and g3 (around 0.6) and slightly greater than 0.5 for Typology g2.

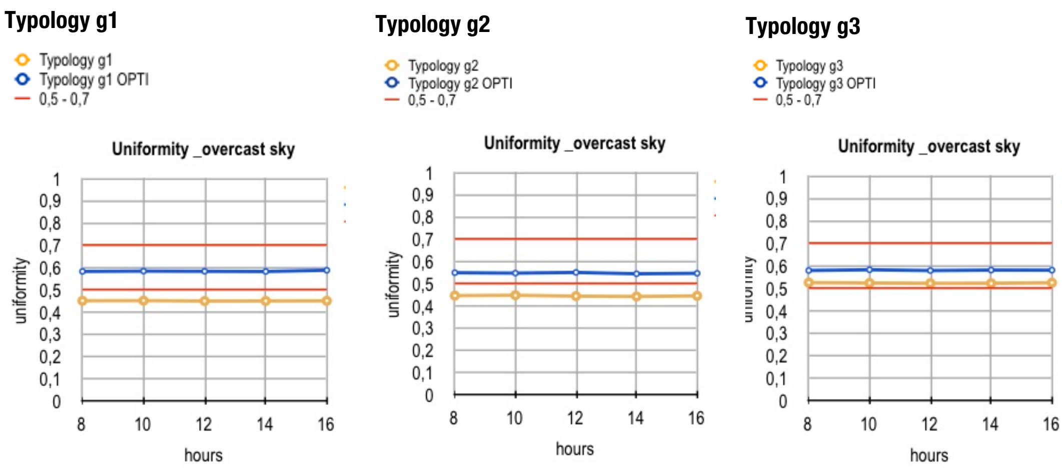


Figure 5.2-17: Daylighting uniformity on the workplane for the optimized East-facing Typologies.

For clear (clear and clear turbid) and intermediate skies, as shown in *Figure 5.2-18*, we can see that for Typology g2 the uniformity was optimized in the first, second and third periods, staying within the 0.5 – 0.7 range; during the fourth period, it presented contrast problems only in the first hours of the morning, to then stay under 0.5. Typology g3 obtained a very similar result. On the other hand, Typology g1, despite being improved in the first and third periods, kept a similar uniformity to that obtained before.

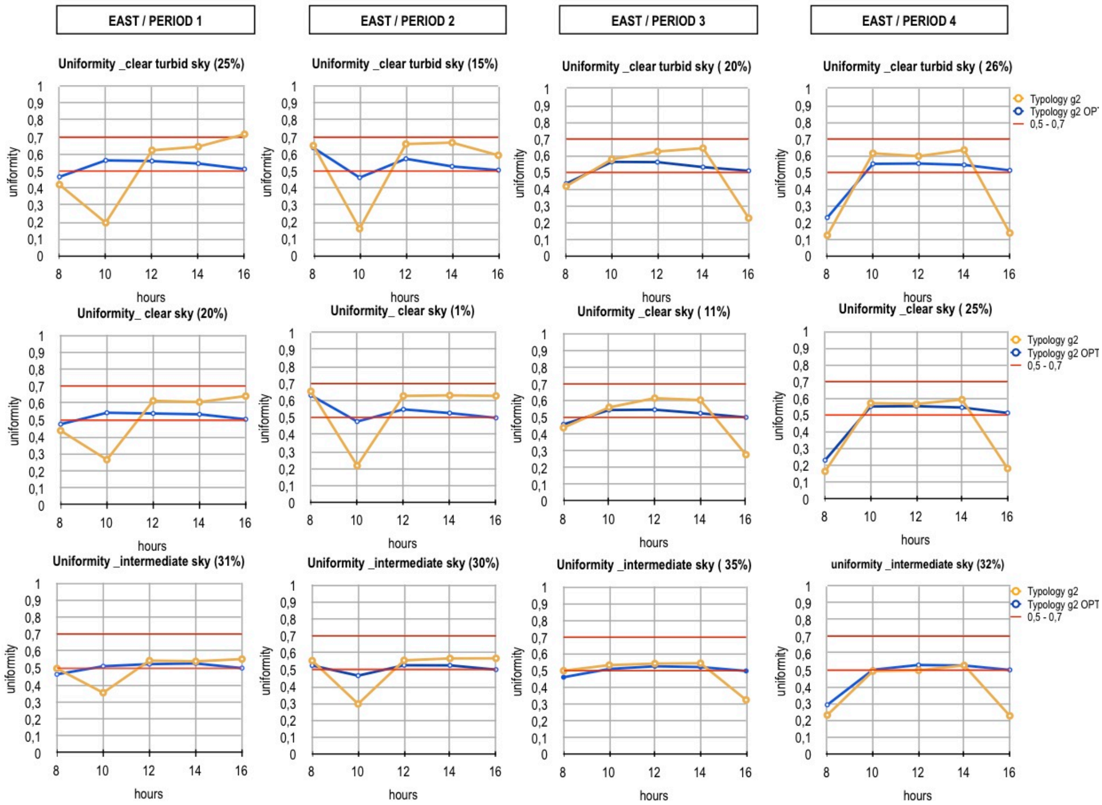


Figure 5.2-18: Daylighting uniformity on the workplane for optimized East-facing Typology g

Criterion 3. Ensure visual comfort in the field of view of students.

Se determinó el DGP para la Tipología g1, se verificó que para la solución arquitectónica propuesta el riesgo de deslumbramiento persiste en los periodos críticos. Al observar los temporal maps se muestra como se reduce levemente el riesgo de tener incomodidad visual en los periodos críticos. In Figure 5.2-19, we can see how the amount of hours for the DGP_{max} was reduced; however, we will have a DGP >40% until midday, which causes a situation, during the whole morning, that ranges from intolerable to disturbing, according to the human subjects rates proposed by Wienold.

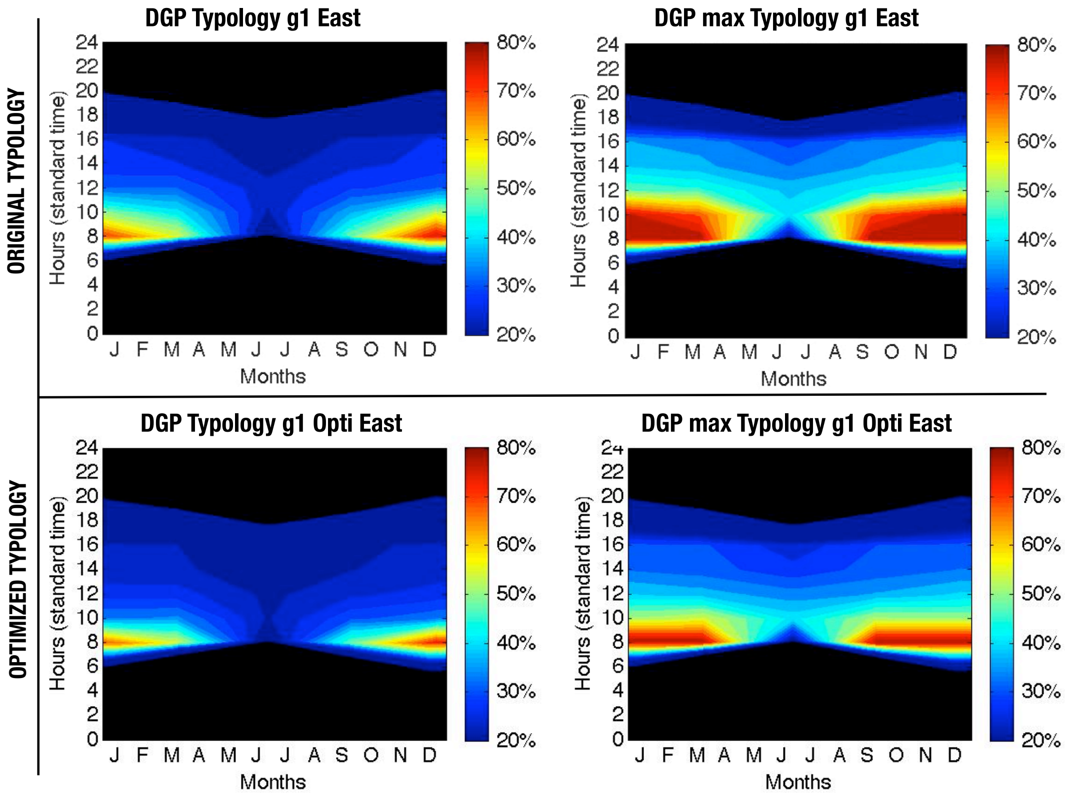


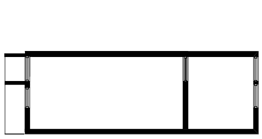
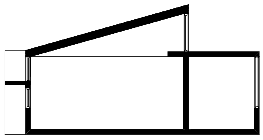
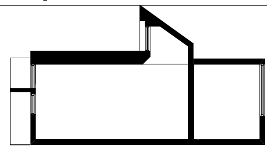
Figure 5.2-19: Temporal DGP and DGP $_{max}$ maps of the original and optimized East-facing Typology g1.

5.2.4 Optimization of West-facing Classrooms

Criterion 1. Providing an adequate amount of daylight in the classroom

a. *Providing an adequate amount of daylight on the workplane:* in *Table 5.2-10* we can see that Typology g1 obtained *optimal daylighting levels,* achieving 55% if the time with “%in range”. In contrast, typologies g2 and g3 stayed under the recommendation. We can see a 17% increase of time with “%in range” in Typology g2; however, this was not enough to achieve what is considered as adequate. In the case of Typology g3, even though it presented a slight “%in range” increase, in the temporal maps it can be seen that there was a greater increase of “%too low”.

Table 5.2-10: Comparison of percentages summarizing the Horizontal Temporal Illuminance maps of the original and optimized West-facing classroom typologies.

Horizontal Illuminance temporal maps - West Optimized					
					
TYPOLOGY g1 Original	OPTI	TYPOLOGY g2 Original	OPTI	TYPOLOGY g3 Original	OPTI
Too Low 34%	37%	Too Low 31%	33%	Too Low 35%	44%
In range 49%	55%	In range 28%	45%	In range 40%	42%
Too high 17%	8%	Too high 41%	22%	Too high 25%	14%

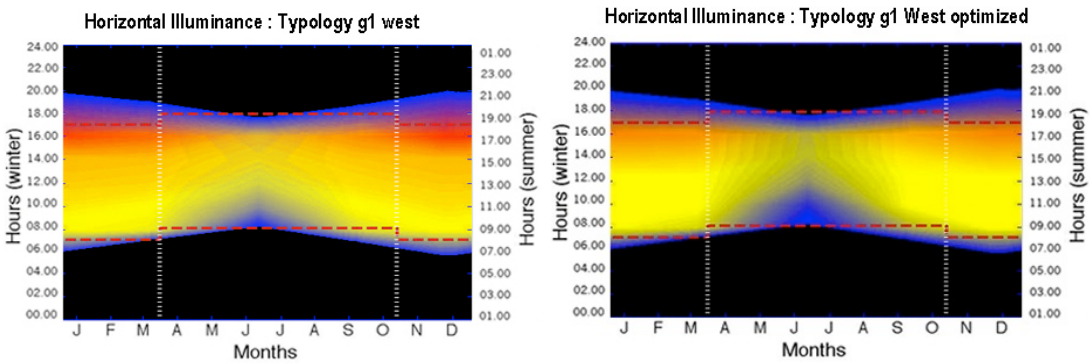
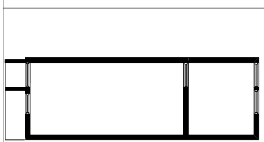
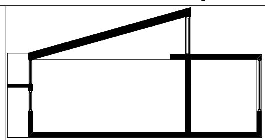
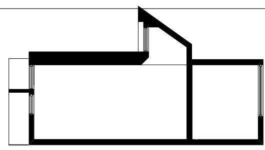


Figure 5.2-20: Comparison of the Horizontal Temporal Illuminance maps of the original and optimized West-facing Typology g1.

The *Spatial Illuminance distribution maps* were reviewed, verifying that they all achieved a *regular spatial distribution* in the classroom. In Table 5.2-11 we can see an increase of the classroom area that obtained illuminances “in range”. Typology g1 came as the most favorable, presenting a 73% of the area with “%in range”; on the contrary, Typology g3 was the most unfavorable, maintaining the “%in range” in the same values and increasing the area with “%too low”.

Table 5.2-11: Comparison of percentages summarizing the Spatial Illuminance maps of the original and optimized West-facing classroom Typologies.

Spatial Illuminance maps - West Optimized					
					
TYPOLOGY g1 Original	OPTI	TYPOLOGY g2 Original	OPTI	TYPOLOGY g3 Original	OPTI
Too Low 11%	17%	Too Low 5%	9%	Too Low 11%	26%
In range 68%	73%	In range 45%	66%	In range 57%	57%
Too high 21%	10%	Too high 50%	25%	Too high 32%	17%

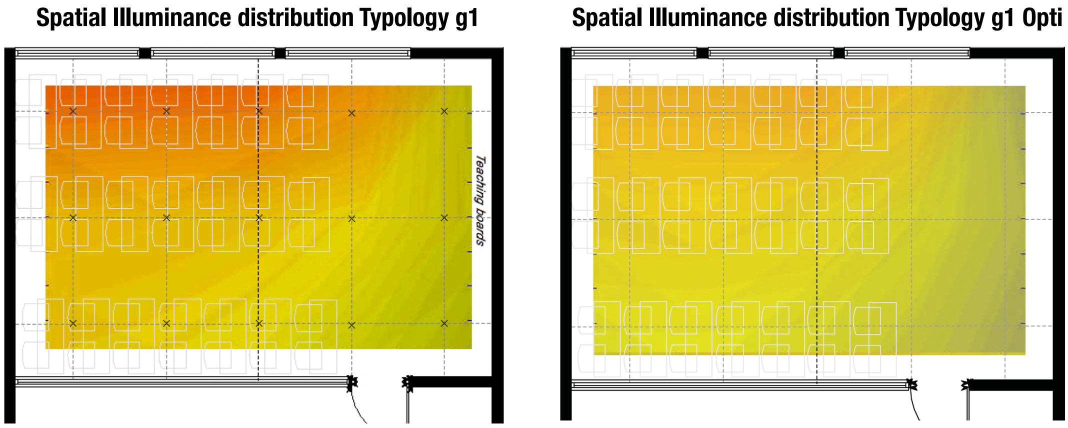


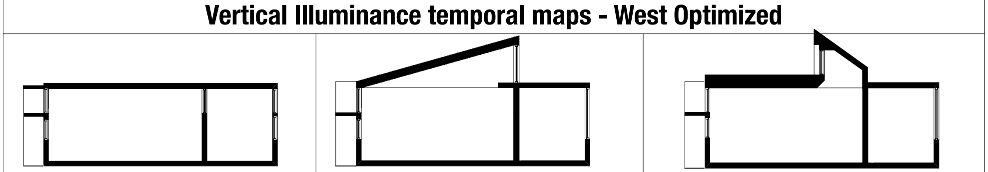
Figure 5.2-21: Comparison of the Spatial Illuminance maps of the original and optimized West-facing Typology g1.

b. *Providing an adequate amount of daylight on the whiteboard:* in *Table 5.2-12* we can verify that a slight increase on the "%in range" was achieved in Typologies g1 and g2, enough to obtain the *adequate daylighting levels.* On the contrary, the solution proposed for Typology g3 was not efficient, increasing the "%too low" and reducing the "%in range".

It can be seen in the temporal maps that Typology g1 obtained "%too low" during the winter mornings. For the whiteboard, in this solution, a lighting system that substitutes the lack of daylight must be considered. We can see that Typology g2 is more favorable, keeping for the same period and adequate "%in range", as can be seen in *Figure 5.2-22*.

Table 5.2-12: Comparison of percentages summarizing the Vertical Temporal Illuminance maps of the original and optimized West-facing classroom typologies.

Vertical Illuminance temporal maps - West Optimized



TYPOLOGY g1 Original		OPTI	TYPOLOGY g2 Original		OPTI	TYPOLOGY g3 Original		OPTI
Too Low	34%	38%	Too Low	31%	33%	Too Low	37%	49%
In range	58%	61%	In range	43%	61%	In range	49%	41%
Too high	8%	1%	Too high	26%	6%	Too high	14%	10%

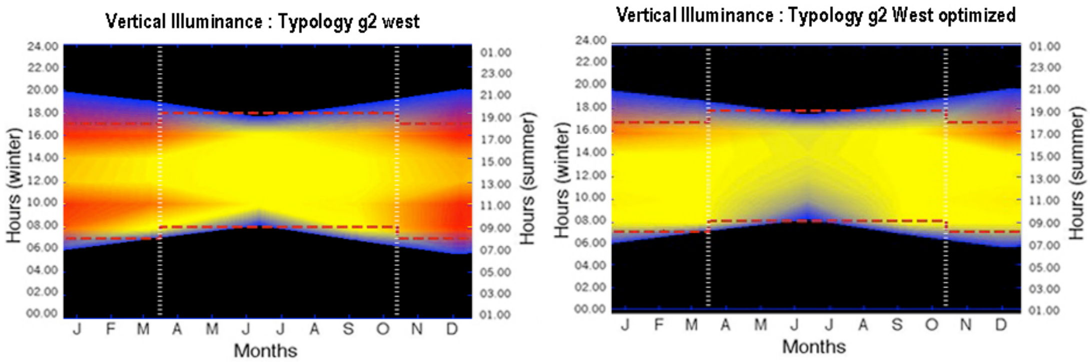


Figure 5.2-22: Comparison of the Vertical Temporal Illuminance maps of the original and optimized West-facing Typology g2.

Criterion 2. Achieving an adequate daylight uniformity in the classroom

Uniformity on the workplane: in the uniformity graph with overcast skies in *Figure 5.2-23*, we can see that this was improved in the studied typologies. With clear and intermediate skies, it was optimized in all the typologies, not presenting great variations in the first, third and fourth periods, staying within the 0.5 – 0.7 range. In the case of the second period, a slight contrast is generated in the afternoon.

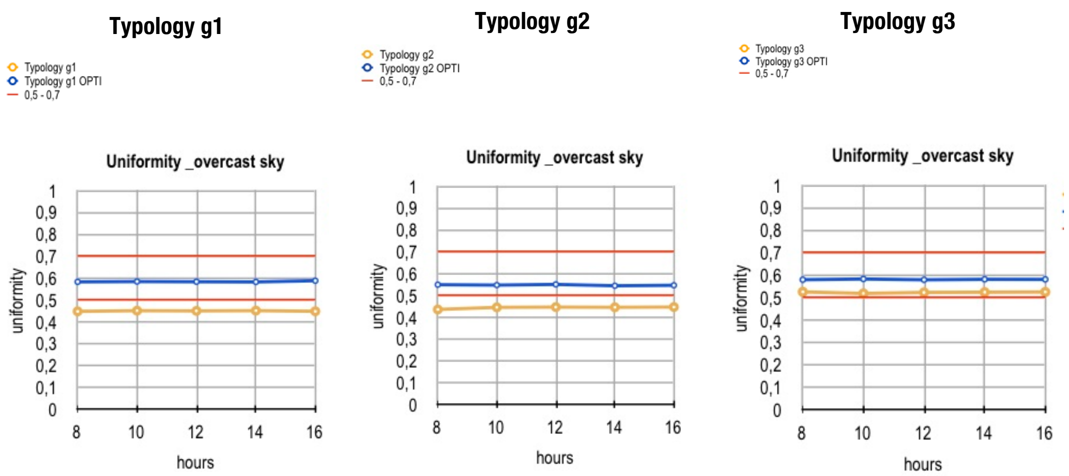


Figure 5.2-23: Daylighting uniformity on the workplane for the optimized West-facing Typologies.

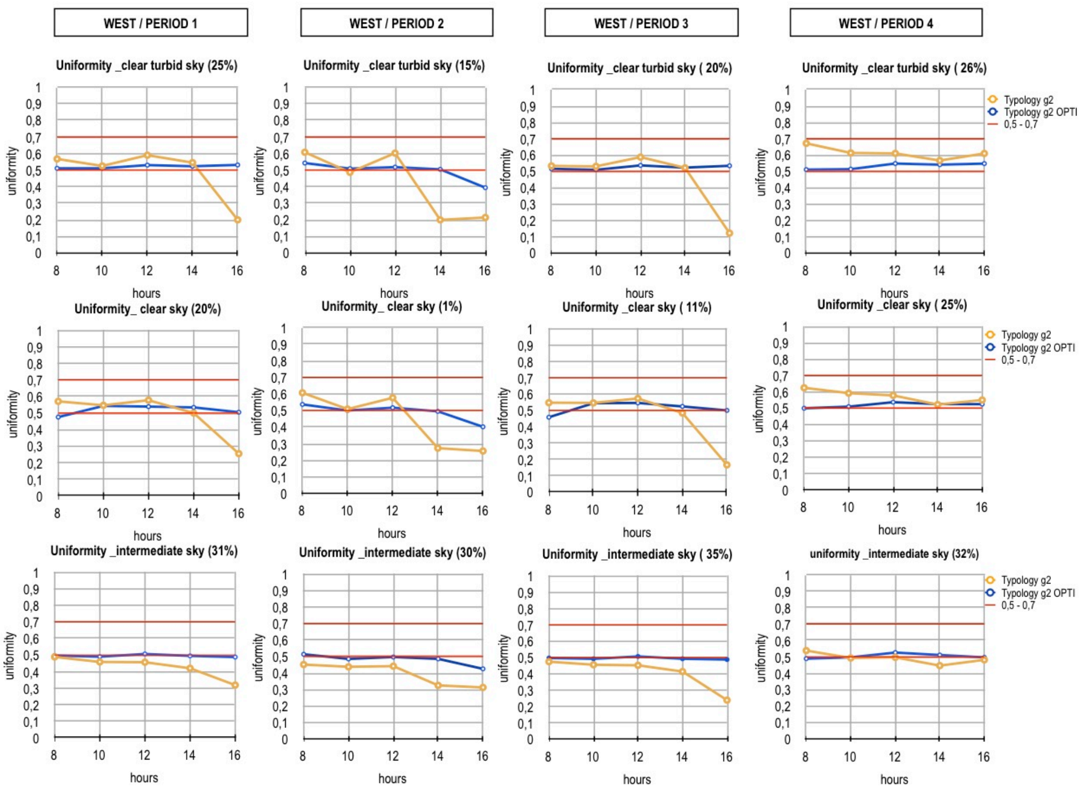


Figure 5.2-24: Daylighting uniformity on the workplane for the optimized West-facing Typology g2.

Criterion 3. Ensure visual comfort in the field of view of students.

The glare risk for Typology g1 was evaluated, as can be seen in Figure 5.2-25. It was demonstrated that the elements placed on the facade are able to reduce the daylighting glare probability (DGP) almost completely, being able to ensure the visual comfort for a major part of the year. As for the $DGP_{max,}$ we could see that the risk of visual discomfort for the most glaring sky was reduced; however, we can still perceive a visual discomfort situation in the afternoons of the first and third periods, as can be clearly seen in the graph.

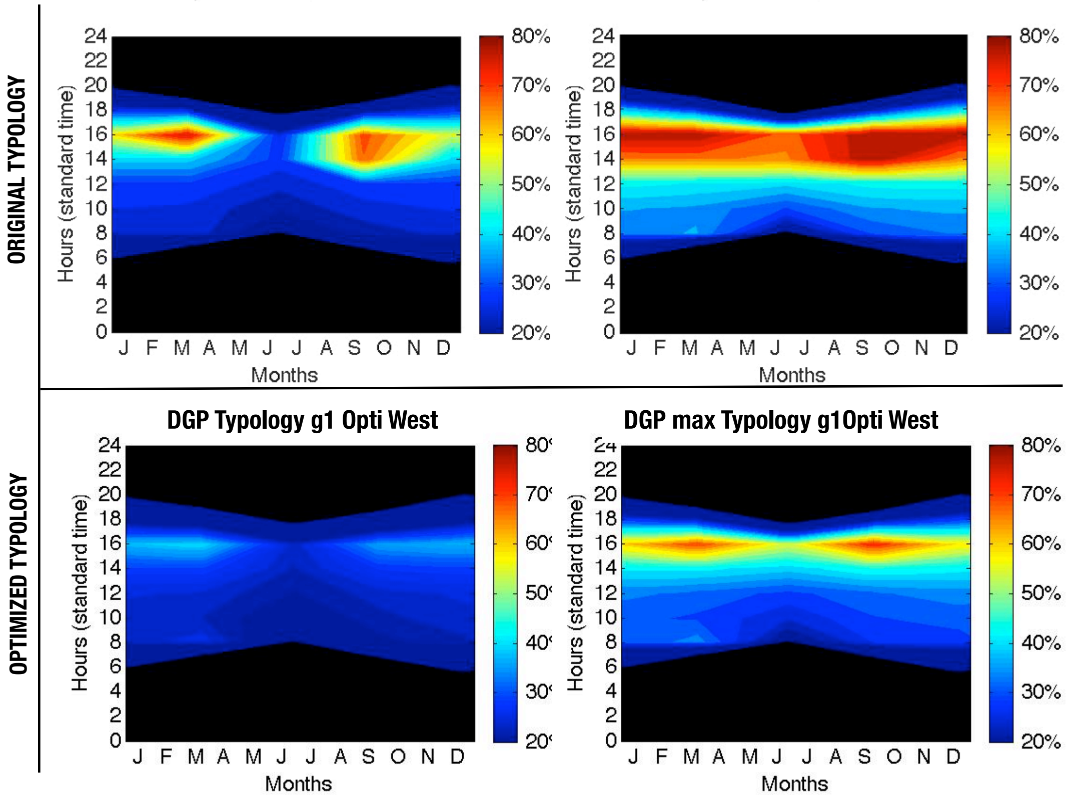


Figure 5.2-25: Temporal DGP and DGP $_{max}$ maps of the original and optimized West-facing Typology g1

5.3 Design Recommendations

The design recommendations are the synthesis of all the simulations carried out, of all that was observed and proved in Chapters 4 and 5. The objective is to provide recommendations that serve as a guideline for the architectural design that will make up the **directives** for classroom's daylight design. Below, general directives are stated, with their design recommendations, and later we provide application guidelines for the proposed strategies versus the evaluated criteria.

5.3.1 Guideline for the Classroom's Daylight Design

In the design of the classroom's organization, three main daylit areas are considered: the critical area, the protected area and the workplane area. These areas present different daylight requirements, which are explained below:

1) *Critical area:* it has been defined in section 4.5 of Chapter 4. Summarizing, it is a stripe next to the façade that, in general, is exposed to too high illuminances, because this area must be considered as a perimeter protection facade of the workplane area.

We recommend that the classrooms with orientations exposed to the incidence of direct sunlight that do not consider, in their design, any sunlight control element, such as lightshelves or others, must carry out a sunlight penetration study to define the critical are keep and thus evaluate the perimeter distance necessary to define the workplane area. The objective is to prevent exposing the students to high illuminances and to sunlight penetration, which have an incidence on the visual comfort, provoking glare. In Figure 5.3-1, we can see an example of this distance, which will lead to an increase of the classroom's total area.

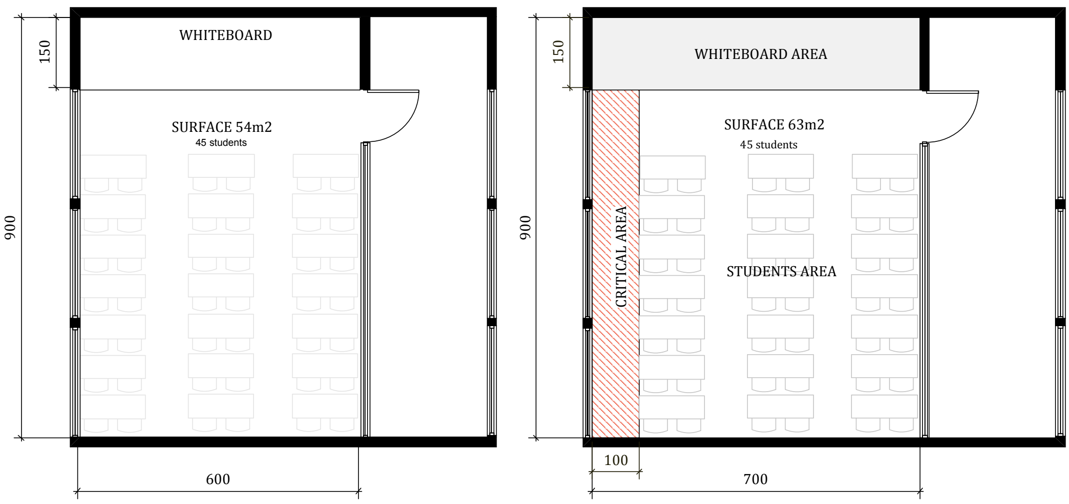


Figure 5.3-1: Schematic classroom plans that portray the increase on the classroom surface, considering a critical area.

2) *Protected area:* it was explained in section 4.5. We recommend that the lighting strategies for this area must be differentiated of separate from the daylight strategy of the classroom. Its design must be focused on avoiding the penetration of direct sunlight and on controlling the variations on luminous intensity.

We recommend that those classrooms with sunlight incidence must keep a minimum separation between the facade window and the whiteboard wall. This distance must be studied according to the position of the workplane in relation to the classroom's orientation and the sun trajectory. In Figure 5.3-2 we can see the distance applied in this study, especially considering that we recommend a minimum of 1.5m.

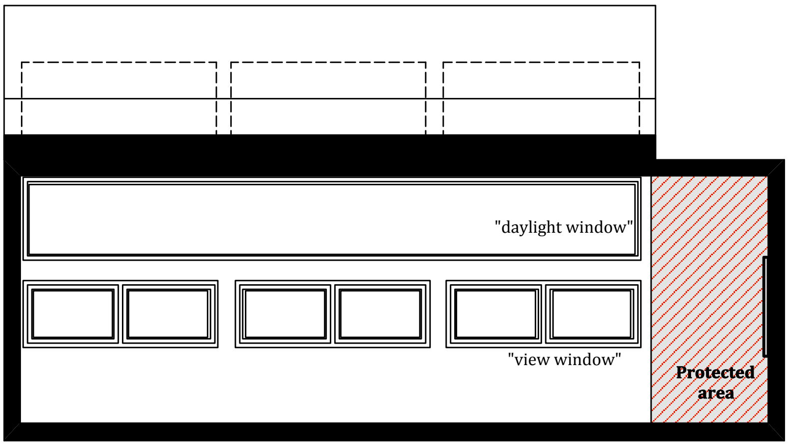


Figure 5.3-2: Sectional cut of the whiteboard protection applied in Typology g3.

3) Workplane area: this area must be protected from direct sunlight penetration through sunlight control elements. In the classrooms with sunlight incidence, the effectiveness of protection for the *critical periods* must be tested.

Starting from that applied in the Typologies, we recommend conceiving, for these areas, a main window with two stripes of windows. The first one located at eye level, to generate a view towards the outside, becoming the "view window"; and the second one at a higher level to maximize the daylight penetration in the classroom, becoming the "daylight window". They must be considered as follows:

a) "View window": its purpose is to allow for the students to have a view of the outside. We recommend considering an area equal or greater than 7% (WFR) of the classroom surface, providing a line of direct vision through a window for 90% of the classroom area (CHPS, 2006).

b) "Daylight window": it is a window on the top part of the facade, whose purpose is to distribute the deeper light in the space and provide a greater comfort for the students. It is located at the top, close to the ceiling line, outside the field of view. It controls and regulates daylighting in the classroom.

Once this general organization is stated, we explain the design considerations to protect the facade window or the light collecting elements. They are based on those evaluated in this study, which were located in the city of Concepción. We have to remember that the view window's protection was always thought as one that did not block the passage of light and the view to the outside; and that the high window was protected in order to control and reduce the "%too high" in the critical area. The recommendations are stated from the problematic to be solved and, then, the recommended elements.

These problems are described below:

1) *Reducing the "%too high" in the perimeter of the critical area:* we could verify and prove the effectiveness of three architectonic elements applied to the Northern facade. They turned out to be effective, because the sunlight penetration is blocked in three of the four evaluated periods. Only in winter do we have direct sunlight penetration, period for which we must consider some sort of mobile protection, such as curtains, only for the view window. These elements are described below:

   a) "Overhang daylight window": located on the top part as protection against direct sunlight radiation, reducing the sunlight contribution in the *critical area*.

   b) "Interior lightshelf": it serves as protection from the incidence or direct sunlight coming from the high window. It acts as a light diffuser and, combined with the "overhang daylight window", protects the students located right under it.

   c) "Overhang view window": located on the view window, its dimension must be equivalent to the height of the view window. It is an efficient protection to achieve the visual comfort of the students located in this perimeter.

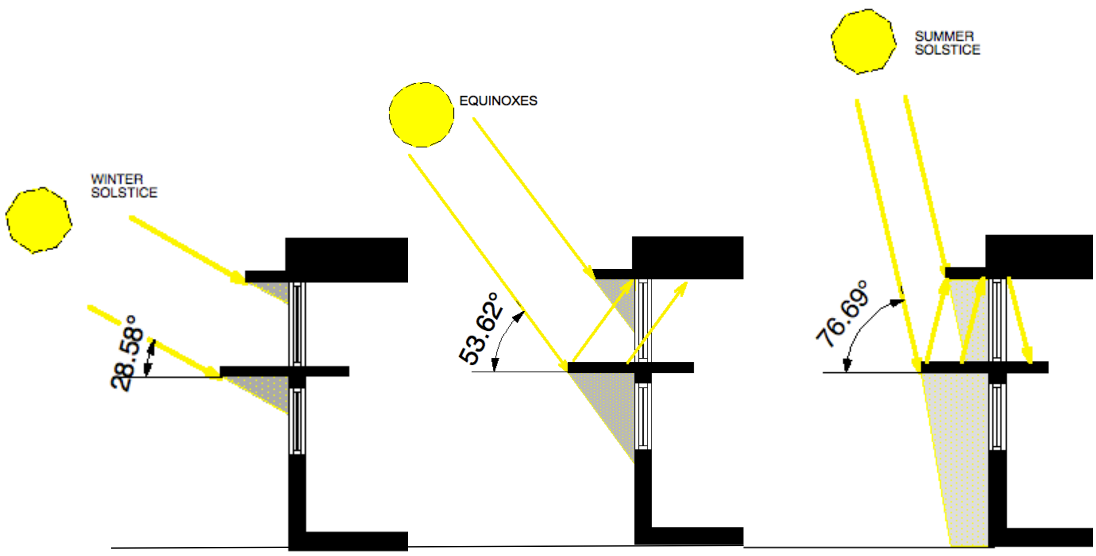


Figure 5.3-3: Application of the "overhang daylight window", "interior lightshelf" and "overhang view window" in the North-facing Typologies in the solstices and equinoxes for the city of Concepción at 12pm.

2) *Reducing the "%too high" in the central area:* when using the lighting strategies such as the "clerestory window", we could prove the effectiveness of applying an exterior overhang (of 0.6m), in the North-facing classrooms with unilateral strategies and in the South-facing classrooms with bilateral strategies.

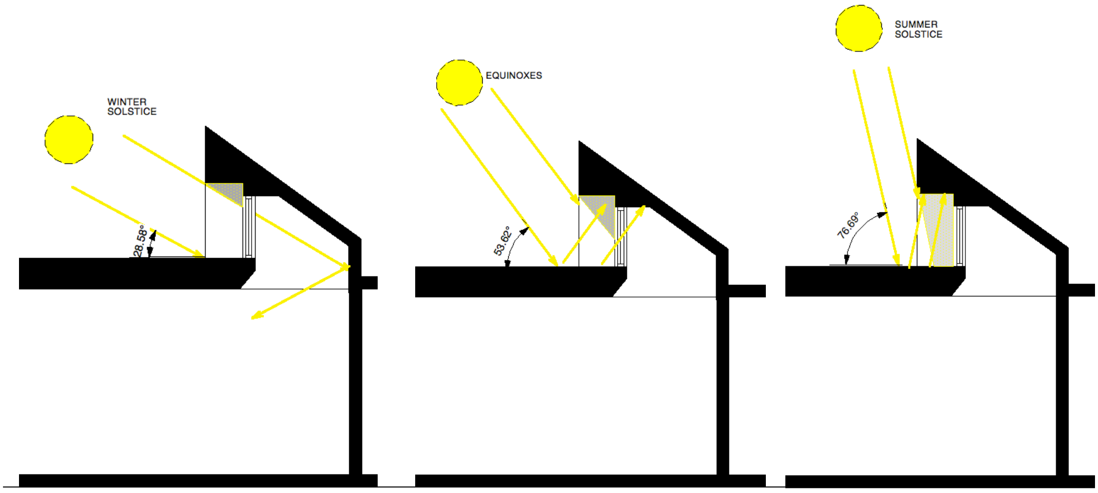


Figure 5.3-4: Application of the "overhang clerestory window" in the North-facing Typologies in solstices and equinoxes for the city of Concepción at 12pm.

3) *Stopping the direct radiation through the glass:* it includes the reduction of the luminous transmission coefficient of the glass. We recommend not to use simple glass since, as it was exposed in Chapter 4, they have a direct incidence on the obtained lighting levels. In any unprotected window, a low luminous transmission coefficient glass must be used. We recommend a glazed glass with 75% of visible transmitted like Double or low E glass, which are also designed to reduce heat loss but admit solar gain (71% solar heat transmitted). This was applied and tested in the Northern facade of the optimized classrooms.

When selecting a daylight strategy, we must prioritize those that allow accessing as deep as possible with the light, and that allow for the reduction of the glare probabilities. With respect to the daylight strategies, we recommend the following:

1) For the North-facing classrooms, we recommend those strategies with bilateral orientation similar to the "bilateral clerestory window" of Typology g2. We proved that the aforementioned, together with the due protection of the Northern window, provides excellent results.

2) For the South-facing classrooms, we recommend the use of unilateral orientation strategies, similar to the “unilateral clerestory window” of Typology g3. These strategies ensure the visual comfort of the students.

Is we decide to use a bilateral orientation strategy (South – North), we must consider the indicated sunlight protections.

3) Even though in the East and West-facing classrooms there were no optimal results, it is important to mention the solutions that were evaluated. We recommend an unilateral daylight strategy, but with indirect light coming from the corridor, similar to the “basic daylighting strategy” of Typology g1. This turned out to be the most efficient one for both orientations.

Likewise, we recommend the use of a strategy similar to the “bilateral clerestory window” of typology g2, which, although it does not achieve what is considered as optimal, has a good application in relation to the distribution and the uniformity. We should only have to foresee more efficient sunlight control elements, such as mobile protections.

5.3.2 Application of the Daylighting Strategies in the Classrooms

Each of the evaluated Typologies represented a light distribution strategy, which responded differently in each of the criterions depending on the orientation, with inherent advantages and disadvantages. A summary table was generated for each orientation, where a rating based on the four application levels, themselves based on that stated in the Best Practice Manual DESIGN (2006), are exposed. It is applied with the purpose of providing options that would guide the architect in their architectural design.

The Typologies that obtained optimal and adequate results are prioritized. The tables are shown below:

Table 5.3-1: Rating for daylighting strategies

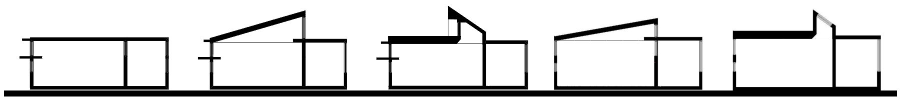
Extremely good application	○○	Poor application	⊙
Good application	○	Extremely poor application	⊙⊙
Mixed benefits	○/⊙	Not evaluated	N.E

T

The North-facing typologies, in general, were found to be very unfavorable in the first stage, in terms of the comfort conditions related to the applied criteria. We were able to demonstrate that the strategies incorporated in the optimization stage were able to control the

"%too high". The optimized Typologies g1, g2 and g3 resulted in an extremely good application for criterion 1 and in a good application for the other criteria, as stated in Table 5.3-2.

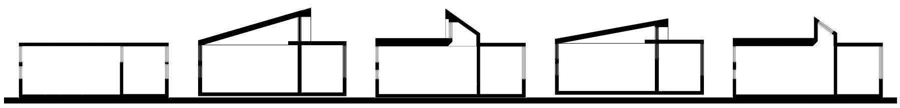
Table 5.3-2: Criteria for daylighting strategies in North-facing classrooms



	Design criteria	Typology g1 Opti Basic and corridor	Typology g2 Opti Clerestory bi-lat window	Typology g3 Opti Clerestory uni-lat window	Typology g4 Clerestory bi-lat and corridor	Typology g5 Skylight
1	Daylight Levels workplane	○○	○○	○	⊙⊙	⊙⊙
	Daylight distribution	○○	○○	○○	○/⊙	○/⊙
	Daylight Levels whiteboard	○○	○○	○○	⊙	○
2	Daylight uniformity workplane	○	○	○	⊙⊙	⊙⊙
	Daylight uniformity whiteboard	○	○	○	○/⊙	○/⊙
3	Low glare	○	○	N.E	⊙⊙	⊙⊙
4	Sunlight penetration	○	○	○	⊙⊙	⊙⊙

South-facing Typologies, as has been previously stated, present daylighting strategies favorable for their application to the architectural design of the classrooms. The applied strategies were able to generate Typologies with extremely good applications (Typologies g1 and g3). The other Typologies resulted in good applications to the design (see Table 5.3-3).

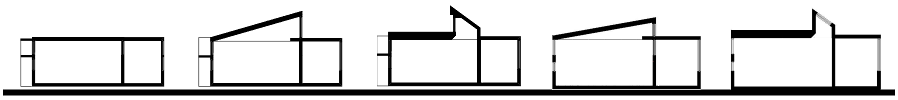
Table 5.3-3: Criteria for daylighting strategies in South-facing classrooms



	Design criteria	Typology g1 Basic and corridor	Typology g2 Opti Clerestory bi-lat window	Typology g3 Clerestory uni-lat window	Typology g4 Opti Clerestory bi-lat and corridor	Typology g5 Opti Skylight
1	Daylight levels workplane	○○	○	○○	○○	○○
	Daylight distribution	○○	○	○○	○○	○○
	Daylight levels whiteboard	○○	○○	○○	○○	○○
2	Daylight uniformity workplane	○	○	○○	○○	○
	Daylight uniformity whiteboard	○○	N.E	○○	○	N.E
3	Low glare	○○	N.E	○○	N.E	N.E
4	Sunlight penetration	○○	○○	○○	○	○○

As for the optimizations in the East-facing classrooms, only for Typology g1 they resulted in extremely good applications for the daylight levels on the workplane. Typology g2 resulted in an extremely good application in relation to daylight spatial distribution. The other Typologies resulted in poor and extremely poor applications for almost all the criteria (see Table 5.3-4).

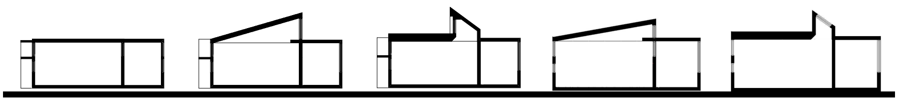
Table 5.3-4: Criteria for daylighting strategies in East-facing classrooms



Design criteria	Typology g1 Opti	Typology g2 Opti	Typology g3 Opti	Typology g4	Typology g5
	Basic and corridor	Clerestory bi-lat window	Clerestory uni-lat window	Clerestory bi-lat and corridor	Skylight
1 Daylight levels workplane	○○	⊙	⊙	⊙⊙	⊙
Daylight distribution	○	○	○/⊙	⊙	⊙
Daylight levels whiteboard	○	○○	⊙	⊙	⊙
2 Daylight uniformity workplane	⊙	○	○	⊙	⊙
Daylight uniformity whiteboard	N.E	N.E	N.E	⊙	⊙
3 Low glare	⊙	N.E	N.E	⊙	⊙
4 Sunlight penetration	N.E	N.E	N.E	⊙⊙	⊙⊙

For the West-facing Typologies, we can state that Typology g1 resulted in an extremely good application in relation to the illuminance levels on the workplane and on the whiteboard. Also, this Typology resulted in a good application for uniformity and low glare (see Table 5.3-5).

Table 5.3-5: Criteria for daylighting strategies in West-facing classrooms



Design criteria	Typology g1	Typology g2 Opti	Typology g3	Typology g4 Opti	Typology g5 Opti
	Basic and corridor	Clerestory bi-lat window	Clerestory uni-lat window	Clerestory bi-lat and corridor	Skylight
1 Daylight levels workplane	○○	⊙	⊙	⊙	⊙
Daylight distribution	○	○	○/⊙	⊙	⊙
Daylight levels whiteboard	○○	○○	⊙	○○	○
2 Daylight uniformity workplane	○	○	○	⊙	⊙⊙
Daylight uniformity whiteboard	N.E	N.E	N.E	○○	○○
3 Low glare	○	N.E	N.E	⊙	⊙
4 Sunlight penetration	N.E	N.E	N.E	⊙	⊙

5.4 Reference

CHPS. (2006). Best Practice Manual DESING (Vol. II). High Performance Schools.

CHPS. (2006). *Best Practice Manual CRITERIA* (Vol. III). High Performance Schools.

Wienold, J. (2009). *Dynamic daylight glare evaluation*. Building simulation., (947-951). Glasgow (UK).

6 Presentation of the Database

In this chapter, the database, which is a tool designed to establish a link between the advanced investigation and the practical application, is presented. The information obtained in the simulations that were analyzed in Chapter 4 is organized, as a base platform that allows for the reading of the information from the dynamic analysis that was applied. This platform allows us to easily organize and visualize the large amount of data contained within it. Below, the foundations for the generation of this platform are shown. The objectives for making it are then presented along with the technical aspects, programs and language used in its implementation. The structure of the platform, based in sections, is explained, as well as the organization of each of the sections.

6.1 Presentation of the Database

6.1.1 Objective of the Database

The objective of the database is to organize, in a simple and orderly way, a series of data that, when interrelated, allows us to analyze the results obtained from the simulations in the classrooms.

The purpose is to establish a link between the research carried out in this thesis and its practical usage by the architects. All the simulation applications used in this thesis require time and advanced knowledge, which is why this database allows the architects to obtain precise and developed information, along with a graphical visualization of the data contained within it, to later incorporate it in their design. This tool is useful, in this way, to make design decisions such as: daylighting strategy, the choice of the most appropriate orientation taking into account the interior light distribution and critical periods, among others.

During the development of this investigation, a large amount of data was obtained with the consequent difficulty in storing it, organizing it and visualizing it. This database was organized initially with data from the simulations for the city of Concepción in such a way that, in the future, data for other weathers and regions of Chile can be incorporated. It may, thus, contribute to a local design that considers the most important light variables, such as the dynamic of the sky types and the seasons of the year.

Among the main characteristics presented in the database are the following:

- Storage of the data of the simulations and dynamic analysis of the light.
- User friendly web interface, that allows for consultations without prior preparation or knowledge.
- Updatable, on the fly graphics where any modification or incorporation of data is reflected immediately in the visualization.
- Help information that aids the user in the interpretation of the data that is shown.

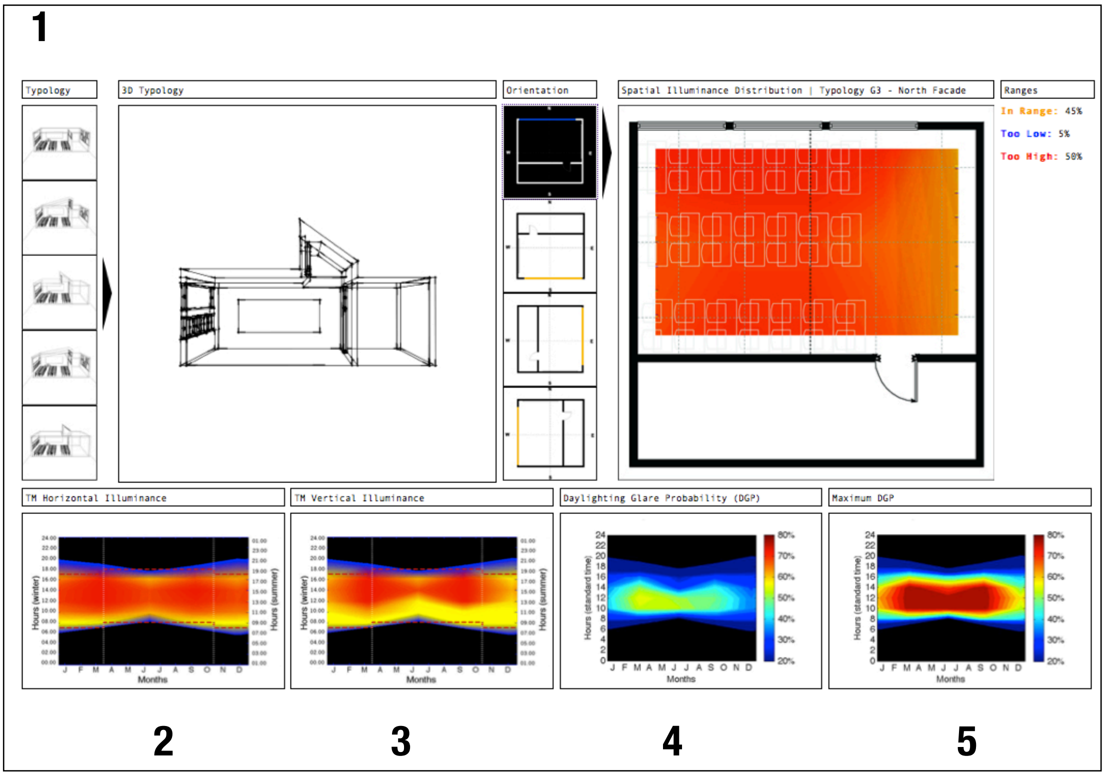


Figure 6.1-1: Main section (1) and secondary sections (2-5).

6.1.2 Architectural Information

The Architectural information is presented in the main section of the platform, where the user selects one of the five typologies, where they can see each one of the typologies with their daylighting strategies.

- Typology: the five typologies with the different daylighting strategies are presented (see section 3.5). When clicking on the boxes, a tridimensional model of the chosen typology is presented in a larger box.

- 3D Typology: the tridimensional model of each typology is presented, allowing for a 360º, x-y plane visualization (see Figure 6.1-2).

Once the typology is established, the user selects its orientations, which can be: North, South, East or West. Upon choosing the orientation, the information in the following box and secondary sections 2-5 automatically changes.

In Figure 6.1-3, four boxes of the main section that correspond to the different orientations are shown. These allow for a first glance before having all the results and for a quick visualization, in case that the orientation and/or typology are modified.

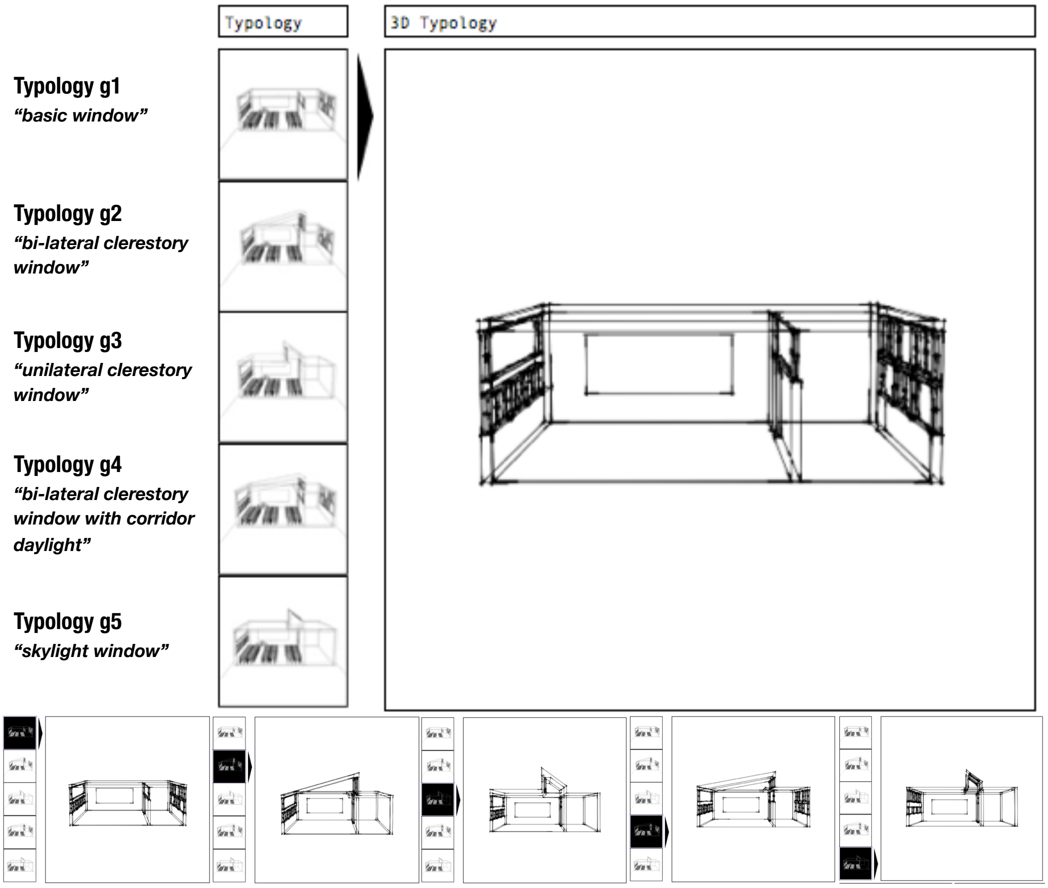


Figure 6.1-2: Section to select the five basic typologies.

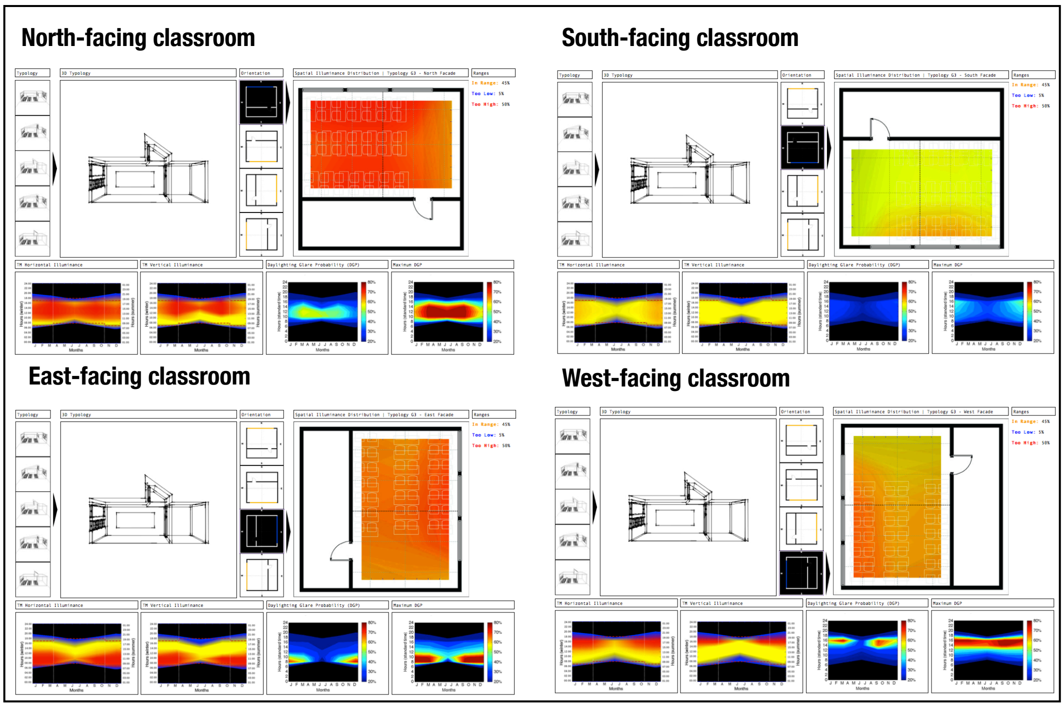


Figure 6.1-3: Main section illustrating each one of the orientations.

6.1.3 Spatial Information

Once the model and orientation have been selected, it is possible to see the graph of the spatial distribution for the weighted illuminances, which is explained in section 3.2.2. The user easily and quickly visualizes the spatial distribution, with the most and least illuminated zones shown. In parallel, the percentage of the area of each range defined, and the type of spatial distribution obtained in the different categories (regular, irregular and optimal) defined in section 3.4.1, are shown.

In Figure 6.1-4 the chart of the Spatial Illuminance distribution map that illustrates how, by modifying the orientation, the spatial distribution of the light changes in the selected typology, is shown.

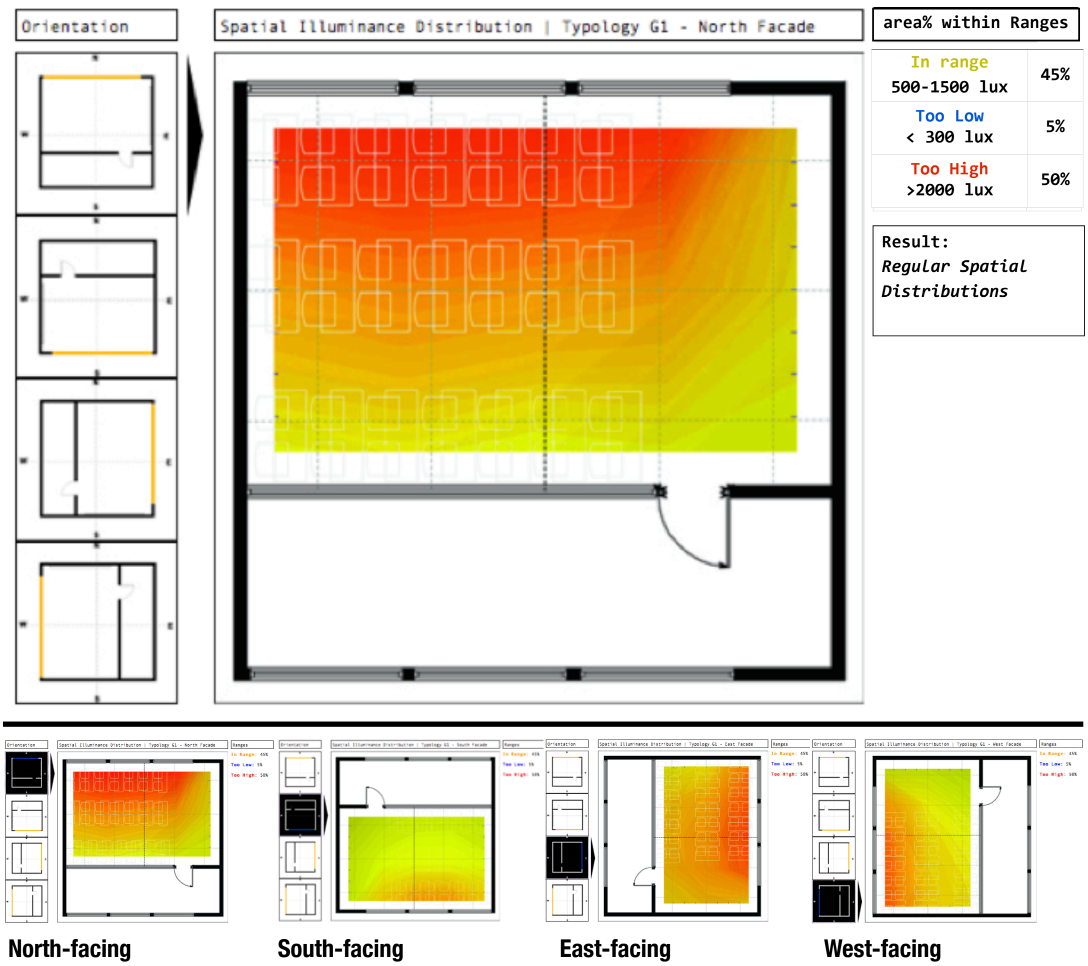


Figure 6.1-4: Spatial Illuminance distribution maps.

6.1.4 Temporal Information

The temporal maps are integrated to the main section, according to that seen in Figure 6.1-1, which correspond to: the illuminance temporal maps (2) (3) explained in detail in section 3.2, and the temporal DGP maps (4) (5) explained in section 3.3. This allows for a general view of the results. In order to see the specific information, each section must be activated, generating a pop-up window.

Secondary Sections (2) (3): Horizontal and Vertical Temporal Illuminance Maps

In the corresponding section, the results obtained from the analysis on the workplane (2) and on the whiteboard (3) are presented, in detail, for each one of the typologies. Figure 6.1-5 shows how the secondary section is presented. The information contained in it is the following:

- *Information of the temporal maps*: the main information in this section is the temporal maps, their scale and the average time in each range (too low, in range and too high). The organization of this section is similar for the Horizontal and Vertical Temporal Illuminance Maps.

- *Complementary Information*: this is complemented with the graph of the average external and average internal illuminance values (of each typology) obtained for each one of the evaluated skies, in each measured moment.

  The external average illuminance graph (E_{av-ext}) allows us to know the available external light and its variations in relation to the different skies.

  The internal average illuminance graph (E_{av}) for the classroom, for the four skies analyzed, allows us to know the average illuminance of the 15 sensors measured inside for each typology, from 8am – 4pm.

- *Information for the predominant sky of each period*: here, the information obtained with the predominant sky of each period is detailed. It is presented in two parts: the first shows a uniformity graph (U), minimum illuminance (E_{min}), maximum (E_{max}) and average illuminance (E_{av}); the second is the light distribution for the predominant sky in the period and hour selected in the temporal maps. In the case of section (2), on the workplane, it shows a spatial model of the typology with a 15-sensor grid measured inside (see Figure 6.1-6). Section (3), on the whiteboard, shows the graph of the illuminance obtained on the whiteboard with the five measuring sensors (see Figure 6.1-7).

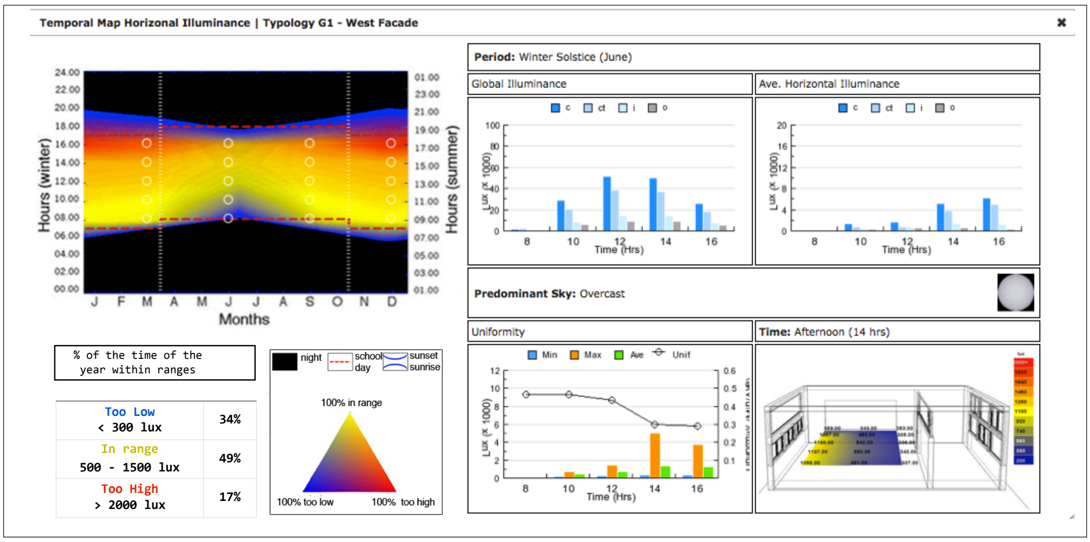


Figure 6.1-5: Section for the Horizontal Temporal Illuminance Map and complementary information.

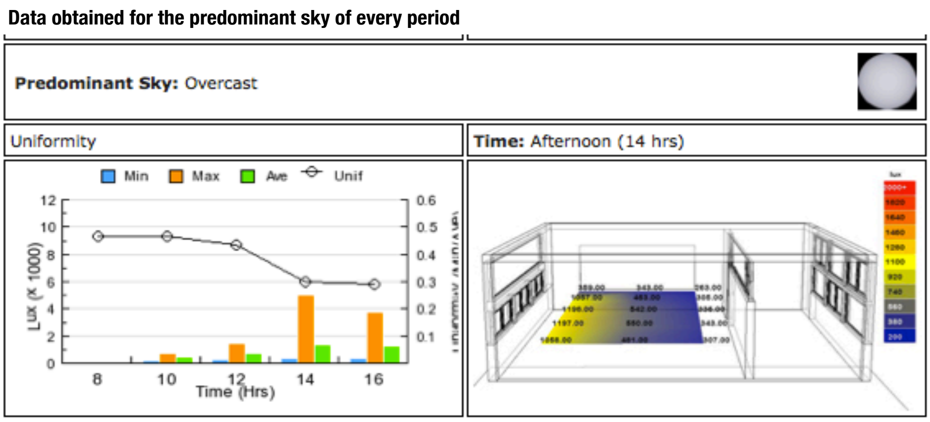


Figure 6.1-6: Information for the predominant sky of each period, on the workplane.

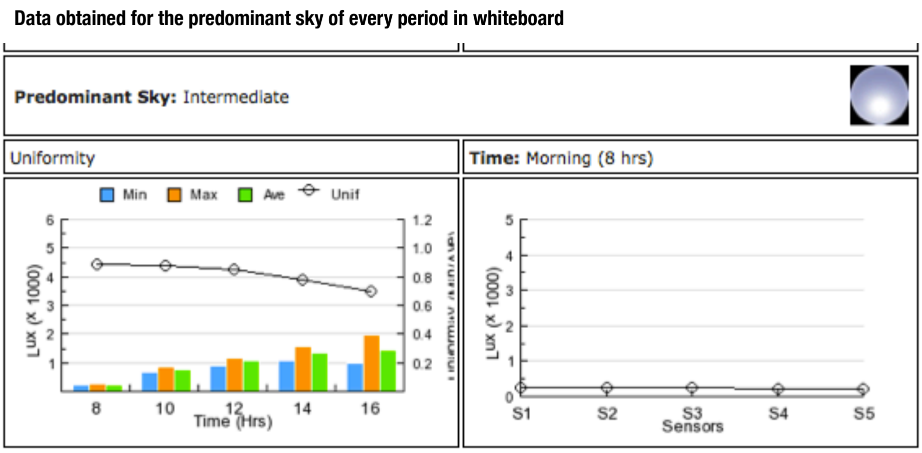


Figure 6.1-7: Information for the predominant sky of each period, on the whiteboard.

Secondary sections (4) (5) Temporal DGP and DGP$_{max}$ maps

The temporal maps of the evaluation of the glare source described in section 3.3 are presented in two separate sections, following the results obtained from the Daylighting Glare Probability: the Temporal DGP maps present the DGP of each weighted sky (see Figure 6.1-8), and the Temporal DGP$_{max}$ maps show the glare probabilities for the most glaring sky (see Figure 6.1-9).

With one click, the 20 moments evaluated in the temporal maps are activated. This allows them to be visualized in the complementary information described below.

This section is complemented by the indication of the observer's position (the view); then, the scene obtained for the predominant sky of each period is presented. Three images are shown: luminance maps of the scene, the glare source image resulting from the glare analysis (evalglare) and, finally, the human vision of the corresponding scene.

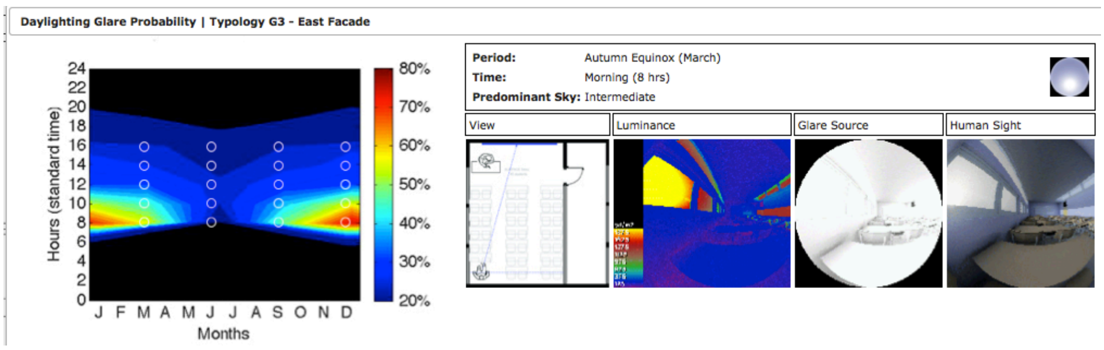


Figure 6.1-8: Section "Temporal DGP maps" and predominant sky information

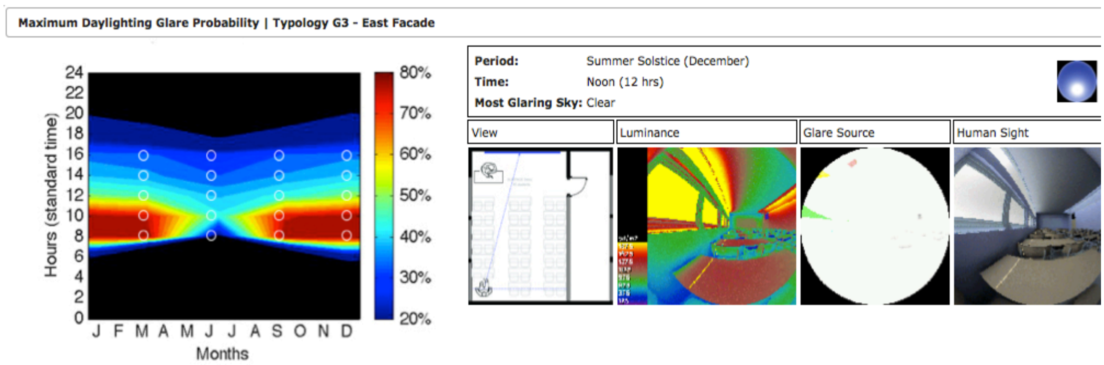


Figure 6.1-9: Section "Temporal DGP maps" and information of most glaring sky.

A preview of the presented platform can be visualized in: http://melolab.org/luminarq/web/. Even though it contains most of the information presented, since it has been loaded temporarily, it may present minor glitches upon its visualization.

The execution of this platform allowed for the reading of the data for the analysis applied in Chapter 4, being able to demonstrate its purpose as a consultation tool. It provides a quick and simple way of visualizing a great amount of information.

7 Conclusions, Discussions and Future Work

7.1 Conclusions and Discussion

The objective stated for the elaboration of this thesis was to define the criteria for daylighting, and their goal values, for classrooms, in order to ensure the visual comfort of the students, which was achieved through the definitions shown in Chapter 3, their application, developed in Chapter 4, and their optimization, generated in Chapter 5. The aforementioned criteria constitute the body of the present thesis.

Four daylighting design criteria were defined and justified for the classrooms. Two of them are based on a dynamic metric, stated based on the weighting of the values obtained. In the generation of the criteria, principles already defined by other authors are integrated, and complemented with the objectives for their verification. For the definition of the targets, two acceptance levels are stated: *adequate,* for all that falls within the expectations and provides good design as a result, where we must consider the presence of negative factors such as the critical area and the critical periods; and *optimal,* for all that provides an environment with high luminous quality, using daylight efficiently in order to reduce the need for artificial lighting. These acceptance levels guide the design, analysis and necessary verifications. With respect to all that mentioned above, we conclude that this methodology may be applied to the design, evaluation and verification of new lighting strategies for other types of buildings, taking into consideration that the targets for each one of the defined criteria should be adapted to the design goals, defining what is adequate and optimal in relation to the activity to be carried out in the building.

In relation to the criteria with their goal values, proposed as *adequate* and *optimal,* and according to that verified in this research, we can say that:

- Although four criteria are defined for the design of classrooms, their verification implies a great amount of time, for which it is necessary to delimit the verification of the criteria, because we conclude that it is possible to achieve good designs for lighting strategies if we focus the verification on two criteria: criterion 1, "*Providing the adequate amount of daylight in the classroom"* and criterion 4, "*Preventing direct sunlight penetration in the classroom"* because, in relation to that exposed in this thesis, upon reaching that defined as optimal for each one of them we will be able to ensure adequate daylight conditions for the development of visual tasks.

- From the proposed daylight strategies and the results obtained we conclude that those classrooms with bilateral daylight strategies, upon obtaining the targets defined as optimal, which is achieving an illuminance "in range" (500 - 1500 lux) > 55% of the time throughout the year we would be ensuring an optimal spatial distribution of the daylight. The aforementioned implies having an area greater than 75% with illuminances rated as "in range" having, as a result, an optimal distribution of daylight and, with this, the achieved uniformity will be in relation to that defined as adequate for criterion (uniformity between 0.5-0.7). As a consequence, a detailed analysis of uniformity will not be necessary. Thus, the following can be stated: with optimal daylighting levels, and an optimal spatial distribution, we can ensure adequate daylighting uniformity in this type of classrooms.

- In relation to the new *Spatial Illuminance distribution maps* developed to evaluate the spatial distribution of the weighted illuminance throughout the year for criterion 1, and according to that mentioned above, referring to the relation between that defined as optimal for them and the adequate uniformity, we can conclude that these spatial distribution maps may be considered as a method to evaluate daylight uniformity throughout the year. Even though for this thesis we elaborated a large number of graphs to characterize uniformity, this makes a quick analysis difficult due to the great amount of data. So, these new maps are able to summarize the daylight distribution into only one image.

- In relation to the verification of criterion 3, it is important to highlight that the DGP evaluation based on dynamic metrics for one typology demands a significant amount of time, and the cost implied in carrying out this study is very high. We conclude that a sunlight penetration study using mid definition RADIANCE parameters would allow for a quick determination of the critical periods for sunlight penetration and, then, we could evaluate the DGP only for the defined critical periods, maintaining as a design goal that defined as adequate and optimal for the criterion that involves glare probabilities.

- In relation to the method used for the evaluation of criterion 4, we conclude that it is necessary to carry out in-depth studies on a method that allows for a clearer visualization of sunlight penetration inside the classroom

- It is important to highlight the relation between criterion 3 and criterion 4, since they are crucial for visual comfort. According to the results obtained with South-facing classrooms, where those typologies without sunlight incidence did not present glare risk, not having sunlight penetration in the visual field reduces considerably the glare probabilities. Therefore, we conclude that having control over direct sunlight incidence will lead to achieving a target defined as adequate or optimal for criterion 4.

In relation to the design of the applied daylighting strategies and their integration to the architectural design, we conclude that:

- The visual comfort of the students will be reached if we achieve a solution, with the daylight strategies, that prevents direct sunlight penetration. Therefore, the design will be a consequence of the application of strategies that achieve a diffuse light inside the classroom without harming the levels and distribution of the light, which must be kept in time and through the different seasons of the year.

- The daylight strategies should consider, in their design, a critical area in relation to that defined for each orientation and consider, for all the cases, a protected area (whiteboard area).

- In relation to lighting distribution and uniformity, those with a double contribution of daylight have been found more efficient. Typology g2 (bi-lateral clerestory window) and Typology g3 (uni-lateral clerestory window), which were the least favorable ones at the beginning, provided optimal results after the sunlight penetration was controlled and regulated, for North and South-facing classrooms.

- In relation to indirect light contribution, the classrooms following Typology g1 (basic window) were the most favorable ones for all orientations. This allows us to conclude that the light contribution from the corridor is favorable to achieve an adequate lighting for the students working in the area farthest from the window.

- In relation to the least advisable recommendation, we conclude that East and West-facing classrooms are the most unfavorable ones due to the limited sunlight control they provide. During the optimization stage we observed that the incorporation of fix sunlight protections may lead to a reduction of the illuminance levels, especially for the critical periods: for the case of East-facing classrooms is the afternoon and for the case of West-facing ones, the morning.

With respect to the methodology used for the comparison of the Typologies, we added a new parameter that allows for an easy evaluation of the differences. These are the average values obtained through Matlab, applied for each type of map, the temporal illuminance maps and the spatial distribution maps. We conclude that these averages, that correspond to the percentage of time and area respectively, provide three quantitative values (in range, too low, too high) that contribute to a better understanding of the results obtained and complement the visual information of the maps.

The issues dealt with in this research and the illuminance requirements demanded by the building standards could be improved with a better daylighting control strategy, incorporating indirect lighting systems that help avoid glare and improve daylighting levels in the classroom. From the method used in this assessment, we can conclude that visualisation of annual daylighting performance allows easy comparison of case studies, be they daylighting design strategies or existing case studies with different orientations and window configurations.

From the studies of the typologies, we state that it is advisable that the current lighting regulations incorporate variables that regulate the design of daylight strategies in the classrooms to achieve a good result for classroom lighting. Currently, the Wall-Floor-Ratio is regulated and the minimum m^2 per student do not consider architectural variables that are linked to aspects directly related to visual comfort. Because of this, we conclude that the regulation systems for classroom design should incorporate the following:

- Foresee in the design and surface of the classroom a critical area, defining the situations where it is necessary to consider some distance between the workplane area and the window, in relation to the presence and type of sunlight control elements used in the daylight strategies.

- Defining the whiteboard area as a protected area, whose objective is to control the incidence of direct incidence of sunlight on this area. The minimum distance between the façade window and the whiteboard wall should be defined.

- Since the most used daylight strategy, and the one with the simplest application, is the “basic” one (unilateral daylight strategy with indirect light contribution), certain daylight contributions should be ensured from the corridor which contribute to achieving a good daylight distribution inside the classroom. For this, the regulation systems or norms should state that, for this daylight strategy, a minimum size for the window leading to the corridor, which should be directly proportional to the width of the corridor.

- With respect to the Chilean norm, as for the lighting of classrooms, the design demands have been limited to requesting a window proportion in relation to the total size of the classroom, the Wall-Floor Ratio. Also, the minimum illuminance levels demanded have been recently increased to 500lux. As demonstrated in this thesis, this WFR ratio does not ensure the adequate levels of lighting because, in most of the studied cases, we obtained too much light, i.e. illuminances “too high” throughout the year. Because of this, we conclude that it is necessary to include more variables that regulate and incorporate the proposed developed criteria, to ensure better lighting conditions for the students.

For the creation of analysis methods, we used specialized simulation method and, from their application, we can conclude that:

- In relation to the illuminance measurements carried out using RADIANCE's "rtrace", we saw that it was possible to reduce the simulation time even more, thus reducing the amount of sensors inside the classroom. For this, we decided to use a 15-measuring-point grid, which still demanded a significant amount of time for its execution. We conclude that the amount of sensors could be adjusted. We recommend always having at least three sensors, transversally placed along the façade window in three parallel lines, on the front (whiteboard area), center (workplane area) and back (facing and opposite from the whiteboard). Even though in order to reduce the time we often reduce the sensitivity of the RADIANCE parameters, we plan not to harm them. Therefore, it is important to maintain the precision of the calculation and delimit the measurement points. Also, this would allow us to study other design option in a quick and efficient way. This simplification would allow us to reduce the time spent obtaining data to then focus on their analysis, verification and checking.

- The use of RADIANCE implies the consideration of a great amount of time for training and to acquire the necessary skills to handle it. Because of the acquired skills, we conclude that it is necessary to have a deep knowledge on UNIX language. This would allow us to reduce the preparation time for the simulation files and data recovery from RADIANCE. The organization of the information was possible thanks to the generation of this database, which allowed us to organize, from this platform, the files necessary for the generation of temporal maps, uniformity graphs and images shown throughout this research.

7.2 Future Work

During the process of the carrying out of the investigation developed in this PhD research, a great number of research fields appeared, which individually make up potential areas for research development.

The future work would imply, on the one hand, to perfect the proposed methodology through the incorporation of criteria that take the energy efficiency as an analysis variable, which allows for the calculation of the energy saving possibilities in artificial lighting throughout the year by using the different daylighting strategies proposed, as well as perfecting the method used in the proposed study of sunlight penetration, as was done in one of the aforementioned criteria

At the same time, this methodology can be applied to other locations to thus contribute to the creation of a local design that considers the dynamic variables of light and the different types of weather, having the possibility of adapting and optimizing the five proposed base typologies to these new variables.

As future work, in relation to the design recommendations and the solutions proposed for the optimization of classrooms, we suggest to study and evaluate other architectural devices that provide results equivalent to those proposed, to then offer a broader spectrum of alternatives for sunlight and glare source control.

In relation to the architectonic contribution for the development of sustainable schools, we propose to explore this new methodology in other kinds of classroom arrangements, more flexible classroom geometries that allow for the incorporation of more dynamic teaching methods. New daylight strategies for other sizes and classroom arrangements would contribute to enriching the study variables and offering a broader variety of applications to architects. In the same way, we propose as future work to complement and enrich that which has been developed here with a study that allows for the definition of daylight strategies for classroom buildings of more than two stories and, also, those that present an arrangement based on a central corridor and classrooms on both sides of it. This type of plant organization is used because it allows for an efficient use of the ground; however, it is very unfavorable for daylight both in the classrooms and in the corridor.

Even though in this study different daylight strategies were incorporated, where the variables were the moments of the year, the types of sky and the orientation, leaving the materials and colors as a fixed parameter for all the classrooms, in a future work we propose the integration of color as a variable of study in the proposed strategies, with the objective of evaluation being the resulting lighting conditions based on the four criteria stated in this thesis.

The future work, in relation to the scientific aspects, should complement and enrich the knowledge generated through a study that incorporates other environmental variables in the classrooms, which are: thermal comfort, acoustic comfort and respiratory comfort. The objective is to look for an architectonic solution for the daylight strategies that integrates these environmental parameters in a way of contributing to the wellbeing of the students and to a sustainable design. It is important to point out that there is a strong relation between the luminous and thermal aspects, given the sunlight incidence in the classroom.

We also propose to carry out a study of the proposed daylight strategies in relation to the cost-benefit, taking into account the main problems that may directly affect the viability of daylight strategies. These matters are: orientation referred to the energy benefits; applied architectonic systems, cost of these systems; the mechanical systems that may be integrated; the electric systems and their control systems and, finally, the acoustic systems integrated to the classroom design.

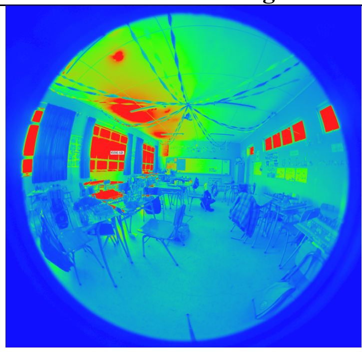
As future work, in terms of the regulations, taking the proposed criteria, related to visual comfort, as a starting point a study should focus on the creation of an ISO (International Standard Organization) regulation, or similar, referring to daylight and, as a complement to the latter, on the aspects related to artificial lighting in classrooms, because in general these only incorporate the aspects related to artificial lighting. The objective of the aforementioned is to integrate the factor here developed, adding new knowledge and contributing with a new tool that allows for the regulation and contribution to an optimal architectonic space for the adequate development of visual tasks.

In relation to the contribution this thesis makes to the country, the future work proposes, starting from the weather files, types of sky and their frequencies (data used in the creation of the methodology) to generate a new luminous zoning for the different areas of Chile, from which a new norm could be generated, which would consider the 4,400 km of length of the country, which goes from latitude 17º 30’ to latitude 56º 30’ South. Currently, the lighting norm for classrooms only refers to three areas: North, Center and South. An assessment of daylighting with climate-based metric would enable target to be drawn up for natural daylighting in schools in Chile, which could in the future be used to develop better illuminance design strategies in order to achieve high quality natural daylighting solutions that minimize glare and maintain a reasonable level of lighting uniformity within the classroom. This is the challenge to be developed.

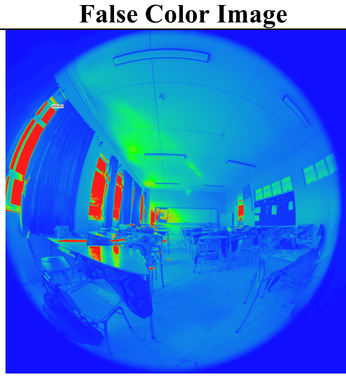
Finally, as future work we leave the strengthening of the database here developed. The available time and resources made it necessary to limit the database to the first simulations carried out. We propose the development of a more consolidated consultation tool, incorporating the optimized typologies and the material that could complement the data in it to contribute to the generation of a consultation tool applicable for the architectonic design.

A.Appendix: Evaluation schools and Preliminary study

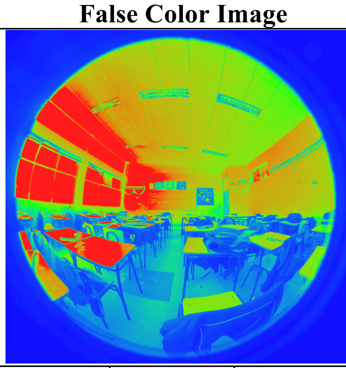
Measures of classrooms with HDR photography

HDR Image_fisheyes	False Color Image	Daylighting Glare Source
		

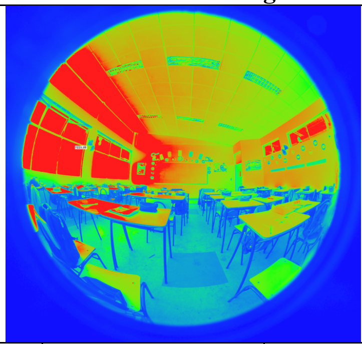
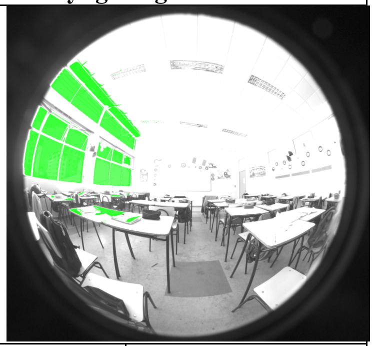
DGP	AV_LUM	E_V	LUM_BACKG	E_V_DIR
31%	79,019538	48,931764	6,15293	29,601764

HDR Image_fisheyes	False Color Image	Daylighting Glare Source
		

DGP	AV_LUM	E_V	LUM_BACKG	E_V_DIR
29%	27,57476	17,070146	2,644018	8,763718

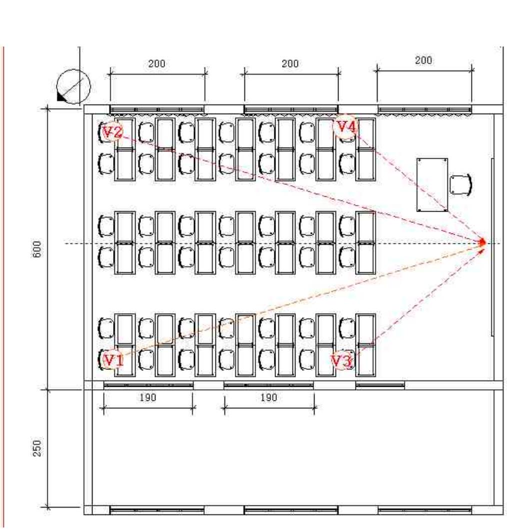
HDR Image_fisheyes	False Color Image	Daylighting Glare Source
		

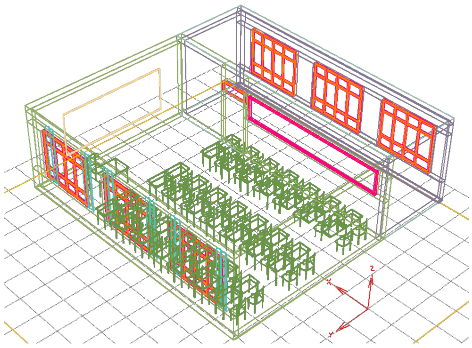
DGP	AV_LUM	E_V	LUM_BACKG	E_V_DIR
28%	131,876795	81,44252	11,844637	44,231495

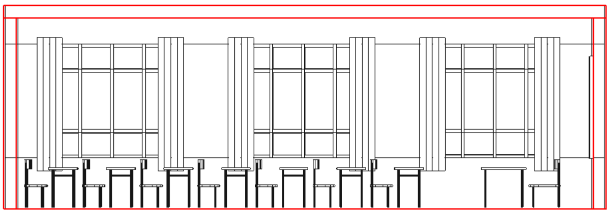
HDR Image_fisheyes	False Color Image	Daylighting Glare Source
		

DGP	AV_LUM	E_V	LUM_BACKG	E_V_DIR
28%	147,374008	91,02881	13,37963	48,995461

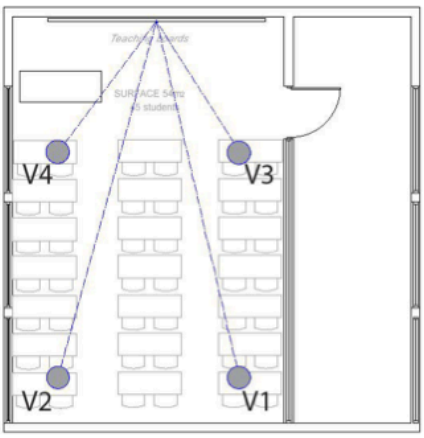
Existing simulation Classrooms

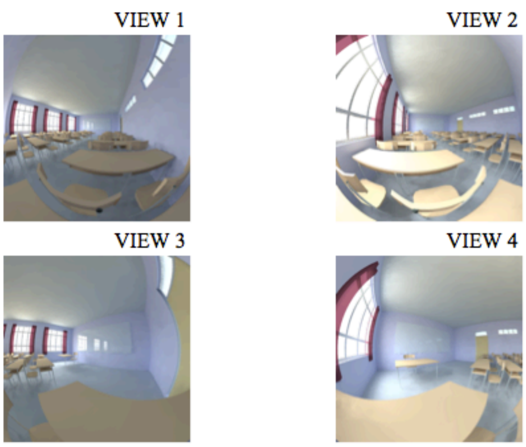


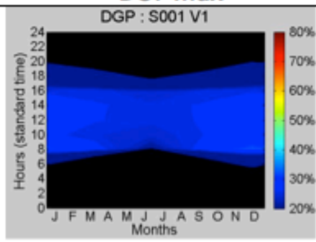
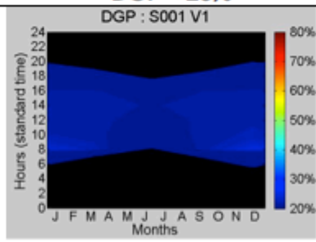
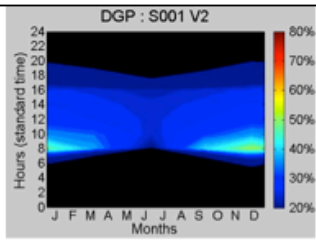
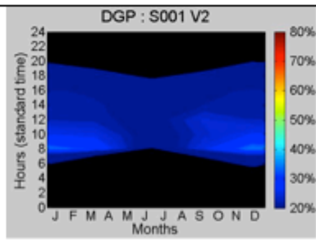
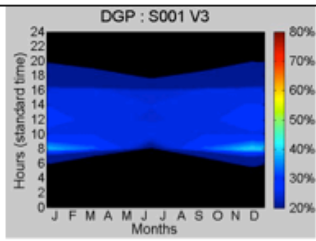
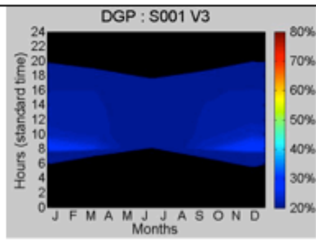
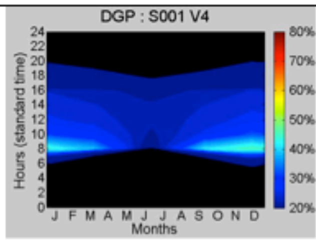
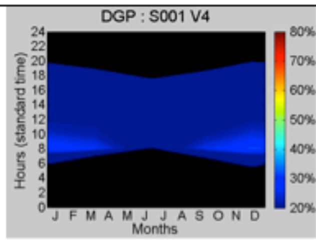




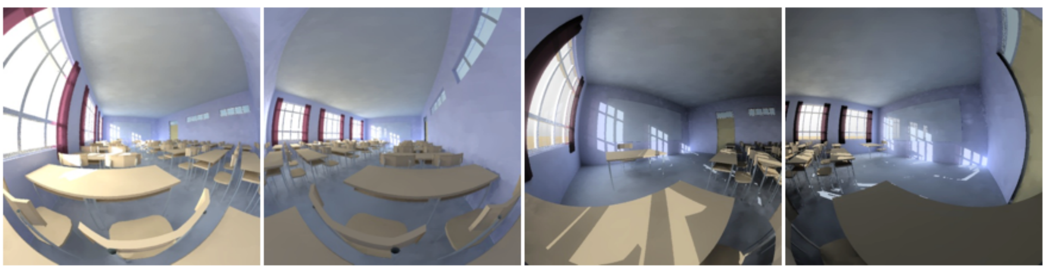
Analysis of Views and DGP





Vue 1	DGP max	DGP < 20%
		
Vue 2		
		
Vue 3		
		
Vue 4		
		

Temporal maps of DGP and DGPmax of Classroom 1



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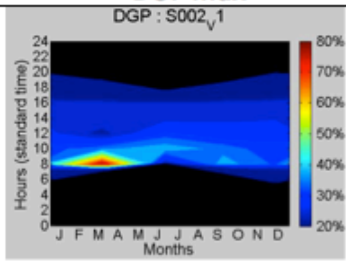
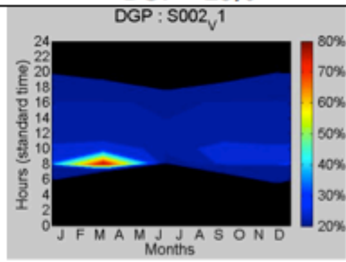
<tr><td></td><td>
</td><td>
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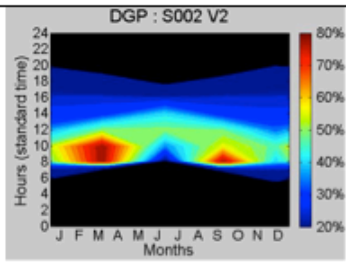
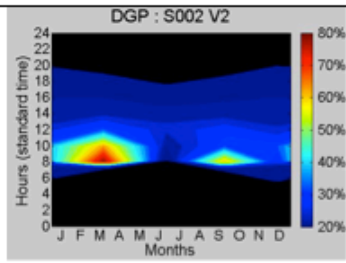
<tr><td></td><td>
</td><td>
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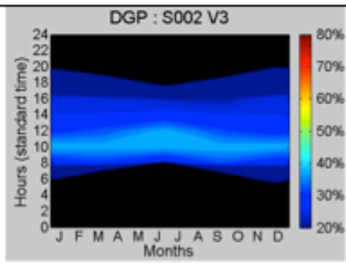
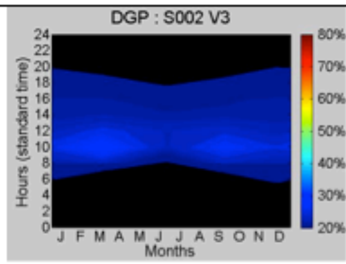
<tr><td></td><td>
</td><td>
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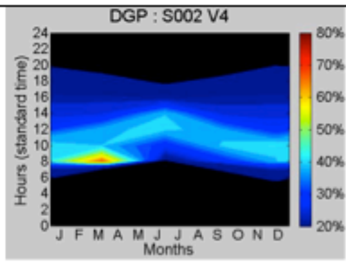
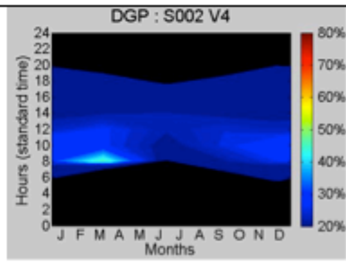
<tr><td>Vue 4</td><td></td><td></td></tr>
<tr><td></td><td>
</td><td>
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</table>

Temporal maps of DGP and DGPmax of Classroom 2

Definition of materiality and color

CATALOGOceresita		Munsell Color			http://www-energie.arch.ucl.ac.be/materi			
		HUE	Value	Chrom	L*	a*	b*	Coef. reflexión
SALA 002 Rene Louvel								
MURO	LRV	H	V	C				
VIOLET PETAL	49	5,7 P	7,3	4,7	73,7	12,1	-13	46,24%
					Cr	Cg	Cb	
					46,9	45	76,7	
Suelo	LRV	H	V	C	L*	a*	b*	Coeff. de réflexion
Gray Pennant	63	7,1Y	8,2	0,2	82,5	-0,4	1,7	61,15%
					Cr	Cg	Cb	
					55,4	64,5	73,5	
Cielo	LRV	H	V	C	L*	a*	b*	Coeff. de réflexion
Impressive Ivory	79%	4,8Y	9,1	1,1	92,1	-1,1	9,07	80,84%
					Cr	Cg	Cb	
					74,8	83,1	82,4	
SALA 001 Rene Louvel								
MURO	LRV	H	V	C	L*	a*	b*	Coeff. de réflexion
Phanton Violet	74%	5,5 P	8,8	2,5	89,1	4,99	-6,2	74,44%
					Cr	Cg	Cb	
					67,9	74,4	102	
Suelo	LRV	H	V	C	L*	a*	b*	Coeff. de réflexion
Gray Pennant	63%	7,1Y	8,2	0,2	82,5	-0,4	1,7	61,15%
					Cr	Cg	Cb	
					55,4	64,5	73,5	
Cielo	LRV	H	V	C	L*	a*	b*	Coeff. de réflexion
Impressive Ivory	79%	4,8Y	9,1	1,1	92,1	-1,1	9,07	80,84%
					Cr	Cg	Cb	
					74,8	83,1	82,4	
ACCESORIOS								
Escritorios	LRV	H	V	C	L*	a*	b*	Coeff. de réflexion
Highland Buff		9,7YR	8	4,5	80,6	6,8	27,5	57,70%
					Cr	Cg	Cb	
					69,9	56,9	37,4	
Pizzarra	LRV	H	V	C	L*	a*	b*	Coeff. de réflexion
Rain Shimmer	83%	7,3PB	9,2	-1,6	92,1	0,12	-1,6	80,97
					Cr	Cg	Cb	
					70,3	83,3	101	
Cortinas	LRV	H	V	C	L*	a*	b*	Coeff. de réflexion
Rich Burgundy	9%	0,9R	3,4	5,7	34,9	27,6	4,07	8,47
					Cr	Cg	Cb	
					17	5,04	8,98	
PASILLO	LRV	H	V	C	L*	a*	b*	Coeff. de réflexion
Floral White	87%	3,5Y	9,4	0,7	95	-0,5	5,78	87,64
					Cr	Cg	Cb	
					79,8	90	95,6	
Puertas	LRV	H	V	C	L*	a*	b*	Coeff. de réflexion
Sahara Gold	67%	2,2Y	8,6	4,9	87,2	1,17	34,5	70,37
					Cr	Cg	Cb	
					79	70	38,7	

Definition Radiance parameters for the color of the classes

													coordonnées RADIANCE										C
	L*	a*	b*	(Y/Yn)^1/3	Y/Yn	(X/Xn)^1/3	X/Xn	(Z/Zn)^1/3	Z/Zn	**X**	**Y**	**Z**	Cr	Cg	Cb	x	y	z	Brightne	R	G	B	
Aula 1 Muro	73,7	12,05	-13,48	0,77	0,46	0,80	0,51	0,84	0,59	**51,11**	**47,54**	**72,12**	46,91	44,97	76,74	0,30	0,28	0,42	47,55	119,63	114,68	195,68	
Aula 1 Suelo	82,46	-0,39	1,7	0,85	0,61	0,85	0,61	0,84	0,59	**61,31**	**62,71**	**71,94**	55,45	64,55	73,47	0,31	0,32	0,37	62,71	141,39	164,59	187,35	
Aula 1 Cielo	92,06	-1,11	9,07	0,93	0,81	0,93	0,80	0,89	0,70	**78,72**	**80,84**	**82,29**	74,83	83,07	82,39	0,33	0,33	0,34	80,84	190,80	211,83	210,09	
Aula 2 Muro	89,13	4,99	-6,22	0,91	0,74	0,92	0,77	0,94	0,82	**75,44**	**74,44**	**97,38**	67,87	74,43	101,52	0,31	0,30	0,39	74,45	173,08	189,79	258,86	
Aula 2 cielo	72,9	-0,02	2,76	0,77	0,45	0,77	0,45	0,75	0,43	**78,72**	**80,84**	**82,29**	74,83	83,07	82,39	0,33	0,33	0,34	80,84	190,80	211,83	210,09	
Escritorios	54,6	0,11	1,04	0,61	0,23	0,61	0,23	0,60	0,22	**60,44**	**59,10**	**40,60**	69,90	56,92	37,43	0,38	0,37	0,25	59,09	178,25	145,14	95,44	
Pizzarra	73,03	-0,17	2,72	0,77	0,45	0,77	0,45	0,75	0,43	**79,45**	**80,97**	**98,04**	70,28	83,27	100,95	0,31	0,31	0,38	80,98	179,21	212,35	257,42	
Cortinas	68,43	-0,56	3,21	0,73	0,39	0,73	0,38	0,71	0,36	**11,84**	**8,47**	**8,69**	17,03	5,04	8,98	0,41	0,29	0,30	8,47	43,42	12,84	22,90	
Pasillo	92,85	-1,28	2,95	0,94	0,83	0,94	0,82	0,92	0,79	**85,67**	**87,65**	**94,52**	79,84	89,98	95,59	0,32	0,33	0,35	87,65	203,58	229,44	243,75	
Puertas	76,56	-0,47	1,38	0,80	0,51	0,80	0,51	0,79	0,49	**69,56**	**70,37**	**43,53**	78,97	70,02	38,72	0,38	0,38	0,24	70,36	201,39	178,54	98,73	

B. Appendix: Definition Radiance Parameters

Radiance parameters

```
C1    rtrace -ab 2 -av 0.01 0.01 0.01 -dp 4096 -ad 1024-as 512
-ar 70 -ms 0.085  -ds 0.2 -dt 0.05 -dc 0.75 -dr 3 -sj 1 -st
0.1 -aa 0.08 -lr 12 -lw .005 -I+ -h config1.oct <grilla2.pts
|rcalc -e '$1=179*($1*0.265+$2*0.67+$3*0.065)' >ill3_21_8o.dat
```

```
C2    rtrace -ab 3 -av 0.01 0.01 0.01 -dp 4096 -ad 1024-as 512
-ar 70 -ms 0.085  -ds 0.2 -dt 0.05 -dc 0.75 -dr 3 -sj 1 -st
0.1 -aa 0.08 -lr 12 -lw .005 -I+ -h config1.oct <grilla2.pts
|rcalc -e '$1=179*($1*0.265+$2*0.67+$3*0.065)' >ill3_21_8o.dat
```

```
C3    rtrace -ab 4 -av 0.01 0.01 0.01 -dp 4096 -ad 1024-as 512
-ar 70 -ms 0.085  -ds 0.2 -dt 0.05 -dc 0.75 -dr 3 -sj 1 -st
0.1 -aa 0.08 -lr 12 -lw .005 -I+ -h config1.oct <grilla2.pts
|rcalc -e '$1=179*($1*0.265+$2*0.67+$3*0.065)' >ill3_21_8o.dat
```

```
C4    rtrace -ab 4 -av 0.01 0.01 0.01 -dp 4096 -ad 2048-as
1024 -ar 70 -ms 0.085  -ds 0.2 -dt 0.05 -dc 0.75 -dr 3 -sj 1 -
st 0.1 -aa 0.08 -lr 12 -lw .005 -I+ -h config1.oct
<grilla2.pts |rcalc -e '$1=179*($1*0.265+$2*0.67+$3*0.065)'
>ill3_21_8o.dat
```

```
C5    rtrace -ab 5 -av 0.01 0.01 0.01 -dp 4096 -ad 2048-as
1024 -ar 70 -ms 0.085  -ds 0.2 -dt 0.05 -dc 0.75 -dr 3 -sj 1 -
st 0.1 -aa 0.08 -lr 12 -lw .005 -I+ -h config1.oct
<grilla2.pts |rcalc -e '$1=179*($1*0.265+$2*0.67+$3*0.065)'
>ill3_21_8o.dat
```

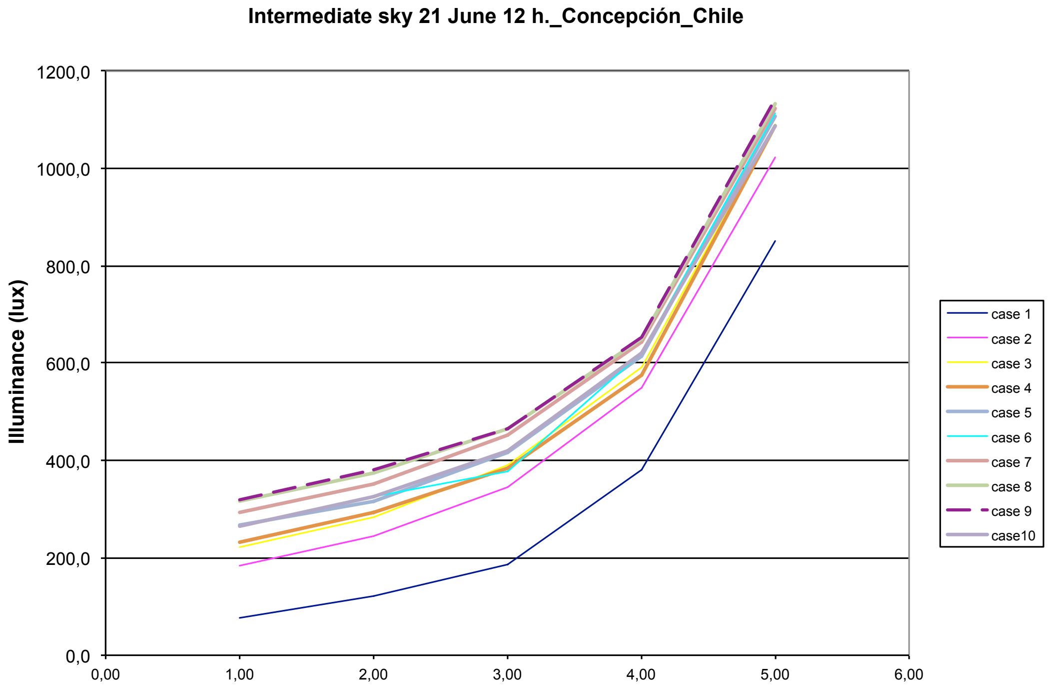
```
C6    rtrace -ab 5 -av 0.01 0.01 0.01 -dp 4096 -ad 2048 -as
1024 -ar 160 -ms 0.085  -ds 0.2 -dt 0.05 -dc 0.75 -dr 3 -sj 1
-st 0.1 -aa 0.08 -lr 12 -lw .005 -I+ -h config1.oct
<grilla2.pts |rcalc -e '$1=179*($1*0.265+$2*0.67+$3*0.065)'
>ill3_21_8o.dat
```

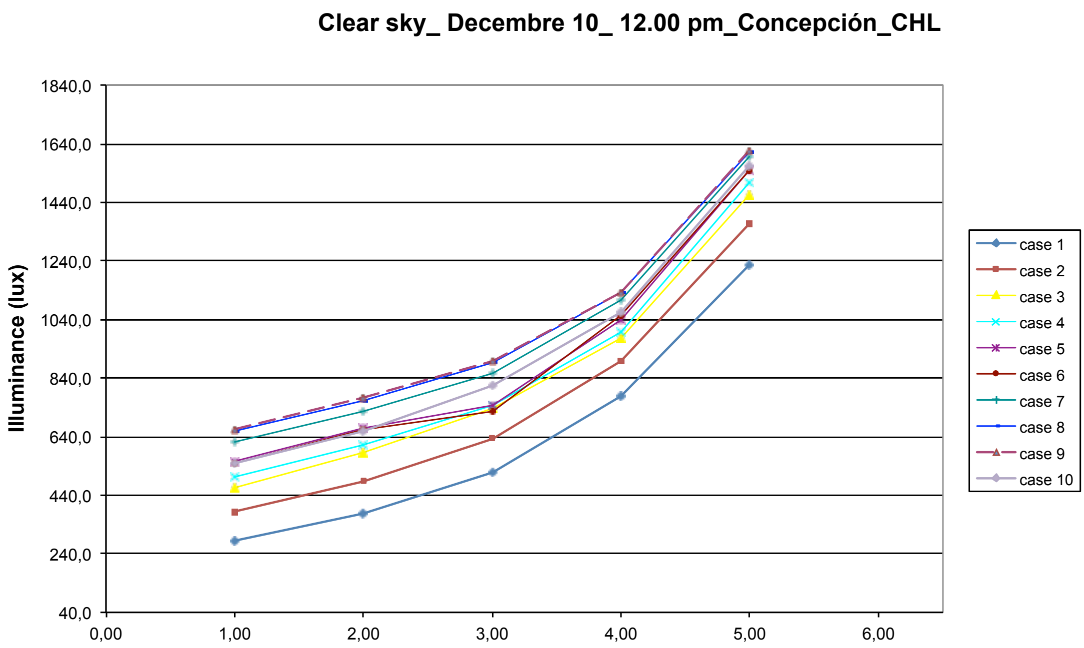
```
C7    rtrace -ab 6 -av 0.01 0.01 0.01 -dp 4096 -ad 4096 -as
2048 -ar 160 -ms 0.085  -ds 0.2 -dt 0.05 -dc 0.75 -dr 3 -sj 1
-st 0.1 -aa 0.08 -lr 12 -lw .005 -I+ -h config1.oct
<grilla2.pts |rcalc -e '$1=179*($1*0.265+$2*0.67+$3*0.065)'
>ill3_21_8o.dat
```

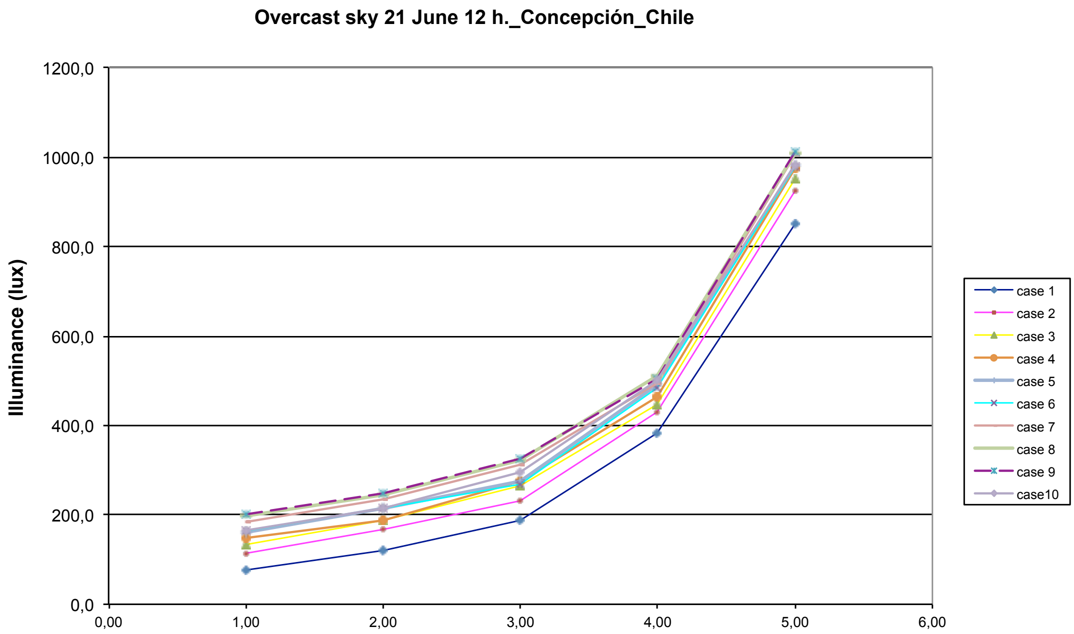
```
C8    rtrace -ab 7 -av 0.01 0.01 0.01 -dp 4096 -ad 8192 -as
4096 -ar 160 -ms 0.085  -ds 0.2 -dt 0.05 -dc 0.75 -dr 3 -sj 1
-st 0.1 -aa 0.08 -lr 12 -lw .005 -I+ -h config1.oct
<grilla2.pts |rcalc -e '$1=179*($1*0.265+$2*0.67+$3*0.065)'
>ill3_21_8o.dat
```

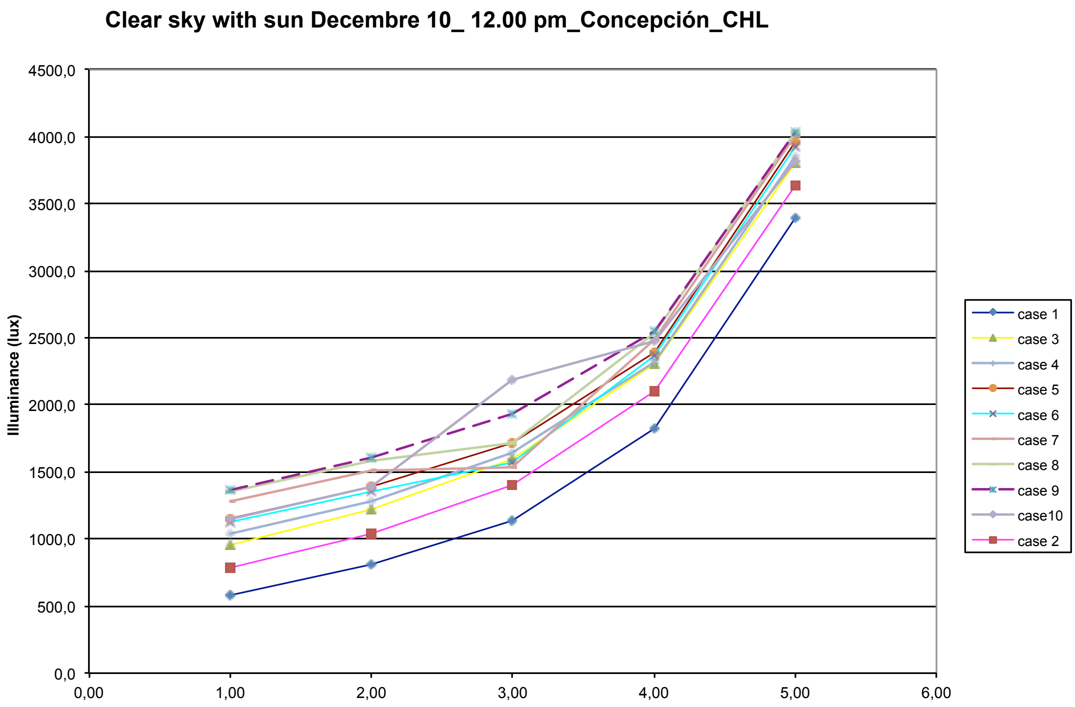
```
C9    rtrace -ab 8 -av 0.01 0.01 0.01 -dp 4096 -ad 8192 -as
4096 -ar 160 -ms 0.085  -ds 0.2 -dt 0.05 -dc 0.75 -dr 3 -sj 1
-st 0.1 -aa 0.08 -lr 12 -lw .005 -I+ -h config1.oct
<grilla2.pts |rcalc -e '$1=179*($1*0.265+$2*0.67+$3*0.065)'
>ill3_21_8o.dat
```

```
C10 (AULA) rtrace -ab 7 -av 0 0 0 -dp 2048 -ad 1024 -as 512 -
ar 256 -dt 0.1 -dc 0.5 -dr 1 -sj 0.7 -st 0.1 -aa 0.08 -lr 8 -
lw .001 -I+ -h config37.oct <grilla3.pts |rcalc -e
'$1=179*($1*0.265+$2*0.67+$3*0.065)' >ill6_21_16o.dat
```






Overcast sky 21 June 12 h._Concepción_Chile
Illuminance (lux)
1200,0
1000,0
800,0
600,0
400,0
200,0
0,0
0,00
1,00
2,00
3,00
4,00
5,00
6,00
case 1
case 2
case 3
case 4
case 5
case 6
case 7
case 8
case 9
case10


Clear sky with sun Decembre 10_ 12.00 pm_Concepción_CHL
Illuminance (lux)
4500,0
4000,0
3500,0
3000,0
2500,0
2000,0
1500,0
1000,0
500,0
0,0
0,00
1,00
2,00
3,00
4,00
5,00
6,00
case 1
case 3
case 4
case 5
case 6
case 7
case 8
case 9
case10
case 2

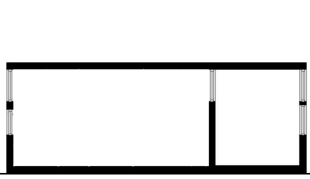
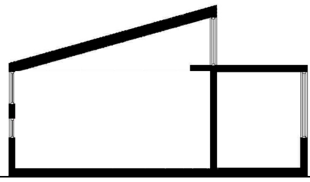
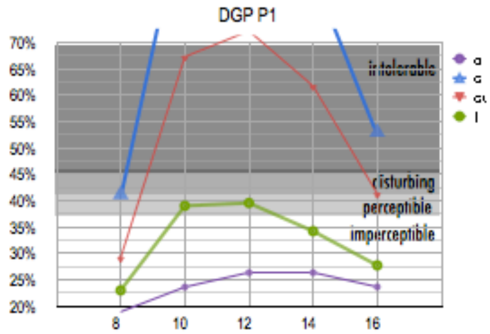
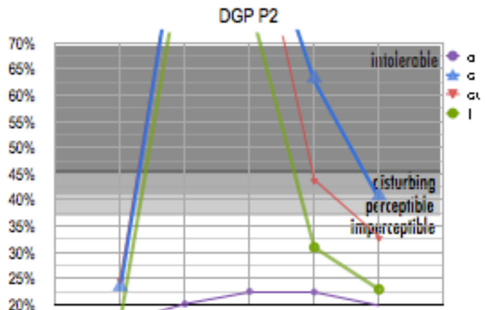
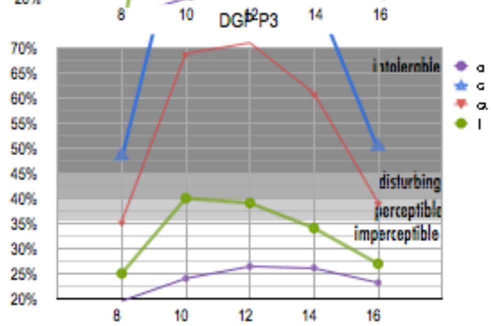
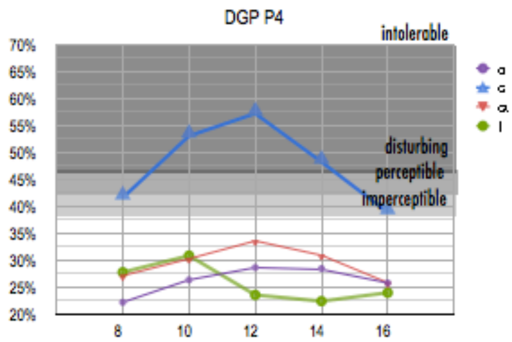
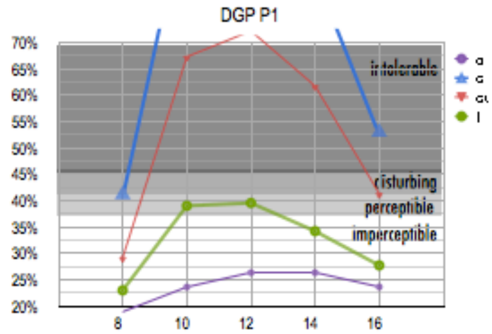
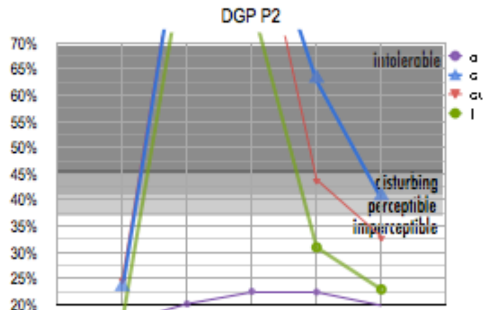
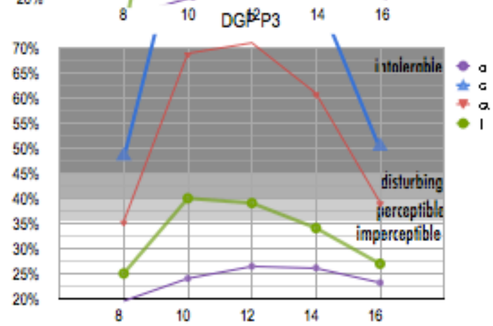
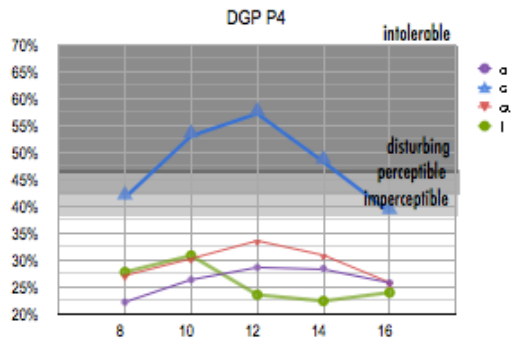
The *Root-Mean-Square Error (RMSE)* And The Relative Mean Bias Error (MBE).

base case_AULA S00	case1		case 2		case 3		case4		case5		case6		case7		case8		case 10	
	rRMSE	rMBE	rRMSE	rMBE	rRMSE	rMBE	rRMSE	rMBE	rRMSE	rMBE	rRMSE	rMBE	rRMSE	rMBE	rRMSE	rMBE	rRMSE	rMBE
overcast sky	743%	-42%	479%	-27%	345%	-20%	283%	-16%	185%	-10%	189%	-11%	85%	-5%	17%	-1%	185%	-10%
clear sky without sun	1.310%	-45%	906%	-31%	605%	-20%	502%	-17%	336%	-11%	340%	-11%	136%	-5%	21%	-1%	322%	-11%
clear sky with sun	1.830%	-43%	1.226%	-28%	830%	-19%	689%	-16%	443%	-10%	462%	-11%	191%	-4%	39%	-1%	459%	-10%
intermediate sky	923%	-44%	614%	-29%	437%	-20%	360%	-17%	236%	-11%	245%	-11%	106%	-5%	17%	-1%	243%	-11%

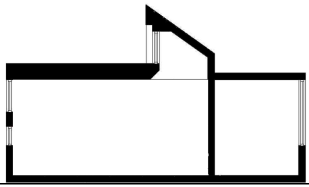
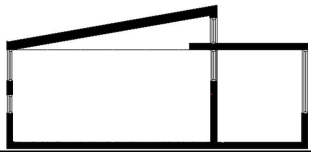
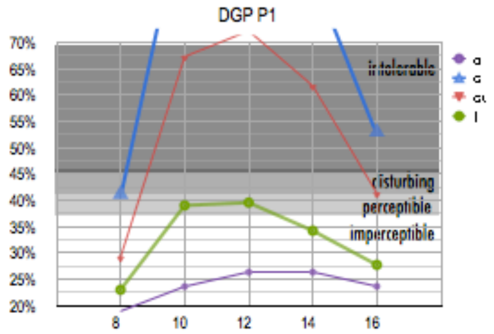
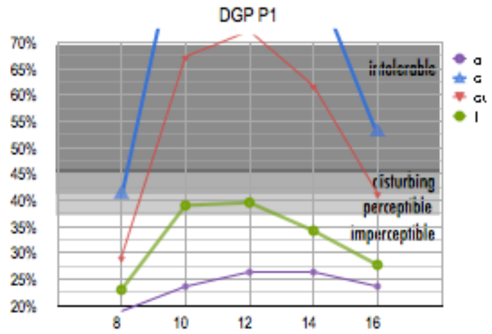
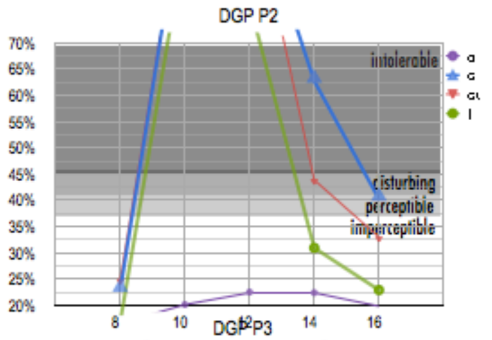
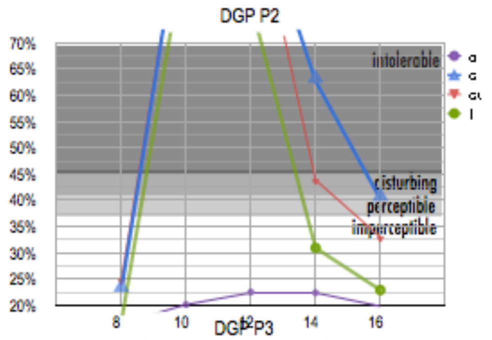
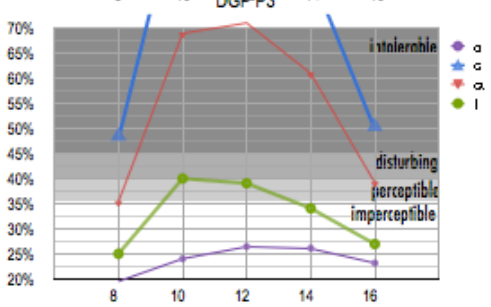
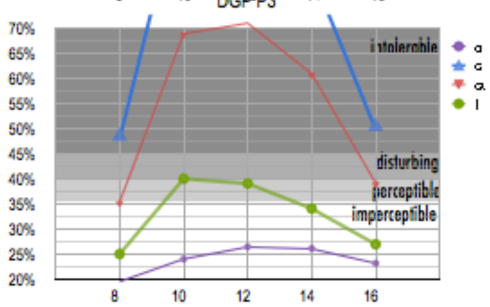
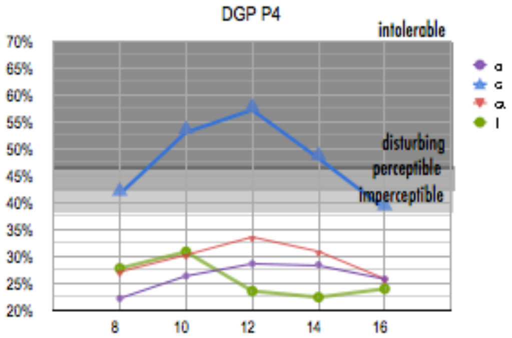
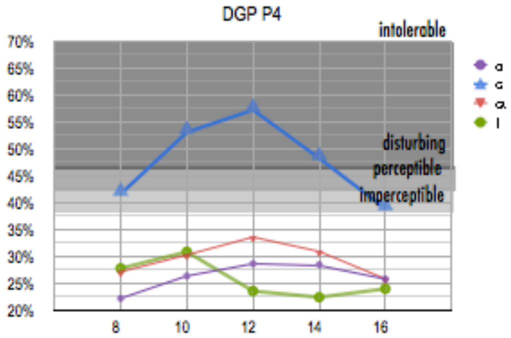
base case_AULA S00	case1		case2		case3		case4		case 5		case 6		case 7		case 8		case 10	
	RMSE (lux)	MBE (lux)	RMSE (lux)	MBE (lux)	RMSE (lux)	MBE (lux)	RMSE (lux)	MBE (lux)	RMSE (lux)	MBE (lux)	RMSE (lux)	MBE (lux)	RMSE (lux)	MBE (lux)	RMSE (lux)	MBE (lux)	RMSE (lux)	MBE (lux)
overcast sky	133,83	-133,28	82,73	-81,54	58,11	-57,00	47,71	-47,10	30,86	-29,67	31,66	-30,39	13,93	-13,13	3,18	-2,18	31,08	-28,79
clear sky without sun	383,81	-383,46	261,46	-260,51	173,31	-172,04	144,00	-143,15	95,65	-94,49	96,47	-95,14	38,29	-37,10	6,27	-5,67	90,81	-88,45
clear sky with sun	782,74	-781,74	511,07	-506,29	339,01	-329,28	283,75	-279,22	180,11	-173,50	189,10	-183,92	77,93	-72,75	16,42	-14,17	187,21	-175,49
intermediate sky	196,00	-195,67	127,99	-127,50	90,08	-88,98	73,78	-72,99	48,53	-47,40	49,60	-48,25	21,56	-20,85	3,77	-2,95	51,21	-49,90

C. Appendix: DGP graphs

NORTH FACING CLASSROOM DGP GRAPHS

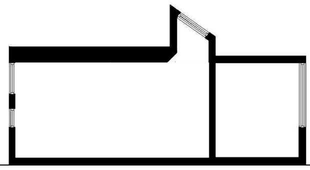
Typology g1 *"basic window"*	Typology g2 *"bi-lateral clerestory window*
	
   	   

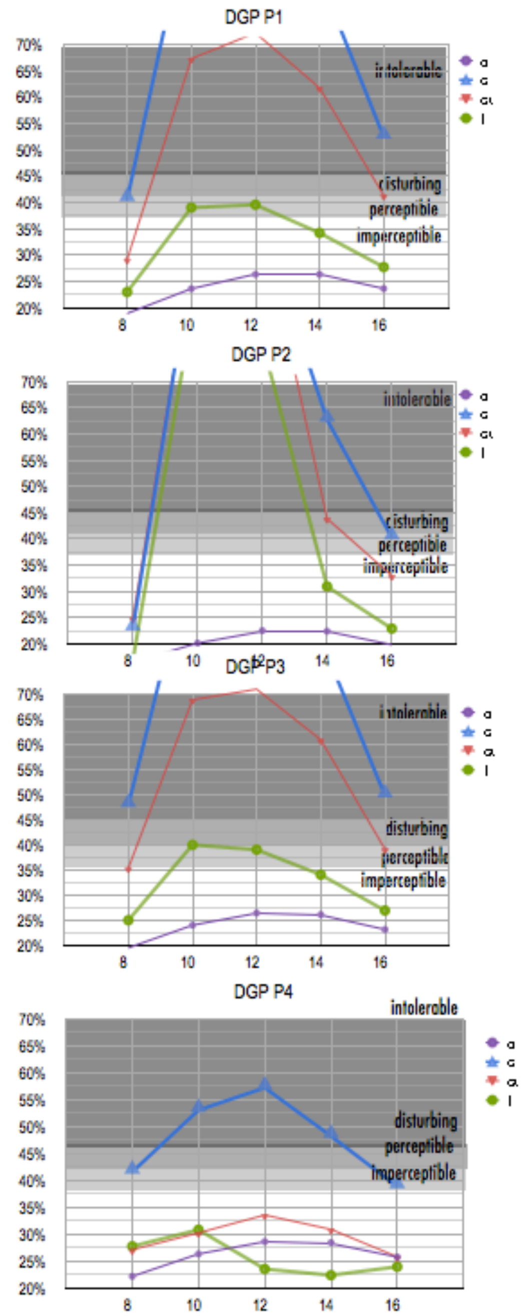
NORTH FACING CLASSROOM DGP GRAPHS

Typology g3 ***“unilateral clerestory window***	Typology g4 ***“bi-lateral clerestory window with corridor daylight”***
	
	
	
	
	

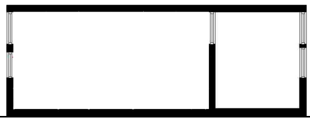
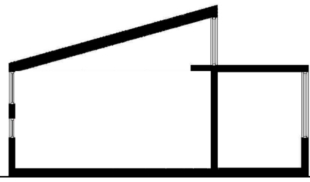
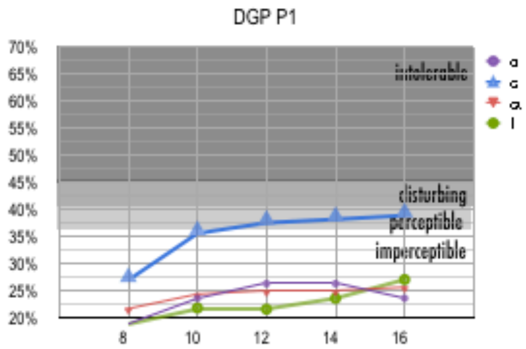
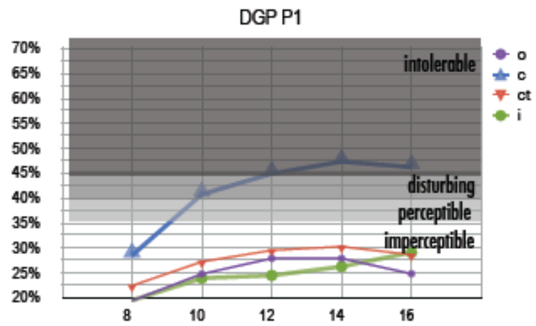
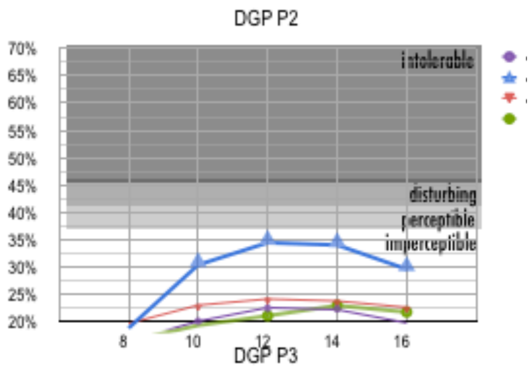
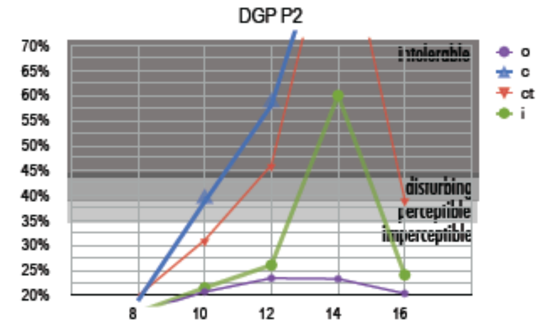
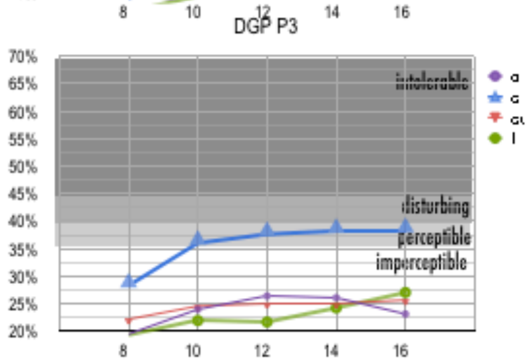
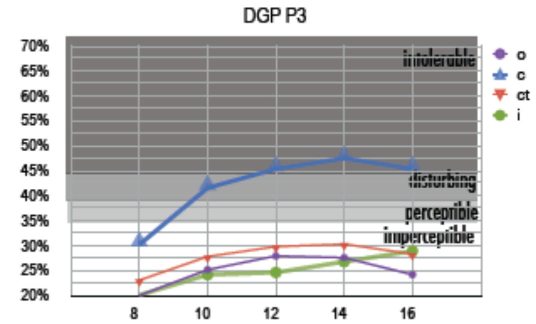
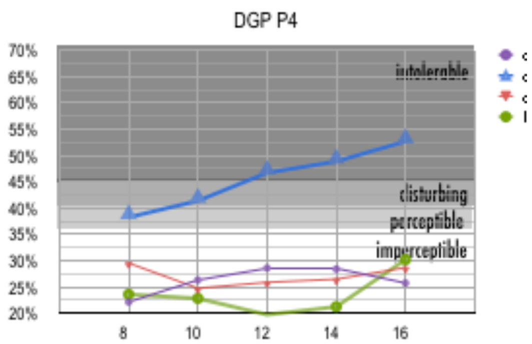
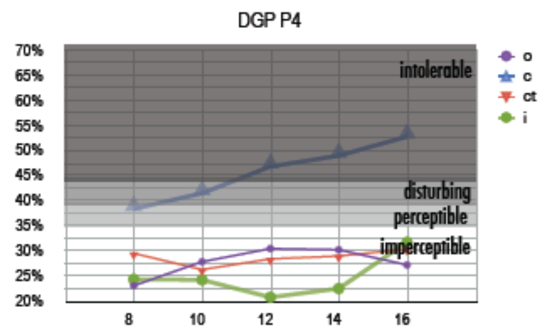
NORTH FACING CLASSROOM DGP GRAPHS

Typology g5
"skylight window"

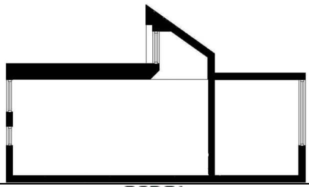
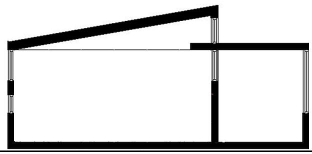
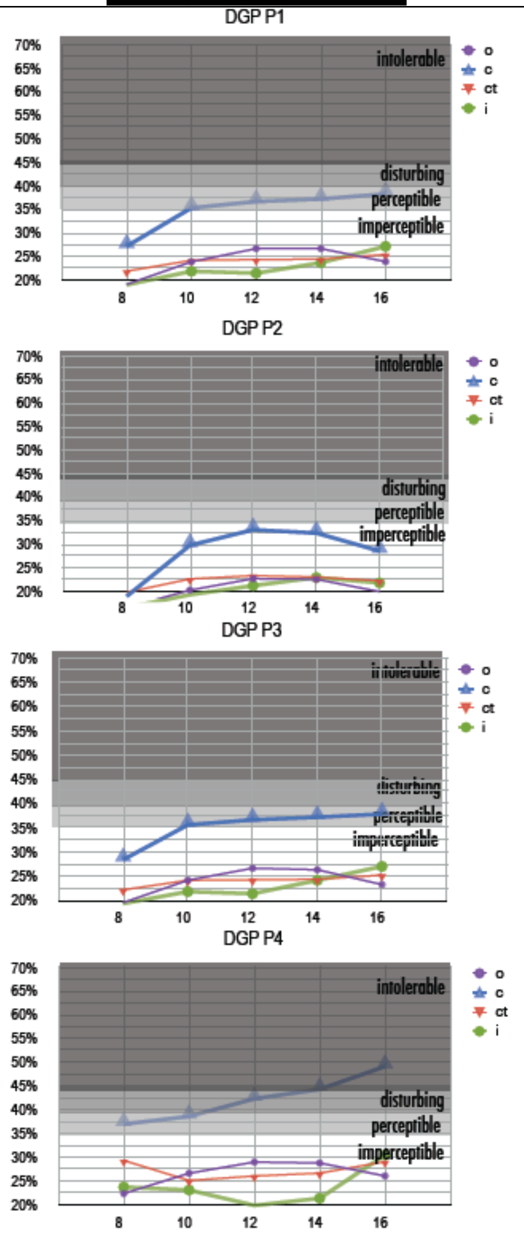
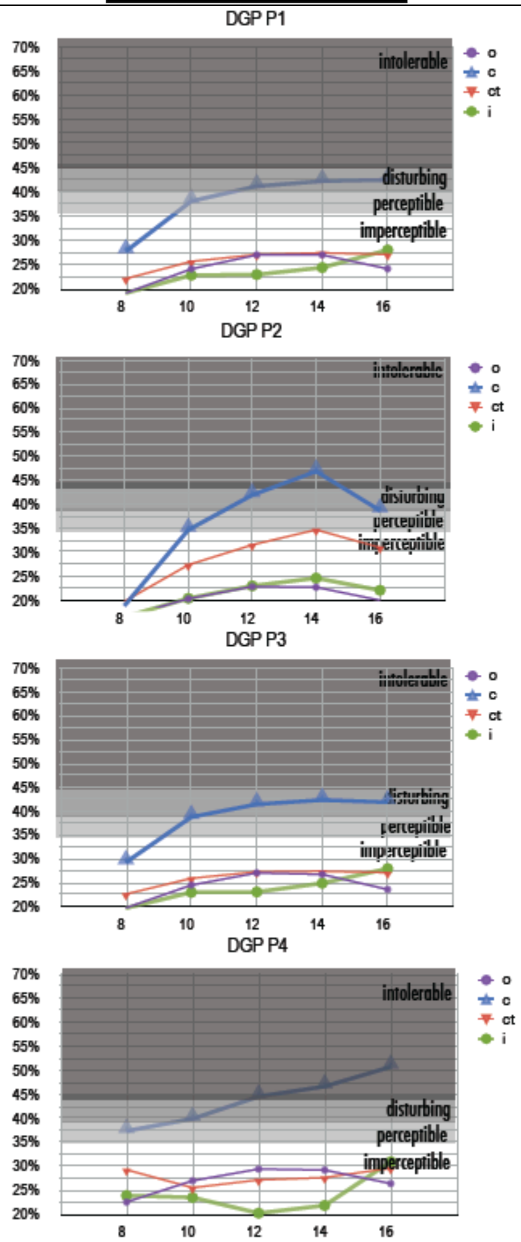




SOUTH FACING CLASSROOM DGP GRAPHS

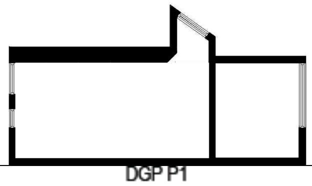
Typology g1 ***"basic window"***	Typology g2 ***"bi-lateral clerestory window***
	
	
	
	
	

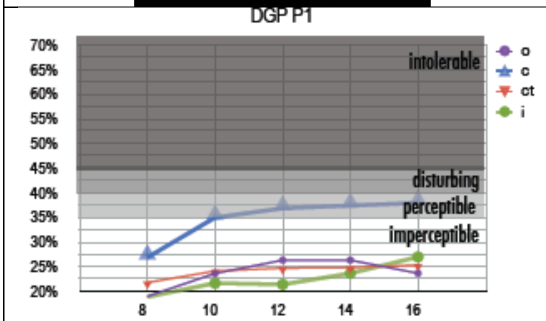
SOUTH FACING CLASSROOM DGP GRAPHS

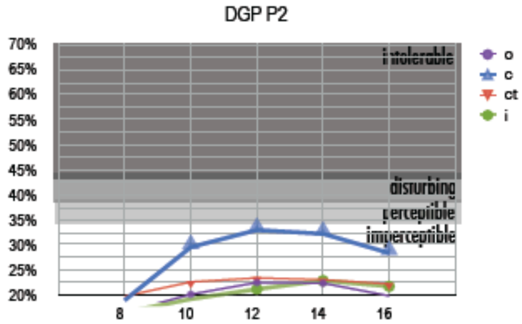
Typology g3 ***“unilateral clerestory window***	Typology g4 ***“bi-lateral clerestory window with corridor daylight”***
	
	

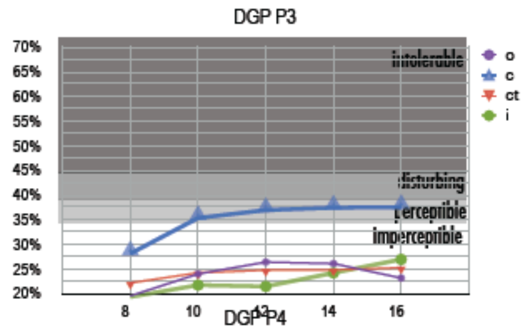
SOUTH FACING CLASSROOM DGP GRAPHS

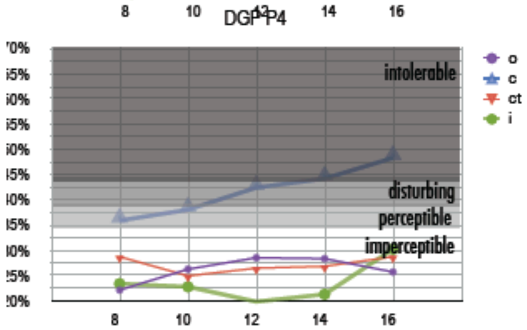
Typology g5
“skylight window”



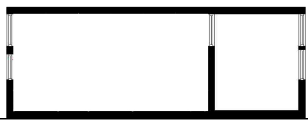
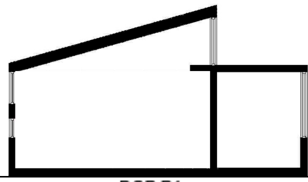
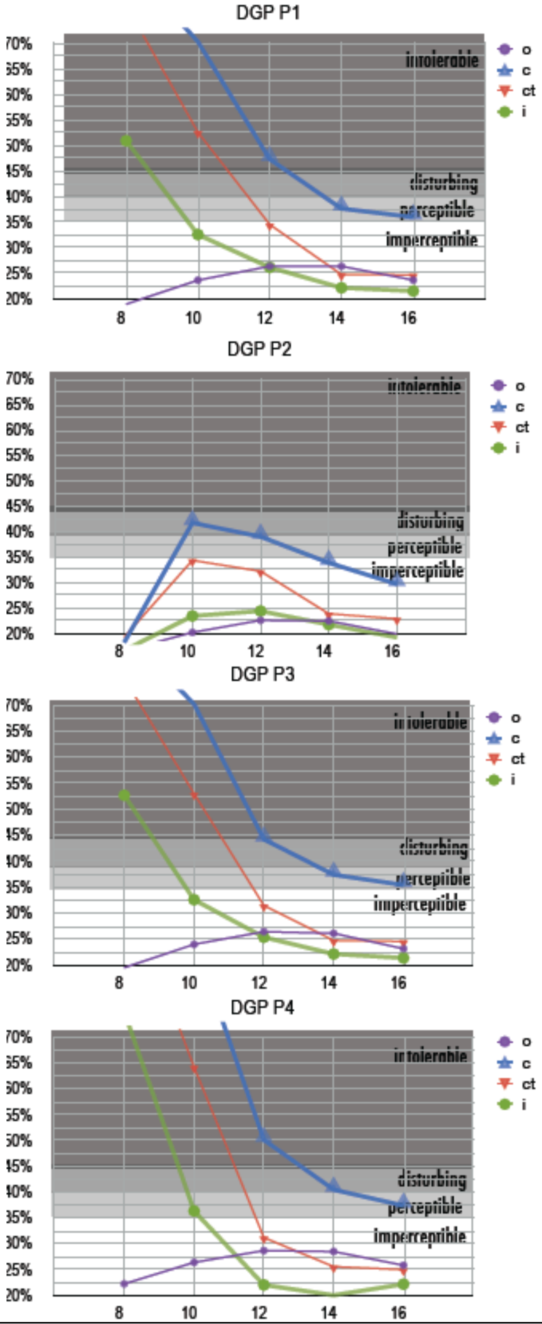
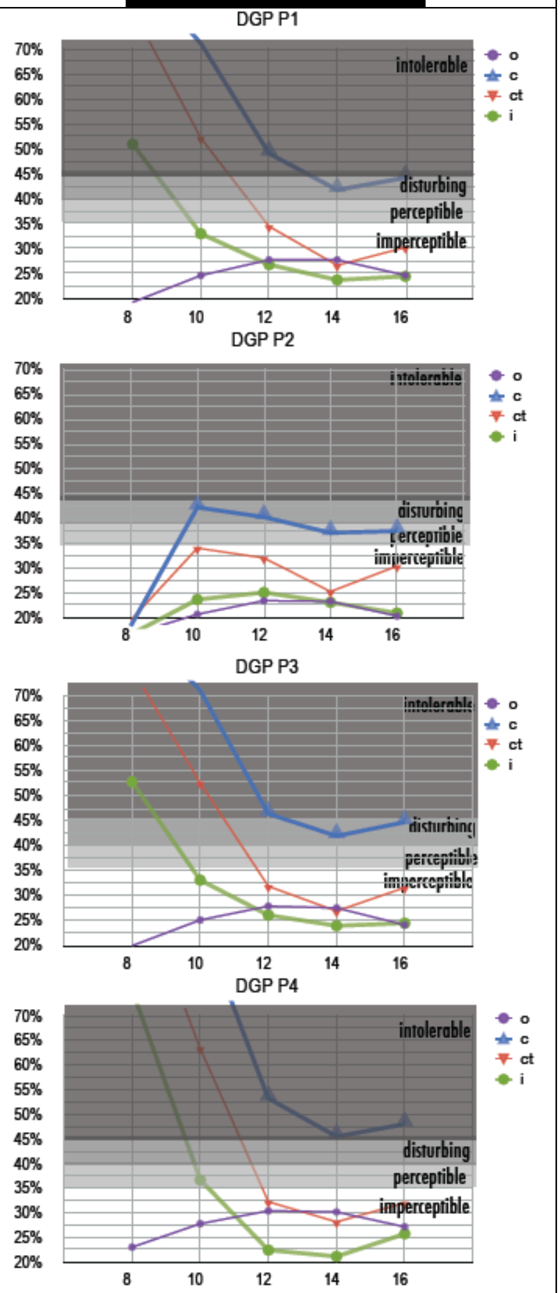








EAST-FACING CLASSROOM DGP GRAPHS

Typology g1 ***"basic window"***	Typology g2 ***"bi-lateral clerestory window"***
	
	

EAST-FACING CLASSROOM DGP GRAPHS

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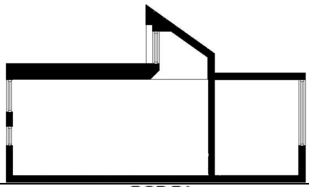
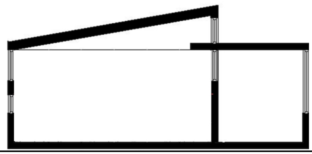
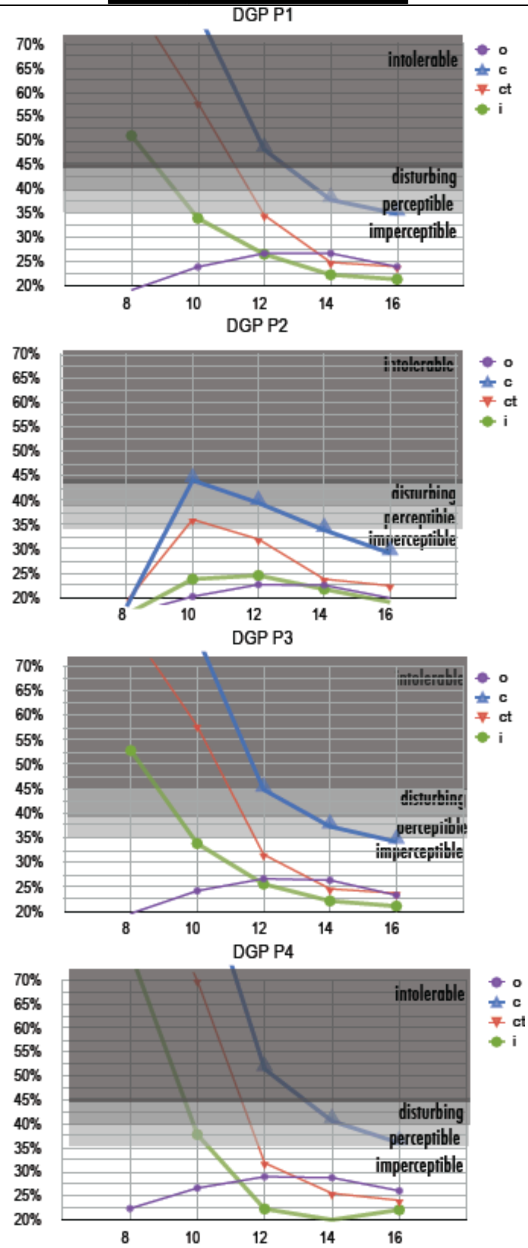
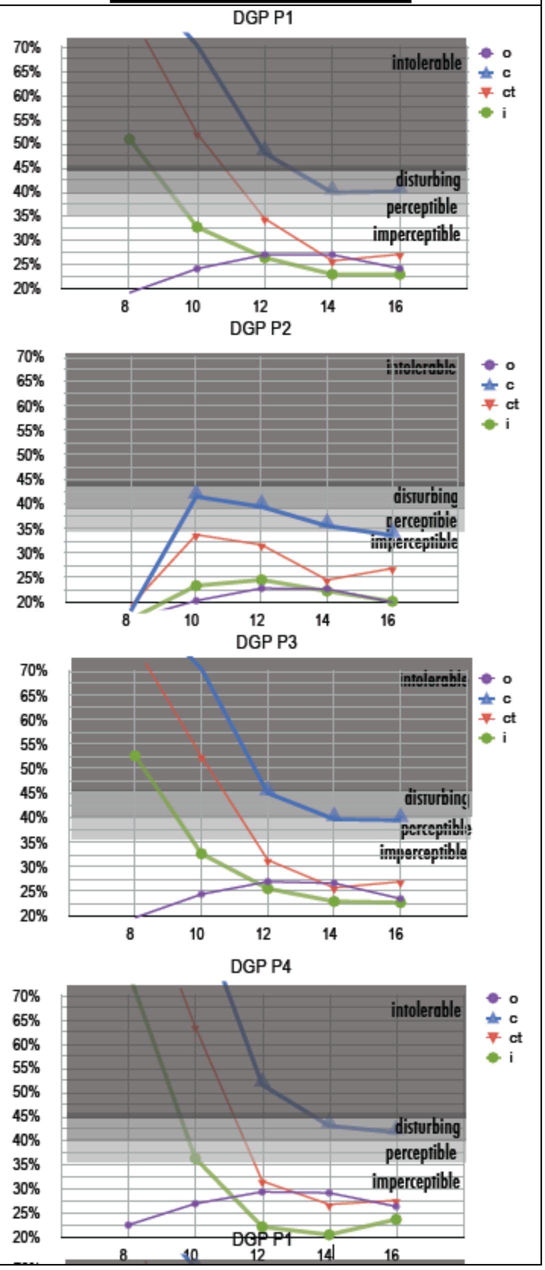
“bi-lateral clerestory window with corridor daylight”</td></tr>
<tr><td></td><td></td></tr>
<tr><td>
</td><td>
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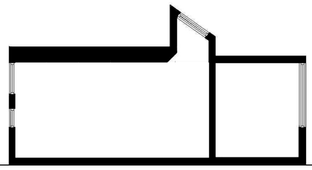
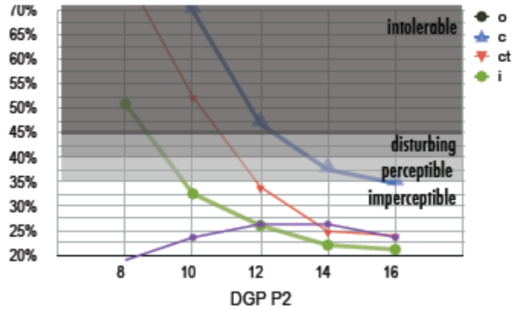
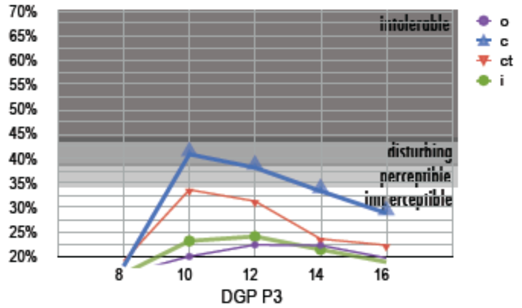
EAST-FACING CLASSROOM DGP GRAPHS

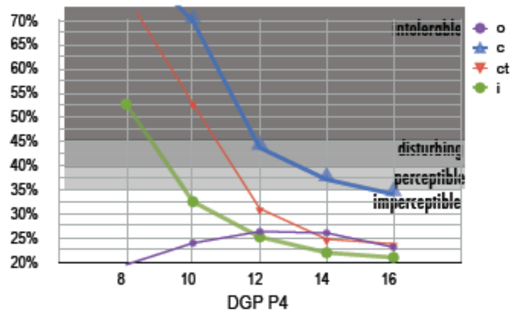
Typology g5

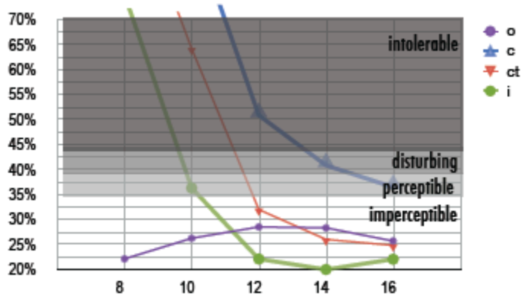
"skylight window"











WEST-FACING CLASSROOM

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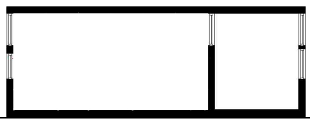
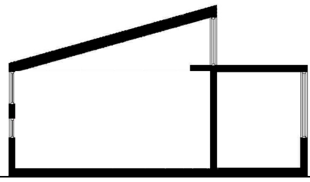
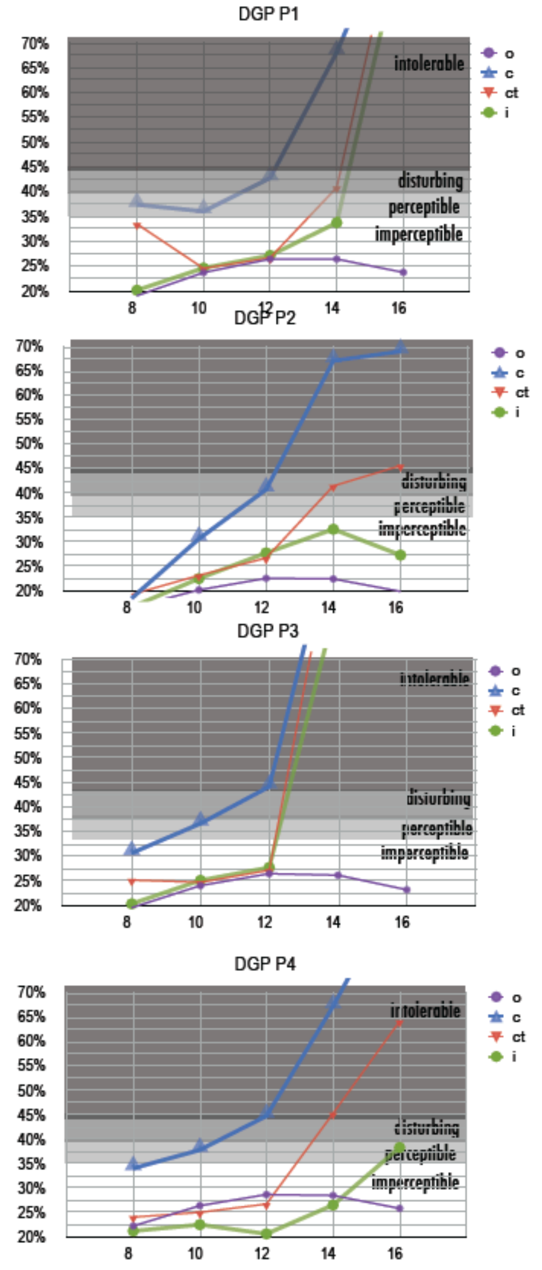
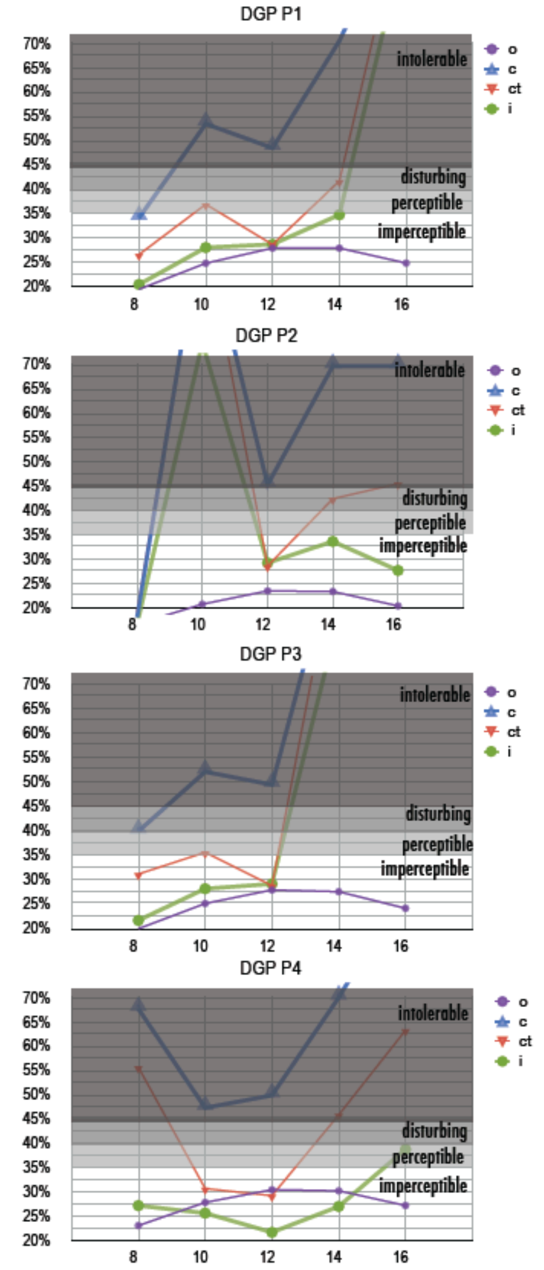
"bi-lateral clerestory window</td></tr>
<tr><td></td><td></td></tr>
<tr><td>
</td><td>
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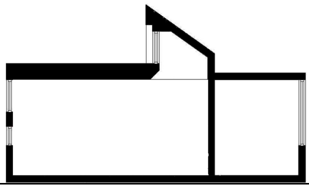
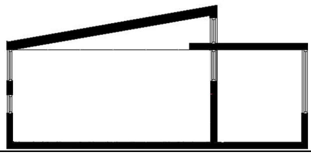
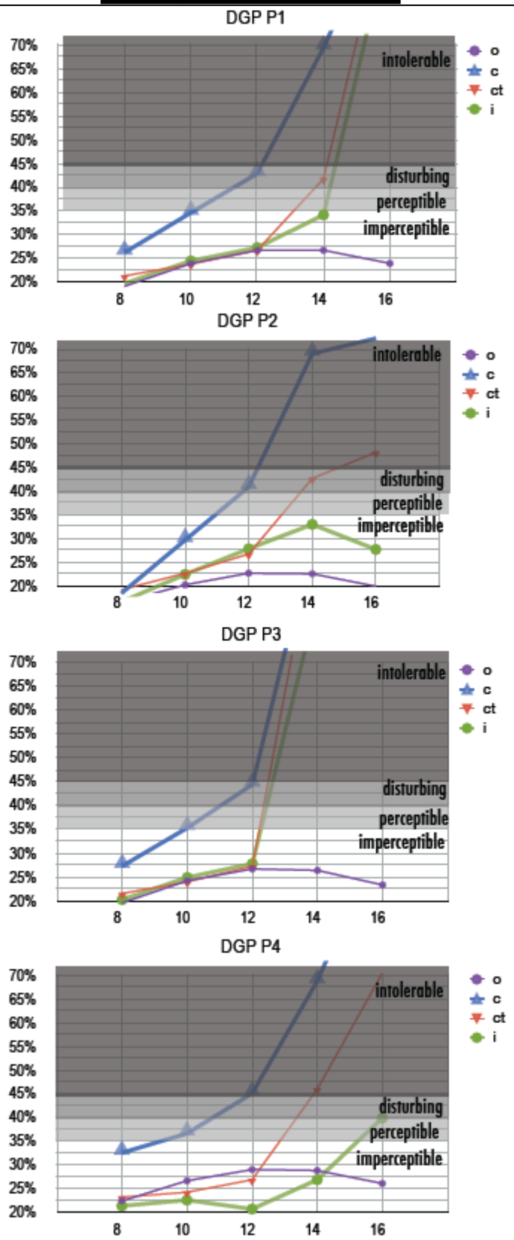
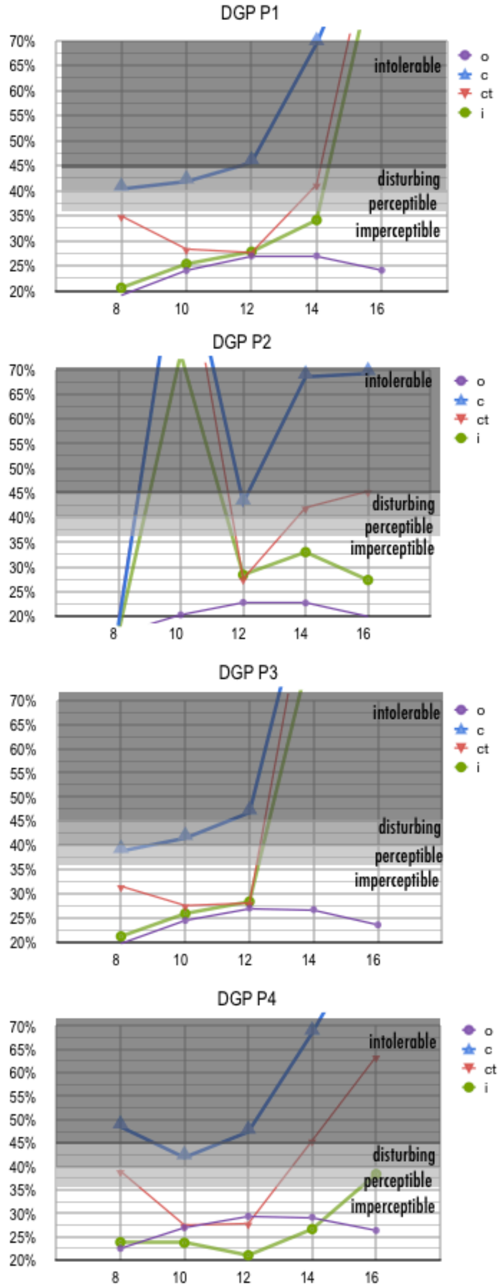
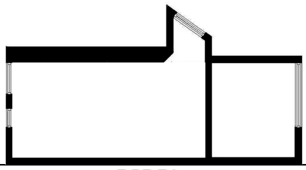
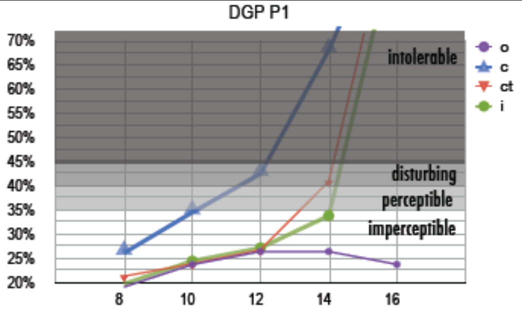
WEST-FACING CLASSROOM

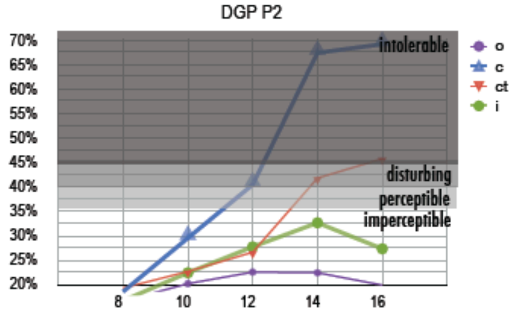
Typology g3 ***"unilateral clerestory window***	Typology g4 ***"bi-lateral clerestory window with corridor daylight"***
	
	

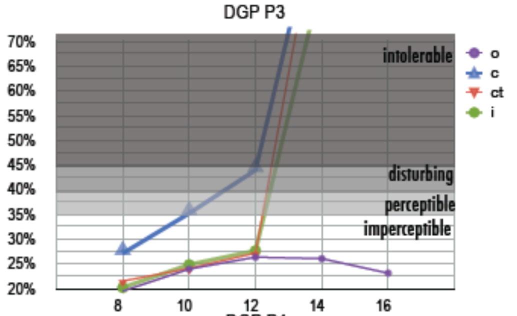
WEST-FACING CLASSROOM

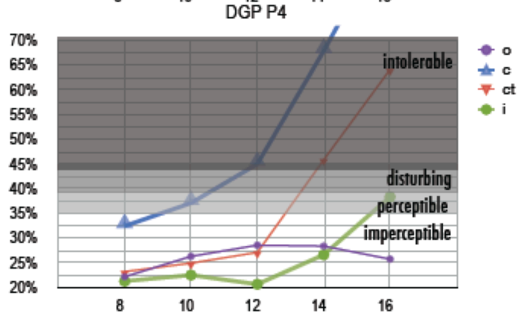
Typology g5
"skylight window"









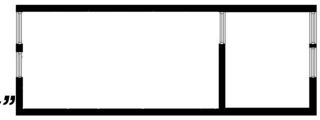


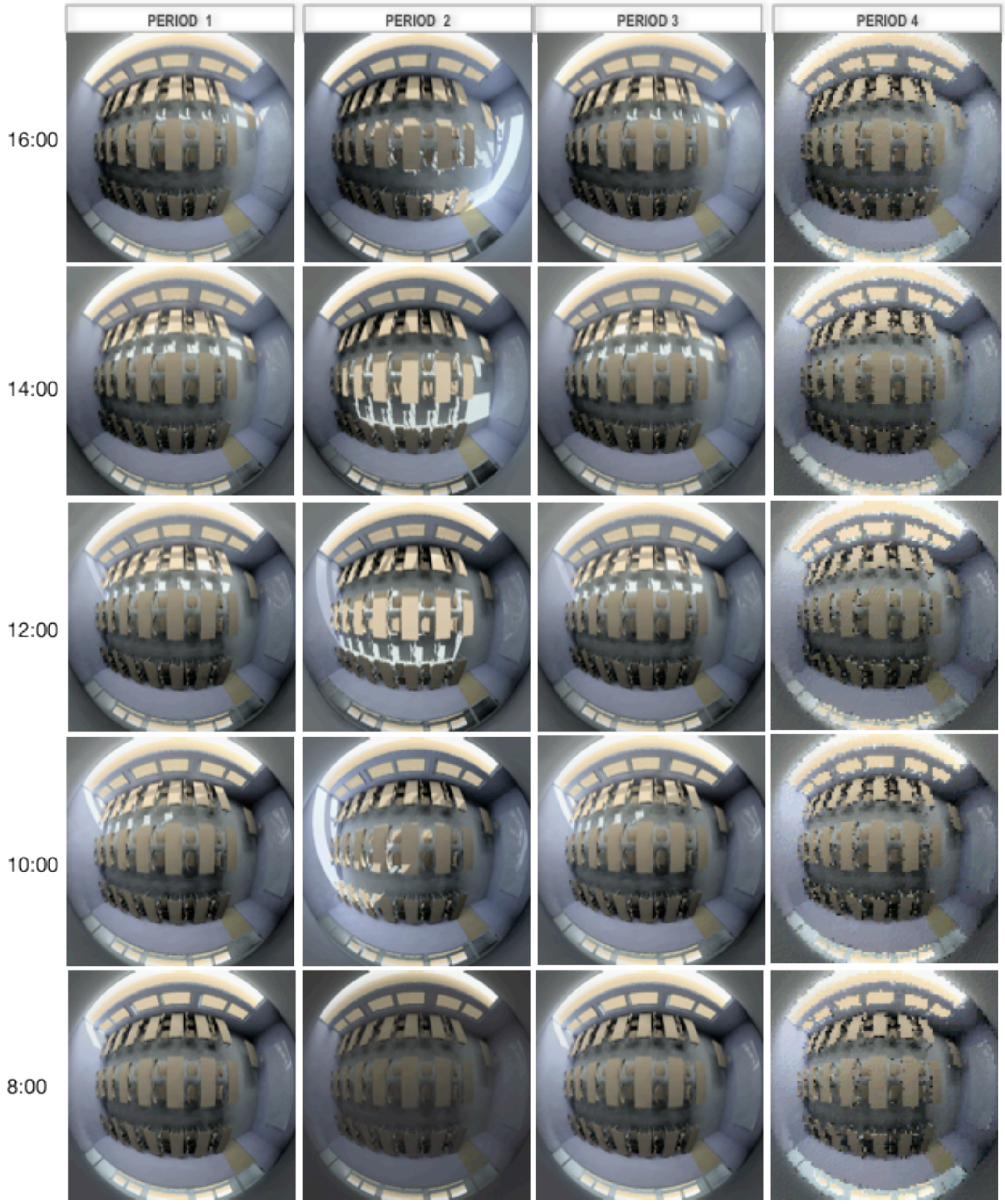
D. Appendix: Sunlight penetration

NORTH FACING CLASSROOM

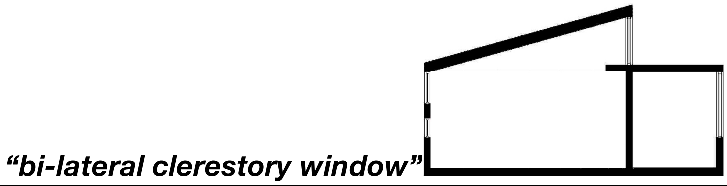
Typology g1 North facing

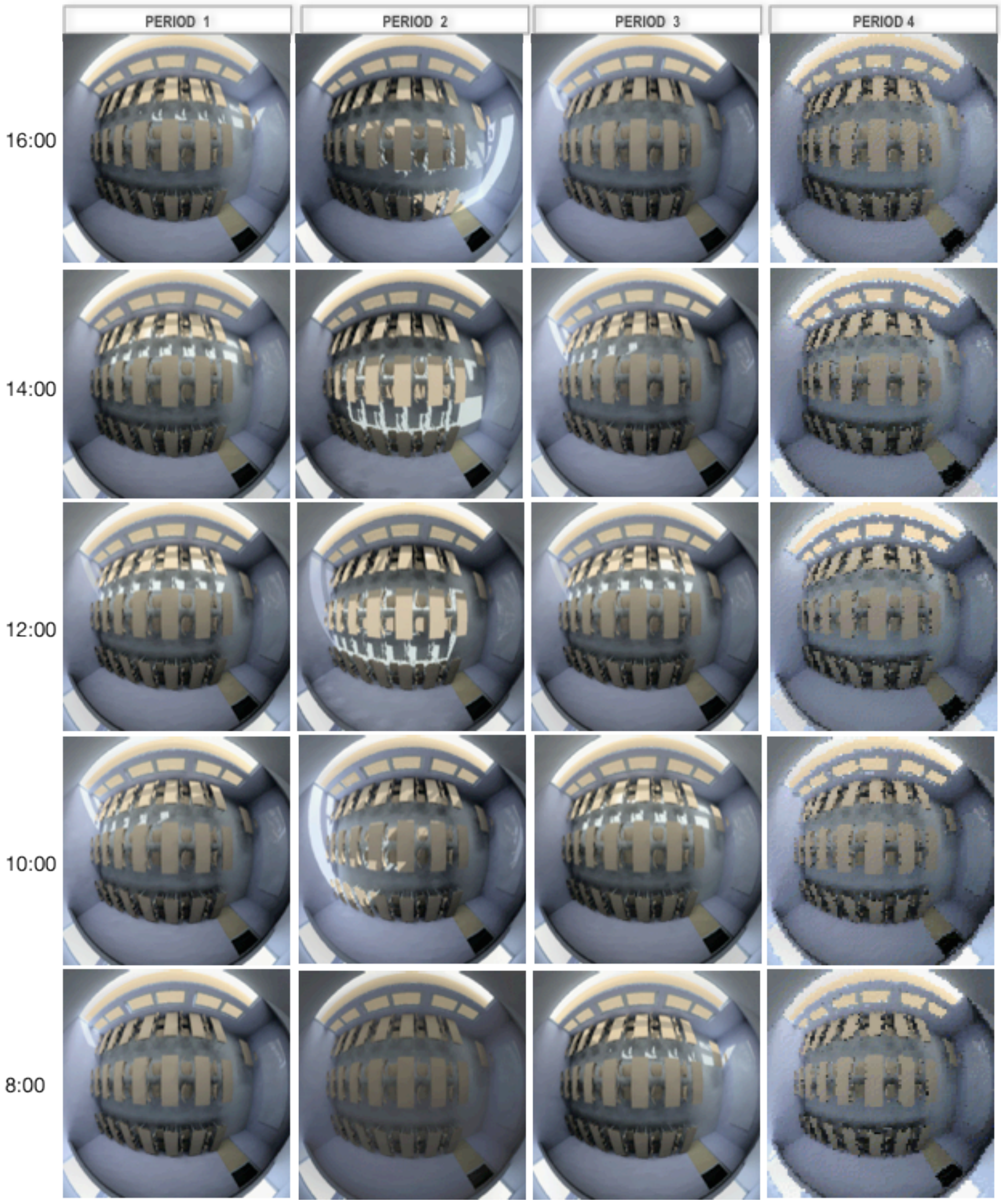
"basic window"



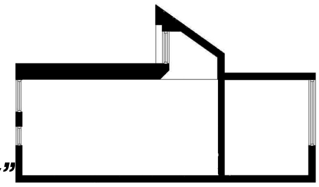


Typology g2 North facing

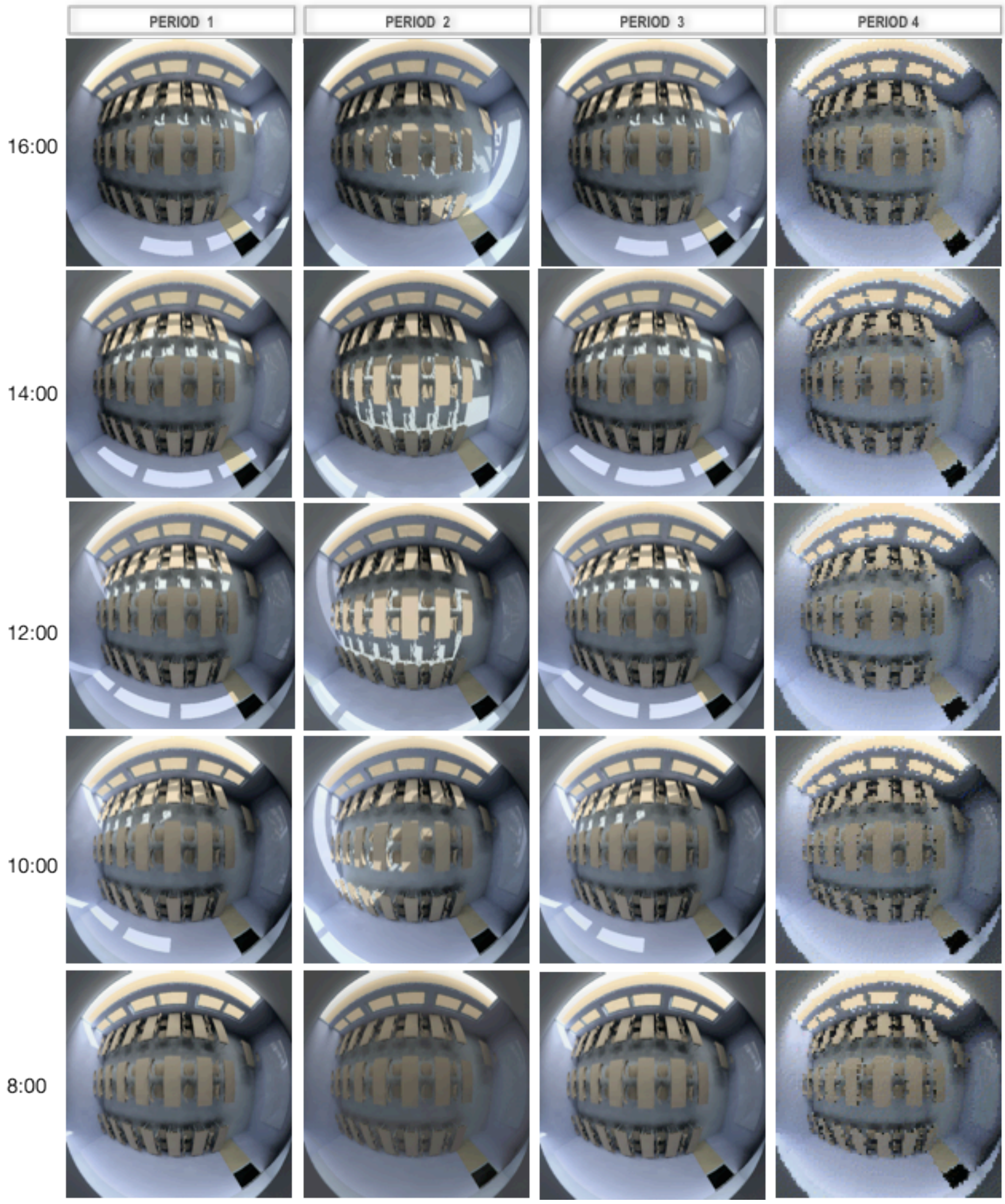




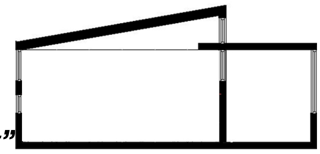
Typology g3 North facing

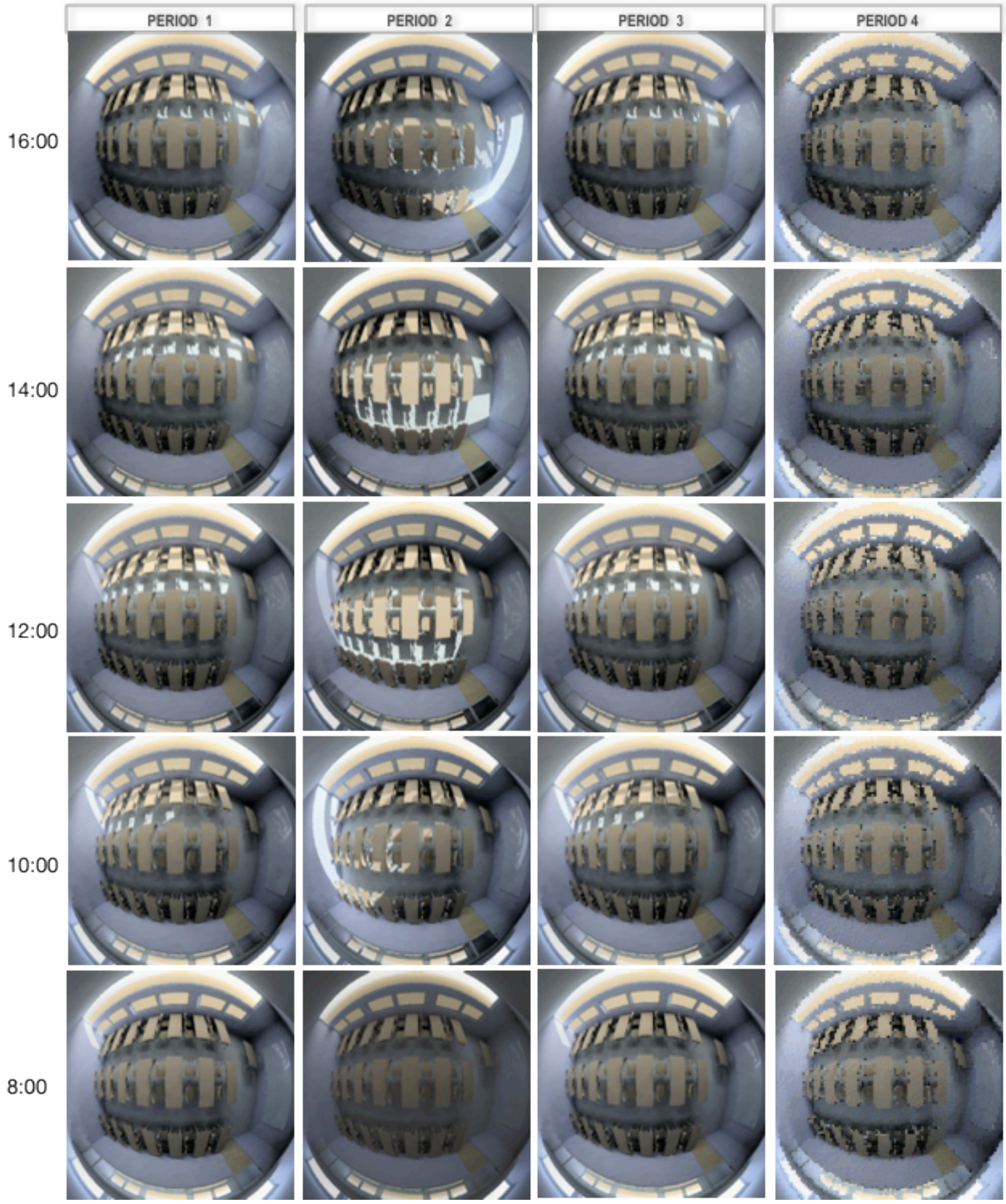


"unilateral clerestory window"



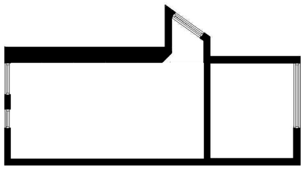
"bi-lateral clerestory window with corridor daylight"

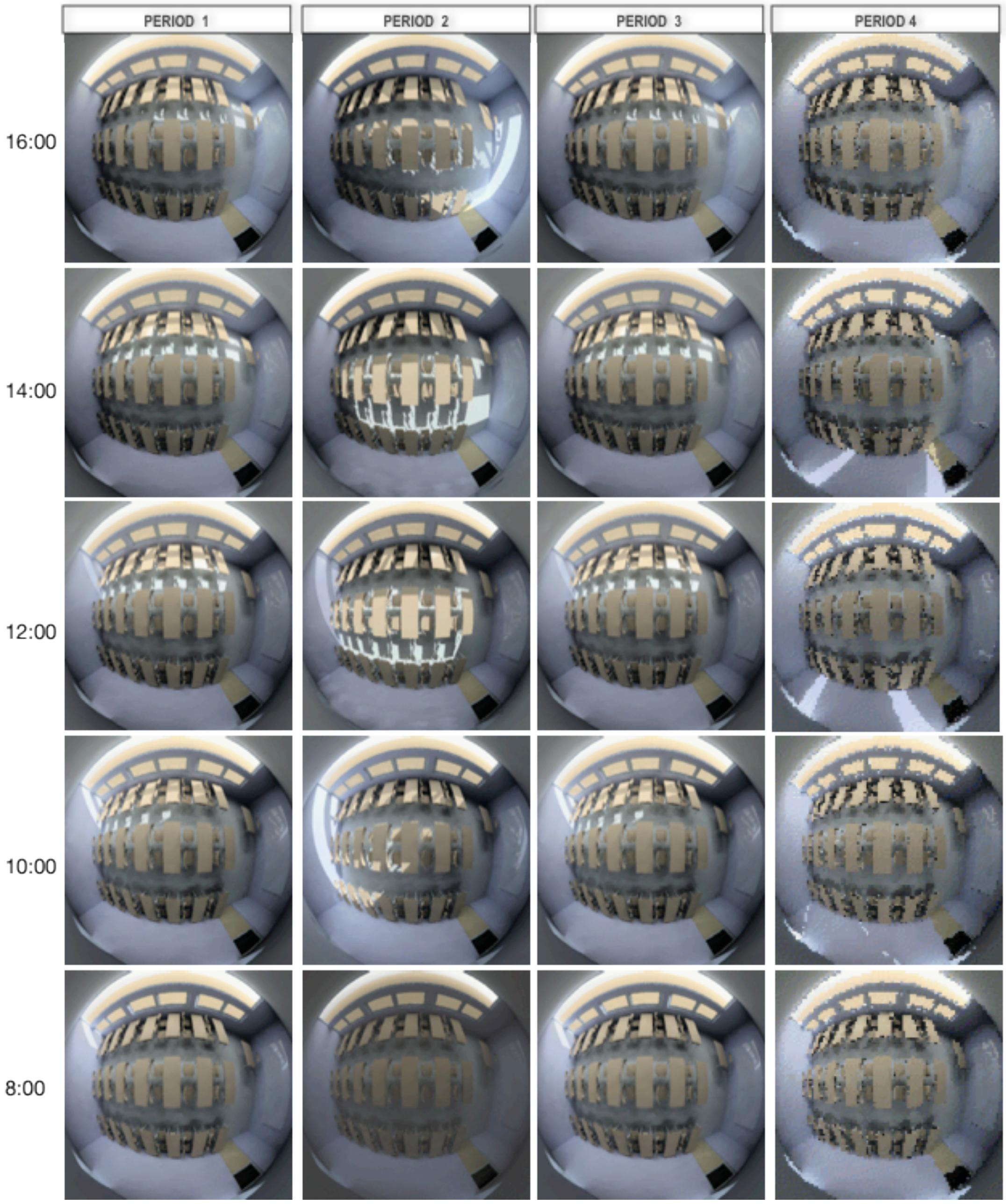




Typology g5 North facing

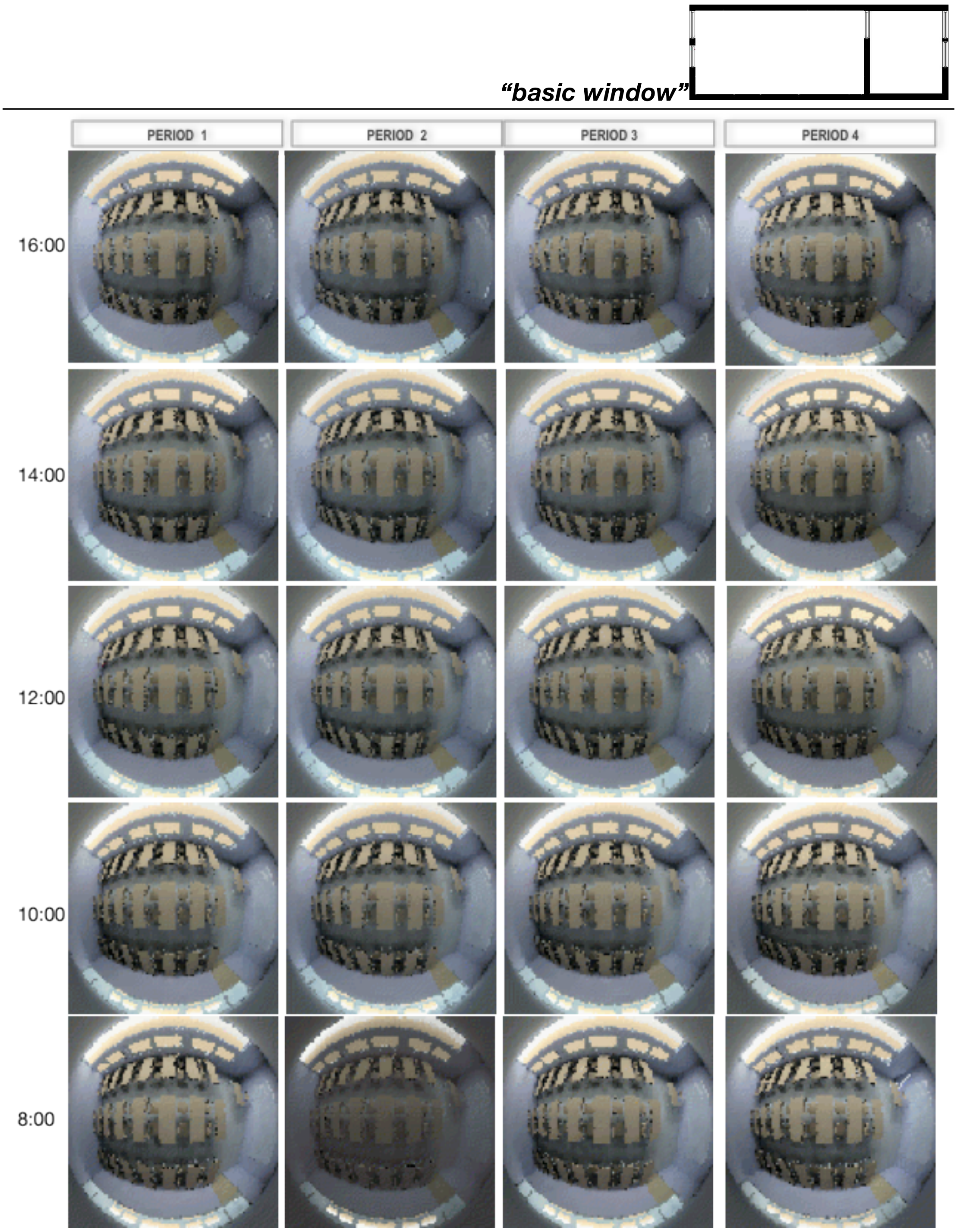
“skylight window”



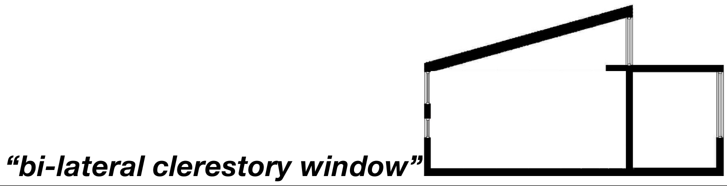


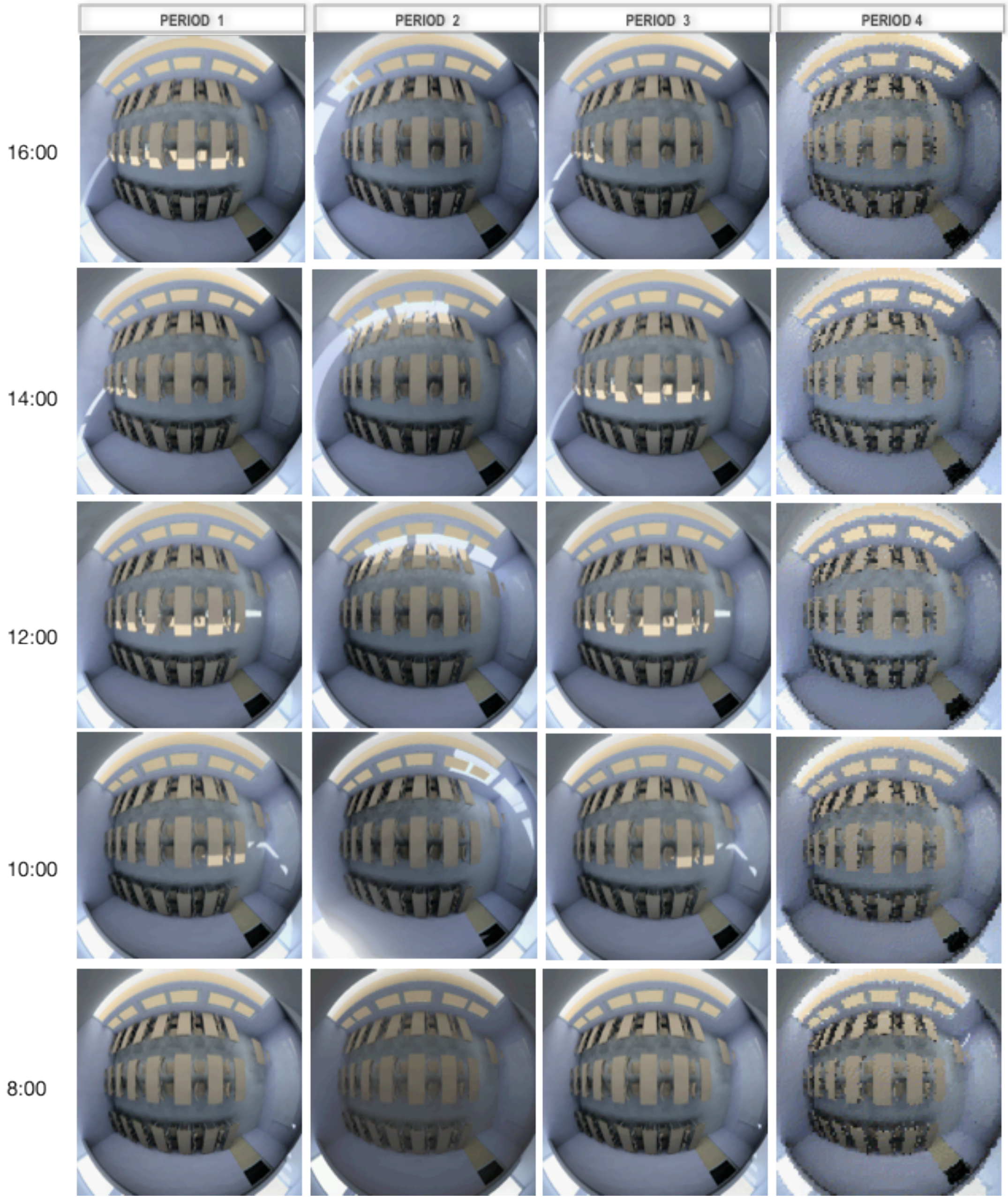
SOUTH FACING CLASSROOM

Typology g1 South facing

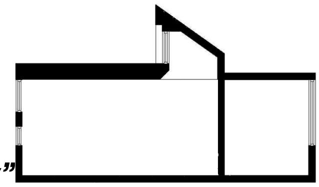


Typology g2 South facing

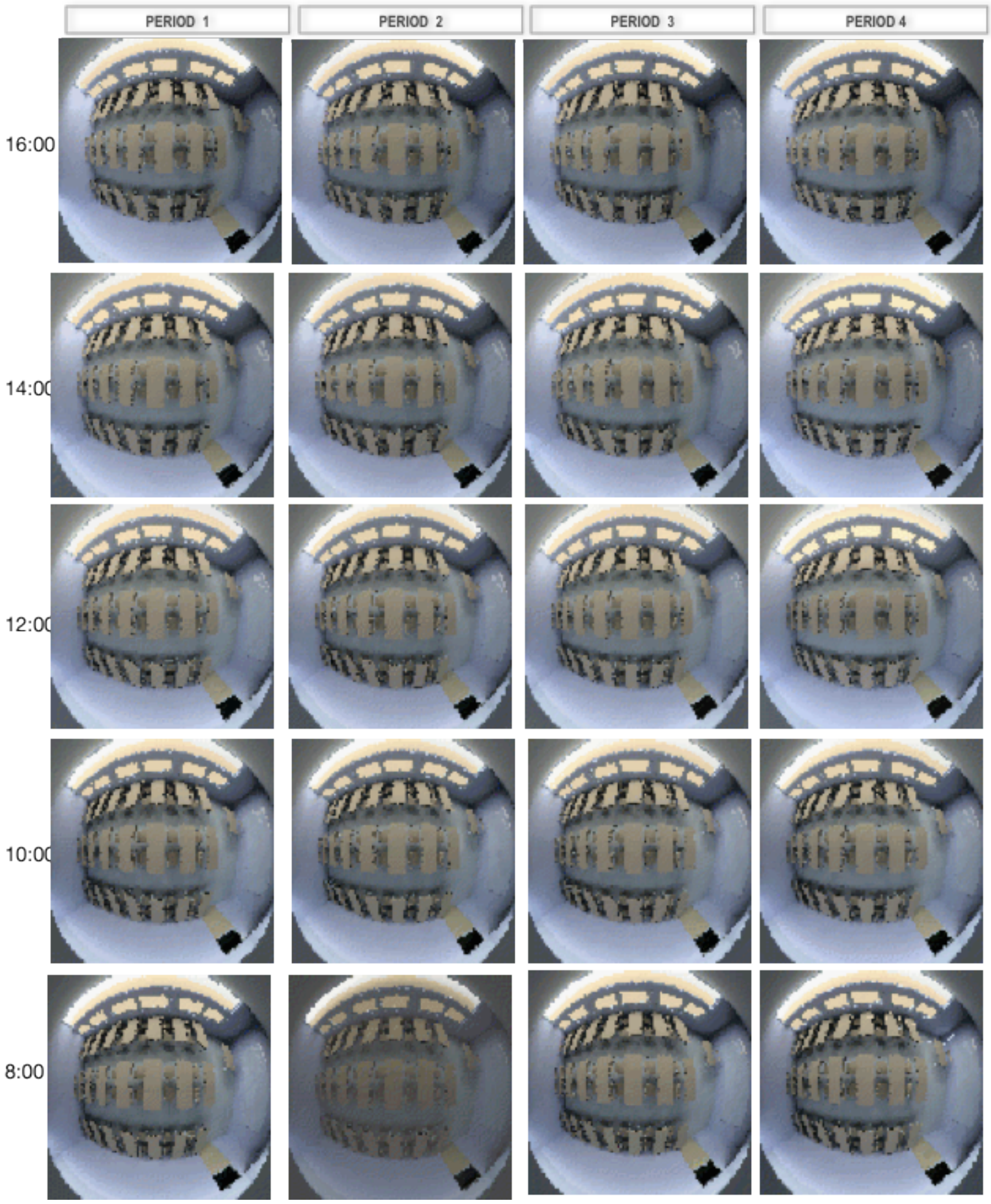




Typology g3 South facing

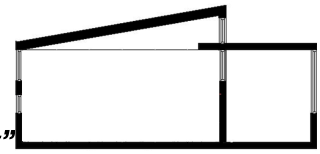


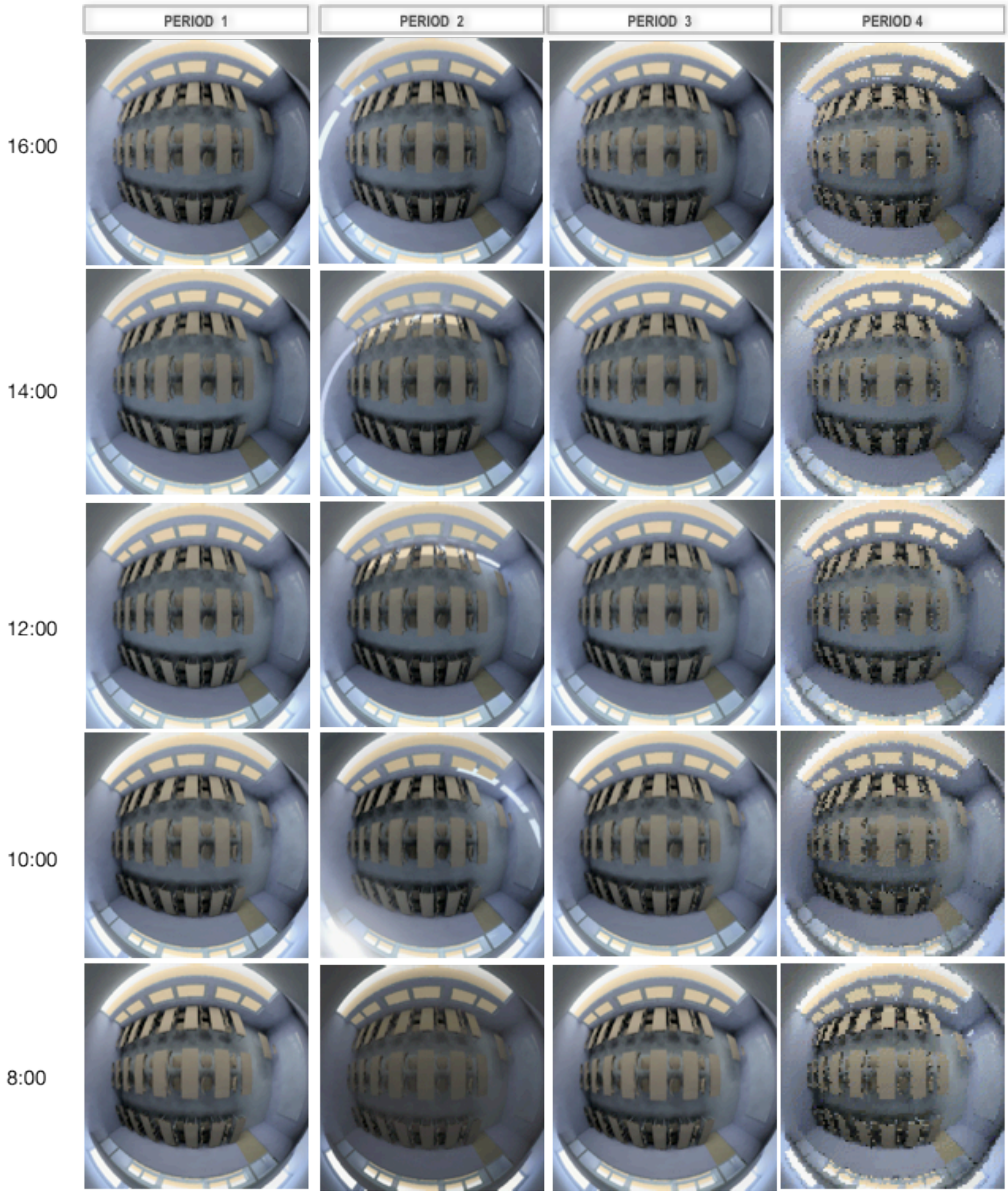
"unilateral clerestory window"



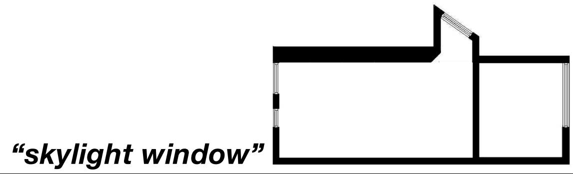
Typology g4 South facing

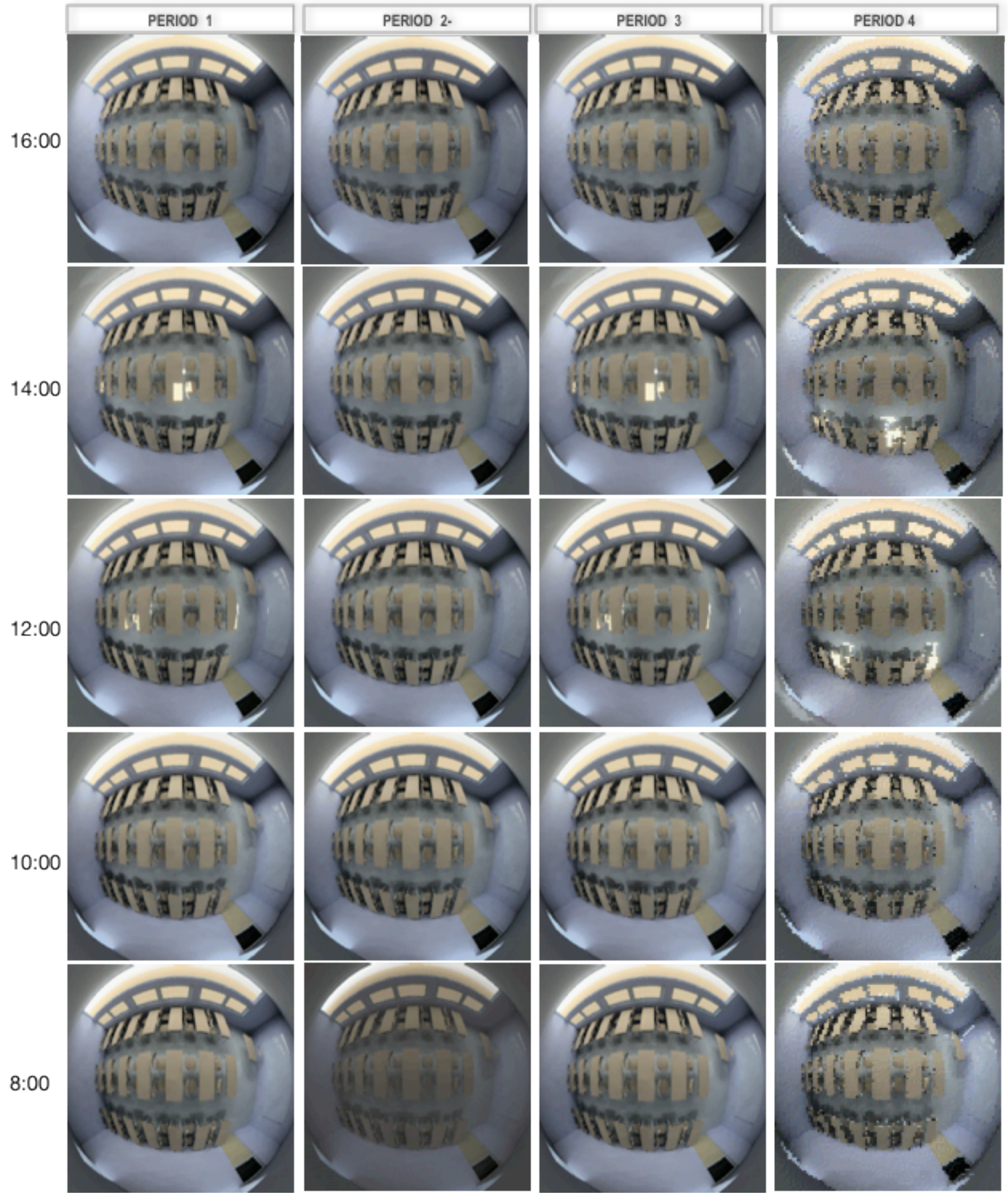
"bi-lateral clerestory window with corridor daylight"





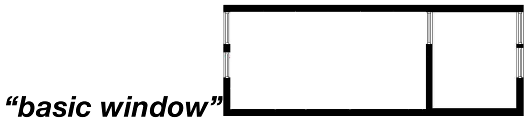
Typology g5 South facing

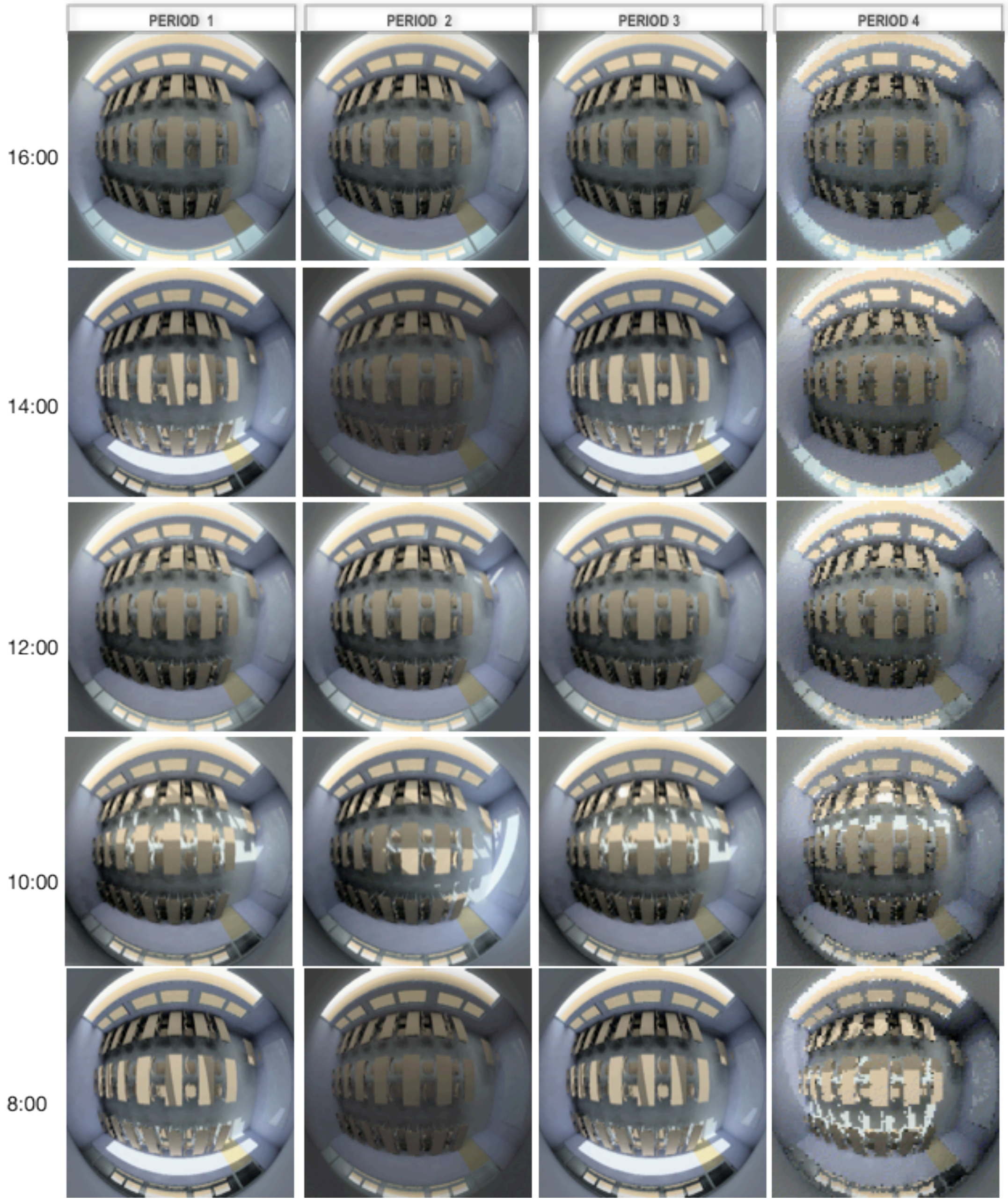




EAST-FACING CLASSROOM

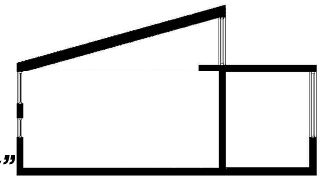
Typology g1 East facing

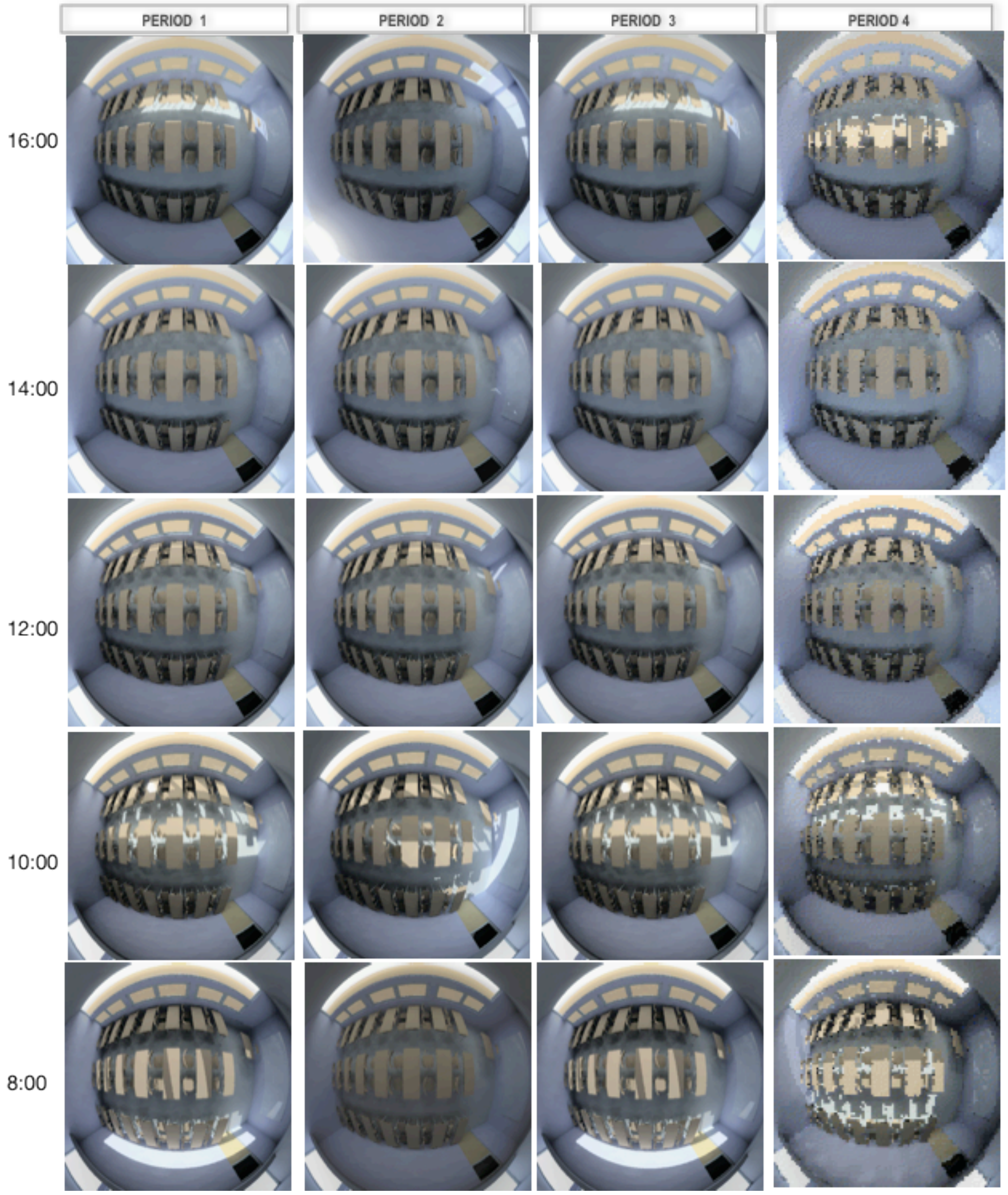




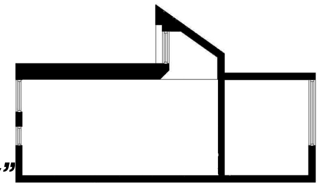
Typology g2 East facing

"bi-lateral clerestory window"

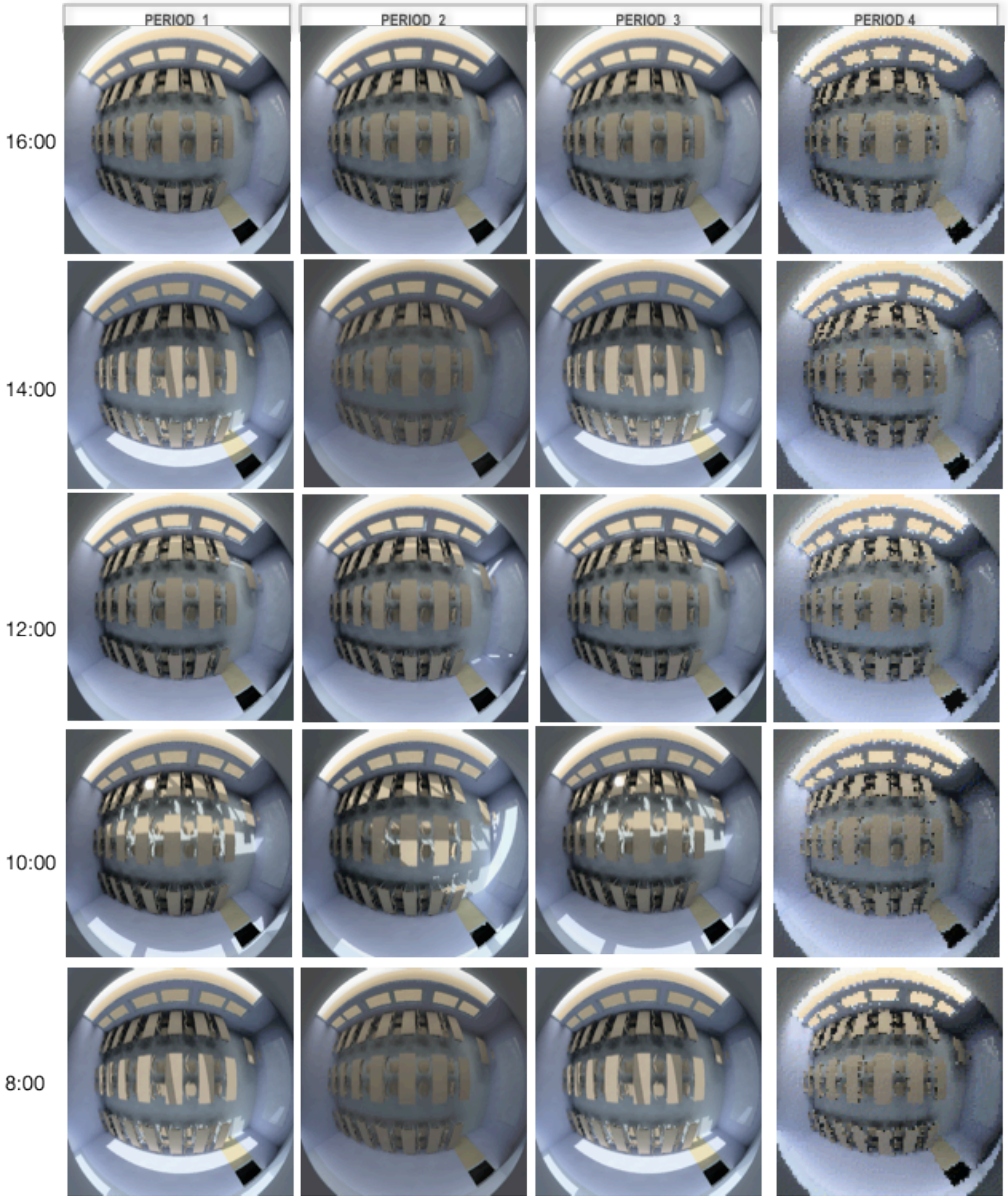




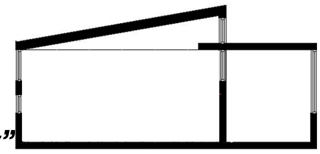
Typology g3 East facing

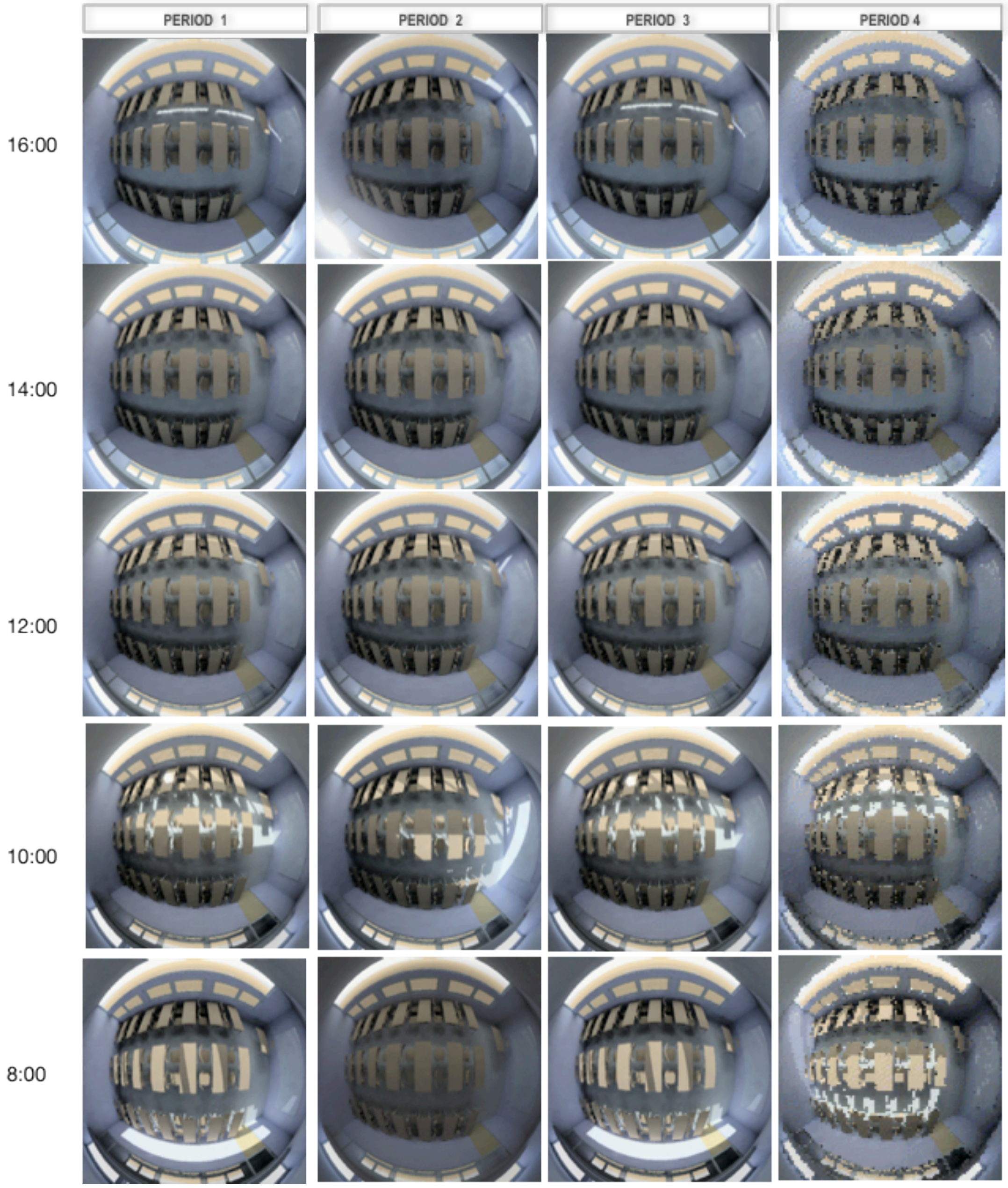


"unilateral clerestory window"



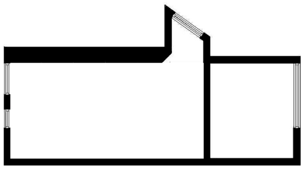
"bi-lateral clerestory window with corridor daylight"

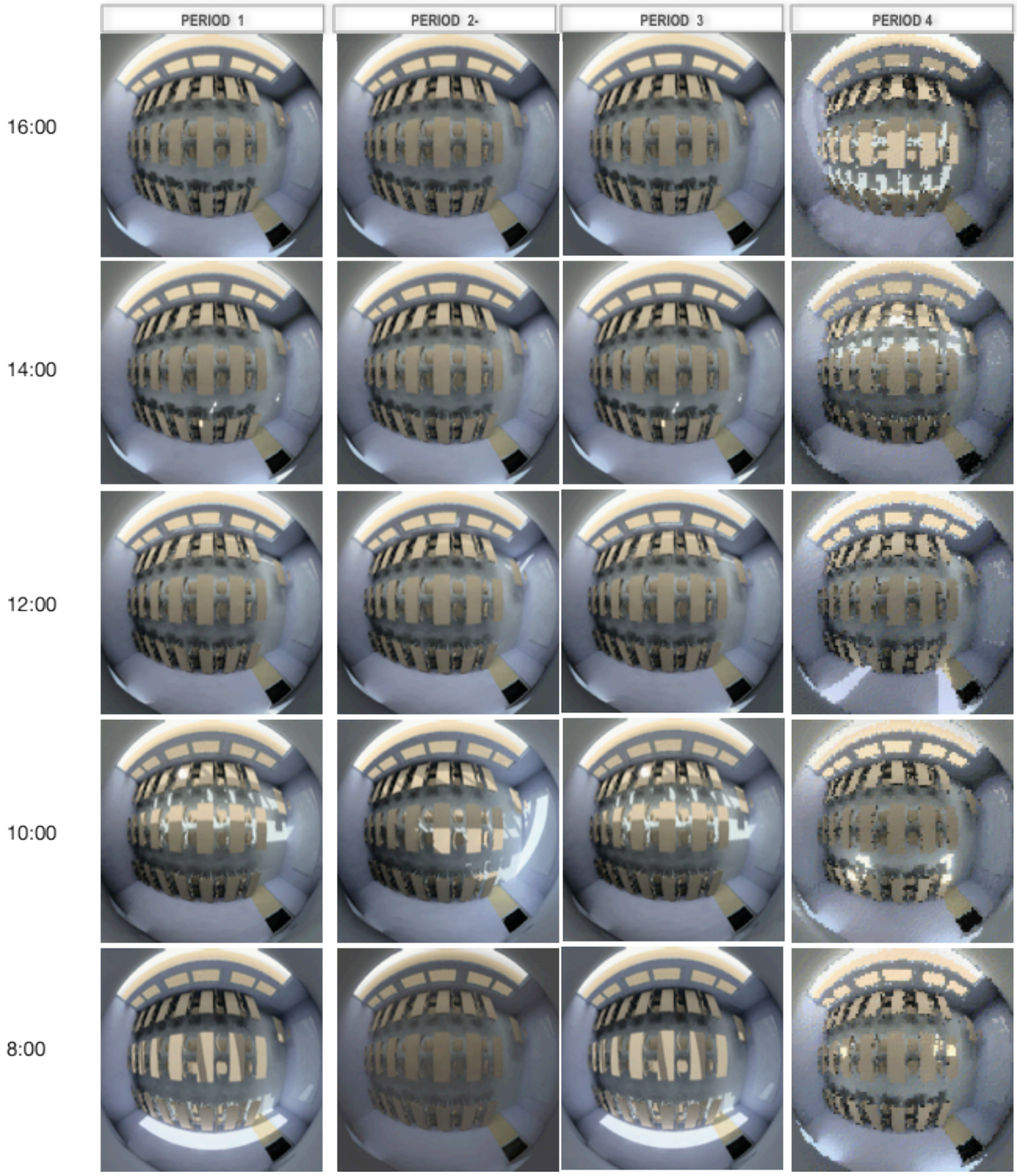




Typology g5 East facing

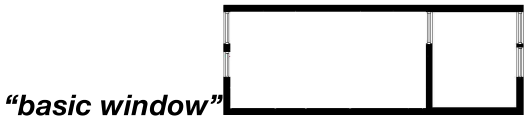
“skylight window”

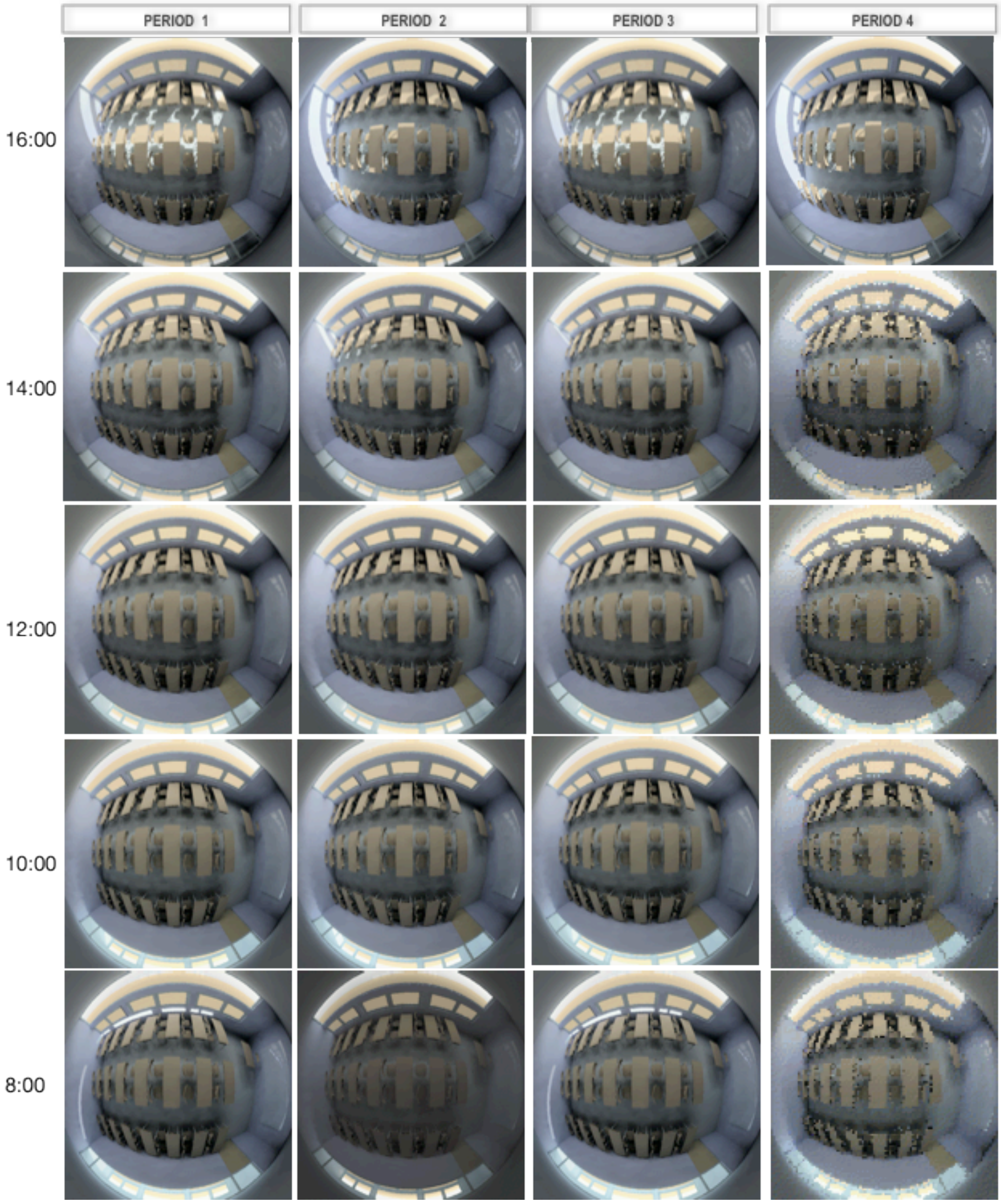




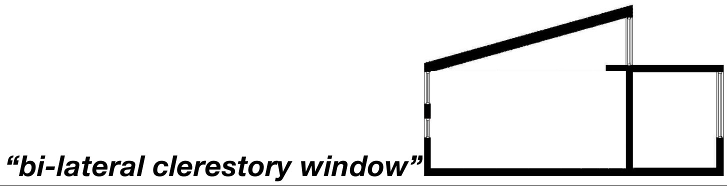
WEST-FACING CLASSROOM

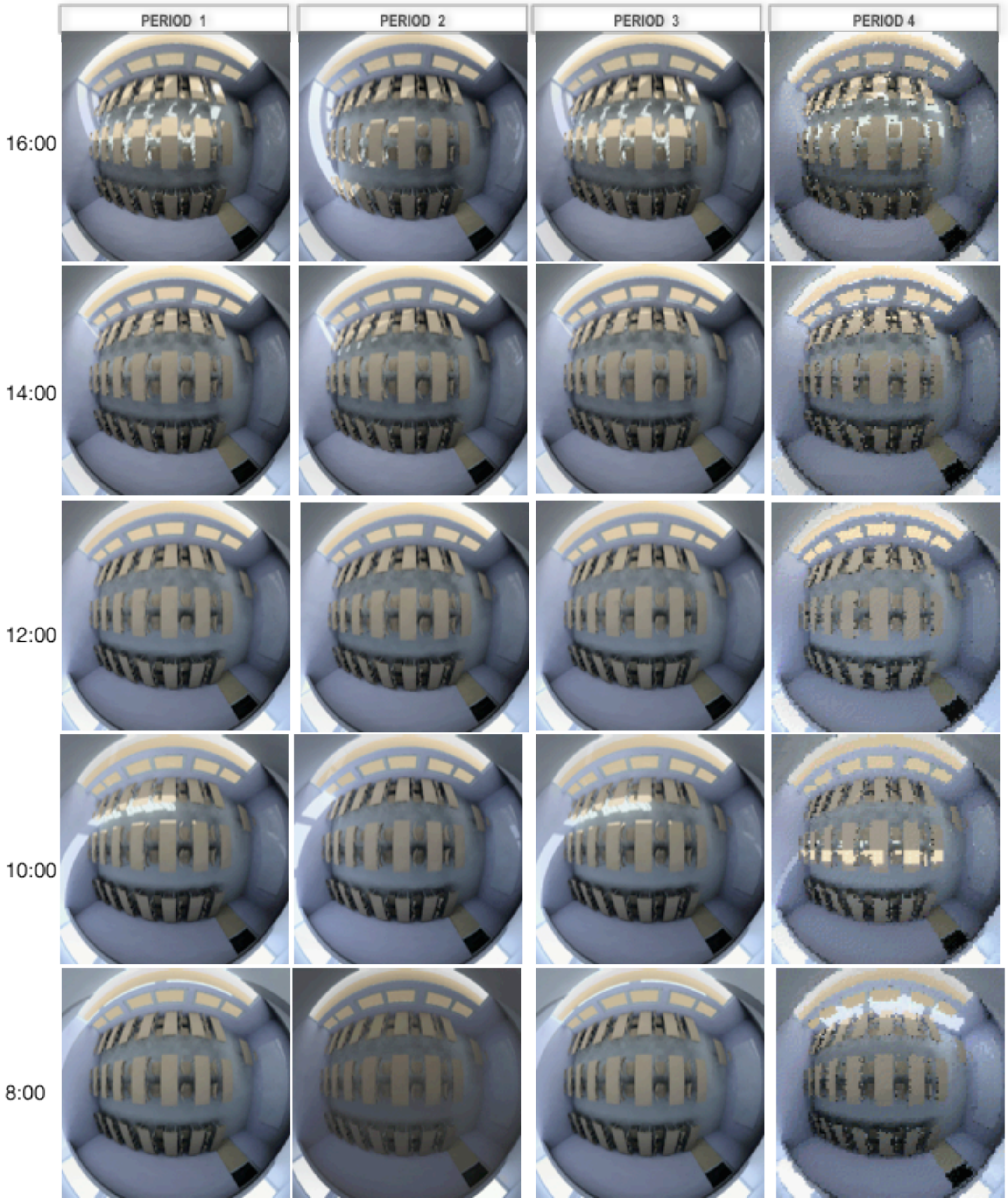
Typology g1 West-facing



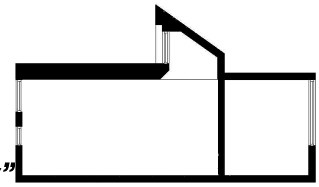


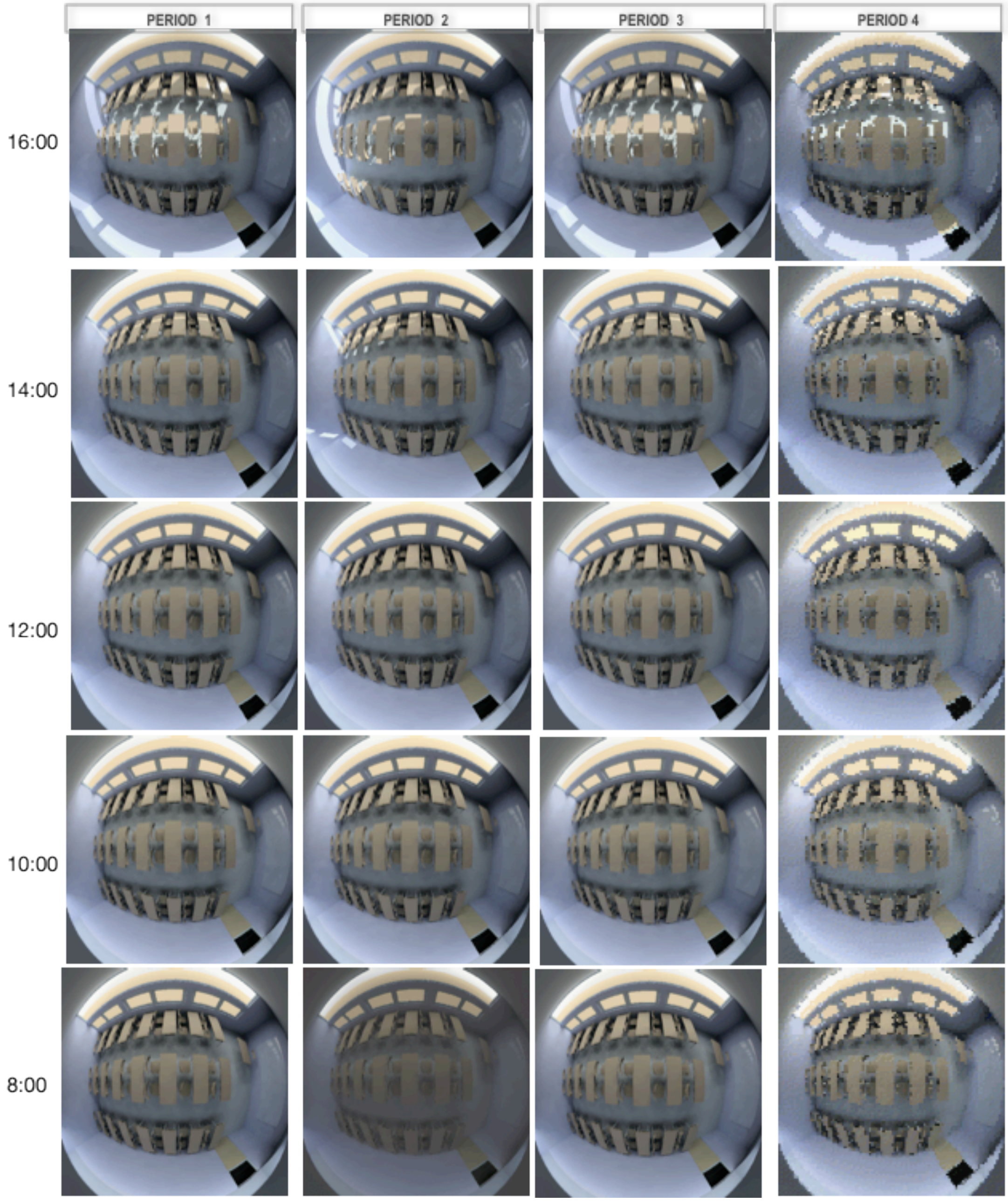
Typology g2 West-facing



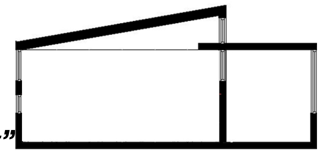


"unilateral clerestory window"

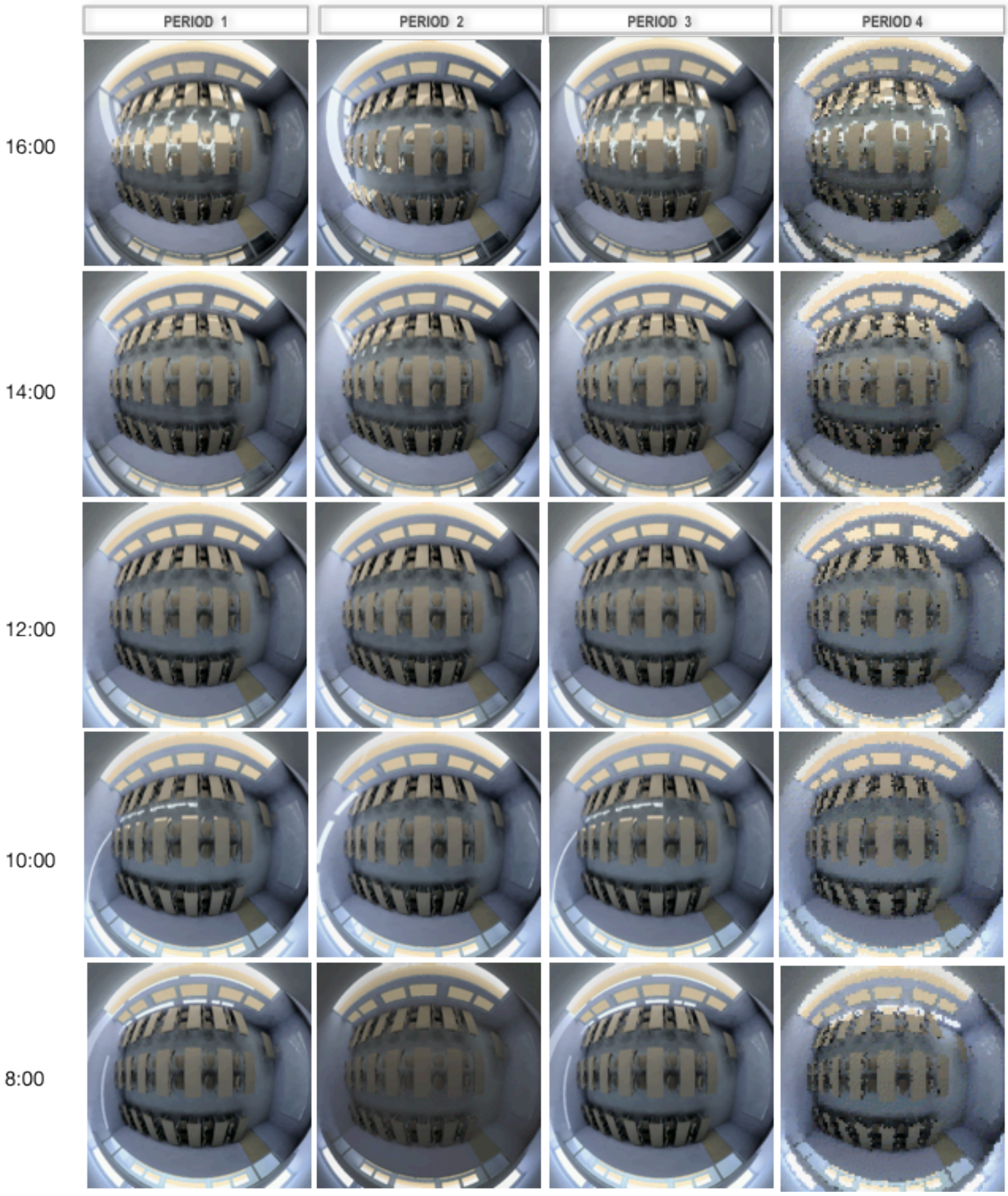




Typology g4 West-facing

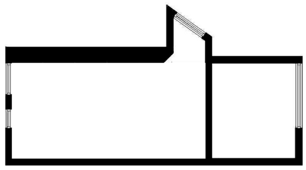


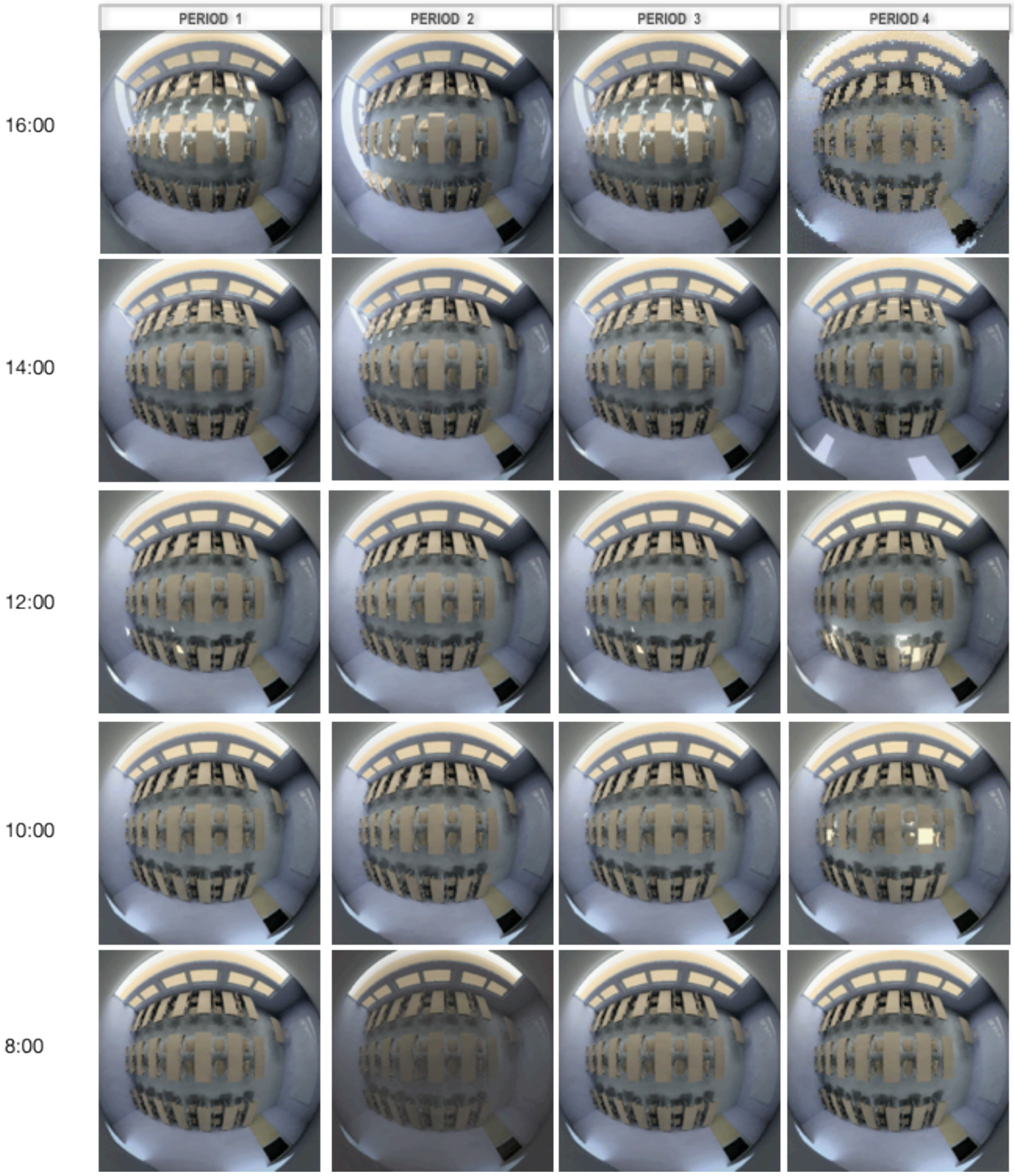
"bi-lateral clerestory window with corridor daylight"



Typology g5 West-facing

“skylight window”





E. Appendix: Comparison method

Analisis estadistico tipología de orientación Norte

MARS ZONE 1

	g1	g2	g3	g4	g5
g1		152,82**	183,58**	41,68	-0,78
g2			30,76	111,13*	153,59**
g3				141,9	184,36**
g4					-42,46

* DHS(0,05)= 108,00

** DHS(0,01)= 136,94

ZONE 2

	g1	g2	g3	g4	g5
g1		266,82**	401,08**	73,66	26,28
g2			134,26	193,16*	240,54**
g3				327,42**	374,8**
g4					-47,38

* DHS(0,05)= 175,36

** DHS(0,01)= 222,34

ZONE 3

	g1	g2	g3	g4	g5
g1		218,7	916,18**	108,14	119,04
g2			697,48**	110,56	99,66
g3				808,04**	797,14**
g4					10,9

* DHS(0,05)= 391,41

** DHS(0,01)= 496,27

SEPTEMBER ZONE 1

	g1	g2	g3	g4	g5
g1		157,63**	191,03**	36,26	-3,94
g2			33,4	121,37*	161,57**
g3				154,78**	194,98**
g4					-40,2

* DHS(0,05)= 108,62

** DHS(0,01)= 137,71

ZONE 2

	g1	g2	g3	g4	g5
g1		273,5**	417,74**	78,68	29,18
g2			144,24	194,82*	244,32**
g3				339,06**	388,56**
g4					-49,5

* DHS(0,05)= 175,38

** DHS(0,01)= 222,36

ZONE 3

	g1	g2	g3	g4	g5
g1		222,72	944,5**	106,98	121,46
g2			721,78**	115,74	101,26
g3				837,52**	823,04**
g4					14,48

* DHS(0,05)= 376,97

** DHS(0,01)= 477,96

JUNE ZONE 1

	g1	g2	g3	g4	g5
g1		171,86**	31,34	62,78	-0,98
g2			- 140,52**	109,08*	172,84**
g3				-31,44	32,32
g4					-63,76

* DHS(0,05)= 88,28

** DHS(0,01)= 111,93

ZONE 2

	g1	g2	g3	g4	g5
g1		233,1**	77,38	68,86	17,7
g2			- 155,72**	164,24**	215,4**
g3				8,52	59,68
g4					-51,16

* DHS(0,05)= 113,42

** DHS(0,01)= 143,81

ZONE 3

	g1	g2	g3	g4	g5
g1		129,34**	169,96**	70,06	79,720*
g2			40,62	59,28	49,62
g3				99,9	90,24*
g4					9,66

* DHS(0,05)= 79,01

** DHS(0,01)= 100,18

DECEMBER ZONE 1

	g1	g2	g3	g4	g5
g1		273,94**	67,18	107,78	13,86
g2			- 206,76**	166,16**	260,08**
g3				-40,6	53,32
g4					-93,92

* DHS(0,05)= 116,03

** DHS(0,01)= 147,11

ZONE 2

	g1	g2	g3	g4	g5
g1		451,3**	193,8**	166,8**	58,8
g2			-257,5**	284,5**	392,5**
g3				27	135
g4					-108

* DHS(0,05)= 108,67

** DHS(0,01)= 137,78

ZONE 3

	g1	g2	g3	g4	g5
g1		330,42**	473,62**	178,06**	218,24**
g2			143,2*	152,36*	112,18
g3				295,56**	255,38**
g4					40,18

* DHS(0,05)= 124,76

** DHS(0,01)= 158,19

Analisis estadistico South-facing classroom

MARS — ZONE 1

	g1	g2	g3	g4	g5
g1		621,68**	-3,96	245,72*	-28,24
g2			-625,64**	375,96**	649,92**
g3				-249,68*	24,28
g4					-273,96*

* DHS(0,05)= 243,81

** DHS(0,01)= 309,13

ZONE 2

	g1	g2	g3	g4	g5
g1		810,72**	40,3	279,5	11,64
g2			-770,42**	531,22**	799,08**
g3				-239,2	28,66
g4					-267,86

* DHS(0,05)= 323,84

** DHS(0,01)= 410,59

ZONE 3

	g1	g2	g3	g4	g5
g1		480,76**	135,54	278,9**	78,56
g2			-345,22**	201,86*	402,2**
g3				-143,36	56,98
g4					-200,34*

* DHS(0,05)= 195,59

** DHS(0,01)= 247,99

September — ZONE 1

	g1	g2	g3	g4	g5
g1		640,66**	-4,76	254,76*	-28,38
g2			-645,42**	385,9**	669,04**
g3				-259,52*	23,62
g4					-283,14*

* DHS(0,05)= 234,34

** DHS(0,01)= 297,13

ZONE 2

	g1	g2	g3	g4	g5
g1		832,78**	38,6	287,38	12,28
g2			-794,18**	545,4**	820,5**
g3				-248,78	26,32
g4					-275,1

* DHS(0,05)= 309,01

** DHS(0,01)= 391,79

ZONE 3

	g1	g2	g3	g4	g5
g1		491,94**	136,18	286,7**	77,78
g2			-355,76**	205,24*	414,16**
g3				-150,52	58,4
g4					-208,92*

* DHS(0,05)= 185,34

** DHS(0,01)= 234,99

JUNE — ZONE 1

	g1	g2	g3	g4	g5
g1		169,74**	28,92	62,46	-1,06
g2			-140,82**	107,28**	170,8**
g3				-33,54	29,98
g4					-63,52

* DHS(0,05)= 88,08

** DHS(0,01)= 111,68

ZONE 2

	g1	g2	g3	g4	g5
g1		231,14**	76,54	67,86	15,66
g2			-154,6**	163,28**	215,48**
g3				8,68	60,88
g4					-52,2

* DHS(0,05)= 113,53

** DHS(0,01)= 143,94

ZONE 3

	g1	g2	g3	g4	g5
g1		129,46**	171,5**	70,78	80,38*
g2			42	58,68	49,08
g3				100,72	91,1*
g4					9,6

* DHS(0,05)= 79,68

** DHS(0,01)= 101,02

December — ZONE 1

	g1	g2	g3	g4	g5
g1		342,98**	44,9	135,7**	4,02
g2			-298,08**	207,28**	338,96**
g3				-90,80**	40,88
g4					-131,68**

* DHS(0,05)= 66,67

** DHS(0,01)= 84,53

ZONE 2

	g1	g2	g3	g4	g5
g1		550,58**	149,56**	196,44**	54,62
g2			-401,02**	354,14**	495,96**
g3				-46,88	94,94
g4					-141,82**

* DHS(0,05)= 100,07

** DHS(0,01)= 126,88

ZONE 3

	g1	g2	g3	g4	g5
g1		384,76	371,5	206,44	2158,28
g2			-13,26	178,32	-1773,52
g3				165,06	-1786,78
g4					1951,84

* DHS(0,05)= 3837,29

** DHS(0,01)= 4865,30

Analisis estadistico East-facing classroom

MARS — ZONE 1

	g1	g2	g3	g4	g5
g1		2198,06	1904,98	1944,62	1785,08
g2			-293,08	253,44	412,98
g3				-39,64	119,9
g4					-159,54

* DHS(0,05)= 2562,0

** DHS(0,01)= 3248,3

ZONE 2

	g1	g2	g3	g4	g5
g1		519,22	271,84	168,68	20,72
g2			-247,38	350,54	498,5
g3				103,16	251,12
g4					-147,96

* DHS(0,05)= 462,23

** DHS(0,01)= 586,06

ZONE 3

	g1	g2	g3	g4	g5
g1		402,44	109,36	149	-10,54
g2			-293,08	253,44	412,98
g3				-39,64	119,9
g4					-159,54

* DHS(0,05)= 372,0

** DHS(0,01)= 471,7

SEPTEMBER — ZONE 1

	g1	g2	g3	g4	g5
g1		1382,42	108,14	157,92	-13,3
g2			-1274,28	1224,5	1395,72
g3				-49,78	121,44
g4					-171,22

* DHS(0,05)= 2141,22

** DHS(0,01)= 2714,85

ZONE 2

	g1	g2	g3	g4	g5
g1		534,7	274,52	174,82	17,28
g2			-260,18	359,88	517,42
g3				99,7	257,24
g4					-157,54

* DHS(0,05)= 454,86

** DHS(0,01)= 576,72

ZONE 3

	g1	g2	g3	g4	g5
g1		344,06	562,94	178,1	94,94
g2			218,88	165,96	249,12
g3				384,84	468
g4					-83,16

* DHS(0,05)= 494,1

** DHS(0,01)= 626,4

JUNE — ZONE 1

	g1	g2	g3	g4	g5
g1		169,58**	29,3	61,98	-2,88
g2			-140,28**	107,6**	172,46**
g3				-32,68	32,18
g4					-64,86

* DHS(0,05)= 87,30

** DHS(0,01)= 110,69

ZONE 2

	g1	g2	g3	g4	g5
g1		232,88**	76,56	66,6	16,64
g2			-156,32**	166,28**	216,24**
g3				9,96	59,92
g4					-49,96

* DHS(0,05)= 113,4

** DHS(0,01)= 143,8

ZONE 3

	g1	g2	g3	g4	g5
g1		129,66	170,7	70,36	79,86
g2			41,04	59,3	49,8
g3				100,34	91
g4					9,5

* DHS(0,05)= 79,34

** DHS(0,01)= 100,59

DECEMBER — ZONE 1

	g1	g2	g3	g4	g5
g1		342,98	44,9	135,7	4,02
g2			-298,08	207,28	338,96
g3				-90,8	40,88
g4					-131,68

* DHS(0,05)= 66,67

** DHS(0,01)= 84,53

ZONE 2

	g1	g2	g3	g4	g5
g1		550,58	149,56	196,44	54,62
g2			-401,02	354,14	495,96
g3				-46,88	94,94
g4					-141,82

* DHS(0,05)= 100,07

** DHS(0,01)= 126,88

ZONE 3

	g1	g2	g3	g4	g5
g1		384,76	371,5	206,44	2158,28
g2			-13,26	178,32	-1773,52
g3				165,06	-1786,78
g4					1951,84

* DHS(0,05)= 3837,29

** DHS(0,01)= 4865,30

Analisis estadistico West-facing classroom

MARS					ZONE 1
	g1	g2	g3	g4	g5
g1		435,22	71,46	164,34	-24,92
g2			-363,76	270,88	460,14
g3				-92,88	96,38
g4					-189,26
			*	DHS(0,05)=	330,39
			**	DHS(0,01)=	418,90

					ZONE 2
	g1	g2	g3	g4	g5
g1		562,46	201	191,3	12,9
g2			-361,46	371,16	549,56
g3				9,7	188,1
g4					-178,4
			*	DHS(0,05)=	417,05
			**	DHS(0,01)=	528,78

					ZONE 3
	g1	g2	g3	g4	g5
g1		370,72	444,76	201,48	130,24
g2			74,04	169,24	240,48
g3				243,28	314,52
g4					-71,24
			*	DHS(0,05)=	508,20
			**	DHS(0,01)=	644,34

JUNE					ZONE 1
	g1	g2	g3	g4	g5
g1		168,58	29,32	63,06	-1,46
g2			-139,26	105,52	170,04
g3				-33,74	30,78
g4					-64,52
			*	DHS(0,05)=	86,32
			**	DHS(0,01)=	109,45

					ZONE 2
	g1	g2	g3	g4	g5
g1		232,02	76,26	66,46	16,18
g2			-155,76	165,56	215,84
g3				9,8	60,08
g4					-50,28
			*	DHS(0,05)=	113,89
			**	DHS(0,01)=	144,40

					ZONE 3
	g1	g2	g3	g4	g5
g1		130,36	170,68	70,34	79,94
g2			40,32	60,02	50,42
g3				100,34	90,74
g4					9,6
			*	DHS(0,05)=	79,42
			**	DHS(0,01)=	100,70

SEPTEMBER					ZONE 1
	g1	g2	g3	g4	g5
g1		344,58	126,58	-587,72	7,84
g2			-218	932,3	336,74
g3				714,3	118,74
g4					595,56
			*	DHS(0,05)=	2511,6
			**	DHS(0,01)=	3184,5

					ZONE 2
	g1	g2	g3	g4	g5
g1		1928,98	300,5	-769,64	47,92
g2			-1628,48	2698,62	1881,06
g3				1070,14	252,58
g4					817,56
			*	DHS(0,05)=	3693,5
			**	DHS(0,01)=	4683,0

					ZONE 3
	g1	g2	g3	g4	g5
g1		350,08	641,24	23,58	149,62
g2			291,16	326,5	200,46
g3				617,66	491,62
g4					126,04
			*	DHS(0,05)=	784,4
			**	DHS(0,01)=	994,6

DECEMBER					ZONE 1
	g1	g2	g3	g4	g5
g1		507,74	69,94	178,18	-4,72
g2			-437,8	329,56	512,46
g3				-108,24	74,66
g4					-182,9
			*	DHS(0,05)=	478,5
			**	DHS(0,01)=	606,7

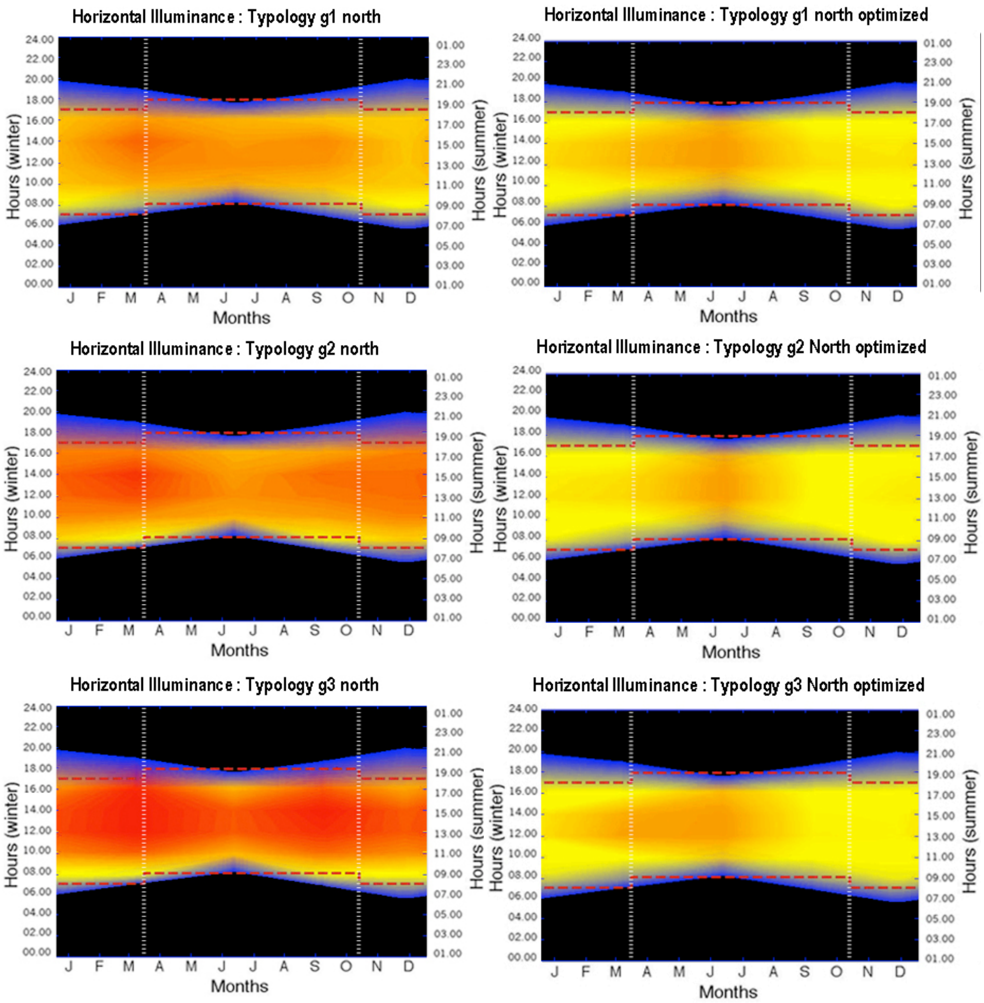
					ZONE 2
	g1	g2	g3	g4	g5
g1		638	192,6	225,48	38,06
g2			-445,4	412,52	599,94
g3				-32,88	154,54
g4					-187,42
			*	DHS(0,05)=	501,9
			**	DHS(0,01)=	636,3

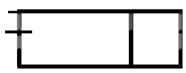
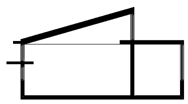
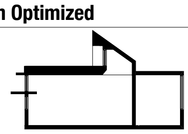
					ZONE 3
	g1	g2	g3	g4	g5
g1		420,52	455,7	239,84	173,38
g2			35,18	180,68	247,14
g3				215,86	282,32
g4					-66,46
			*	DHS(0,05)=	604,3
			**	DHS(0,01)=	766,2

G.Appendix: Optimization data

NORTH FACING CLASSROOMS OPTIMIZED RESULTS

ORIGINAL TYPOLOGY | OPTIMIZED TYPOLOGY

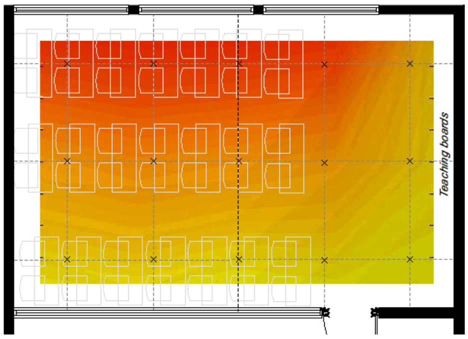


Horizontal Illuminance temporal maps-North Optimized								
								
TYPOLOGY g1 Original		OPTI	TYPOLOGY g2 Original		OPTI	TYPOLOGY g3 Original		OPTI
Too Low	34%	36%	Too Low	32%	35%	Too Low	32%	35%
In range	42%	55%	In range	32%	59%	In range	25%	55%
Too high	24%	9%	Too high	37%	6%	Too high	44%	8%

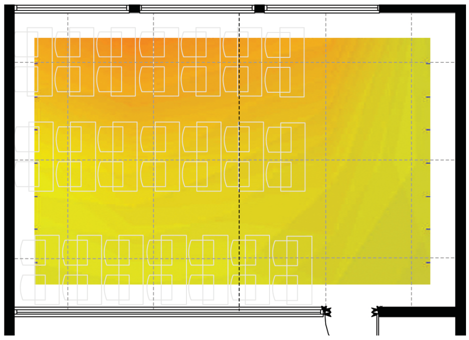
NORTH FACING CLASSROOMS OPTIMIZED RESULTS

ORIGINAL TYPOLOGY | **OPTIMIZED TYPOLOGY**

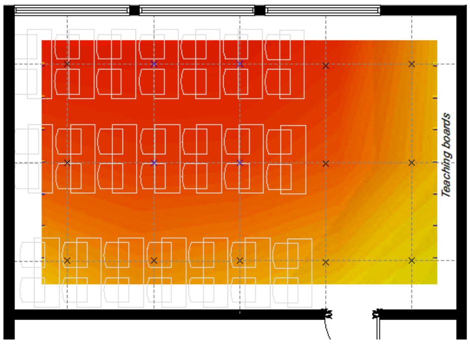
Spatial Illuminance distribution Typology g1



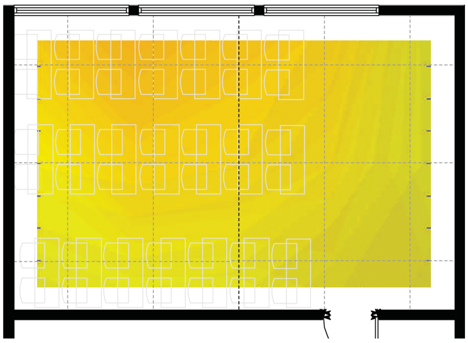
Spatial Illuminance distribution Typology g1 Opti



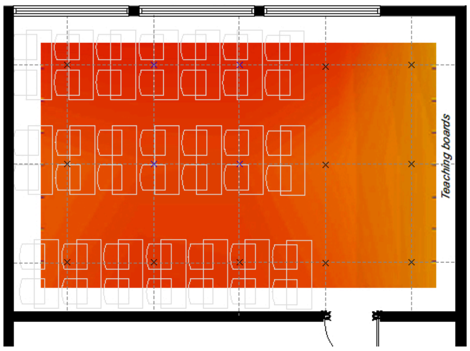
Spatial Illuminance distribution Typology g2



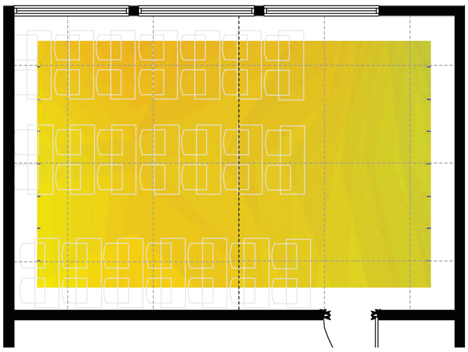
Spatial Illuminance distribution Typology g2 Opti

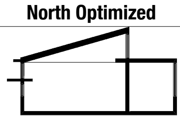
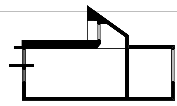


Spatial Illuminance distribution Typology g3

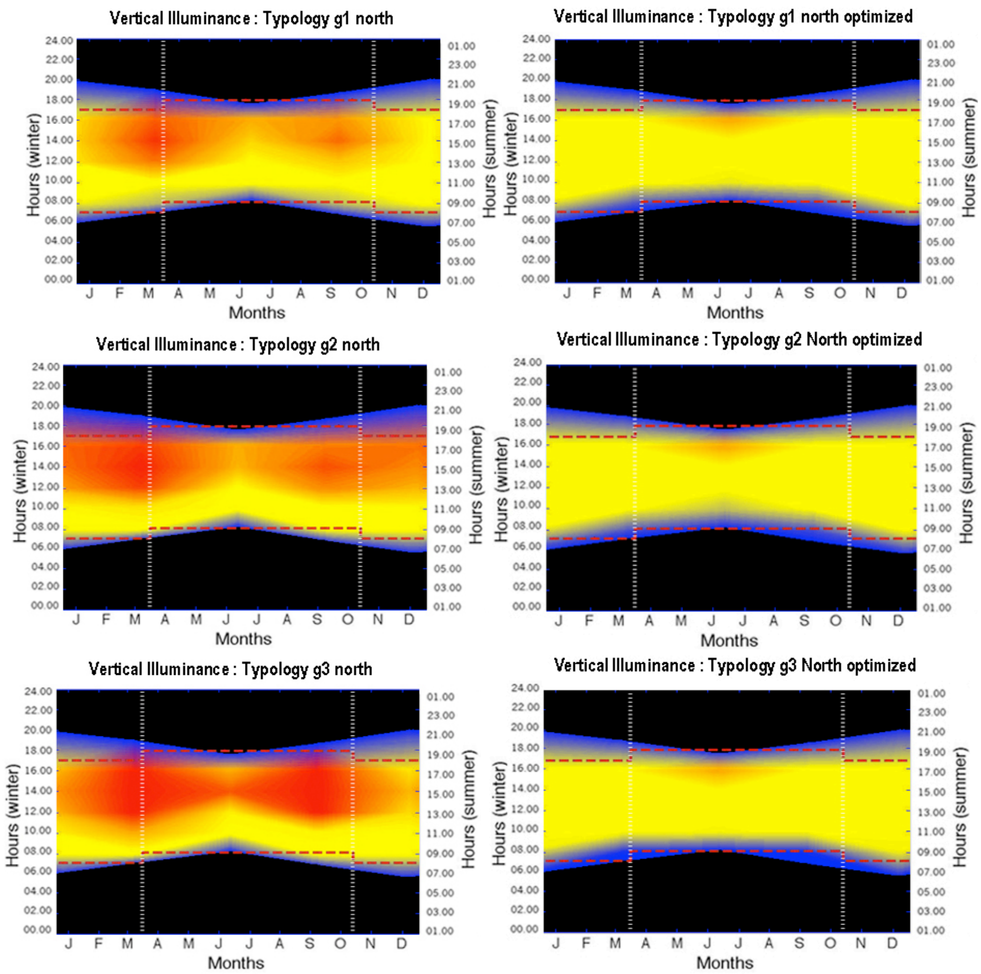


Spatial Illuminance distribution Typology g3 Opti

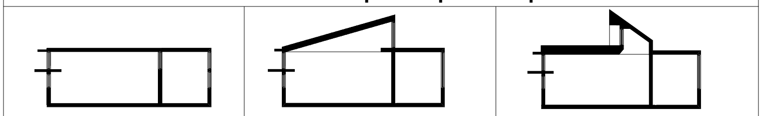


North Optimized								
								
TYPOLOGY g1 Original		OPTI	TYPOLOGY g2 Original		OPTI	TYPOLOGY g3 Original		OPTI
Too Low	9%	12%	Too Low	6%	11%	Too Low	6%	11%
In range	57%	75%	In range	45%	79%	In range	34%	77%
Too high	34%	13%	Too high	49%	10%	Too high	60%	12%

North facing classrooms optimized results

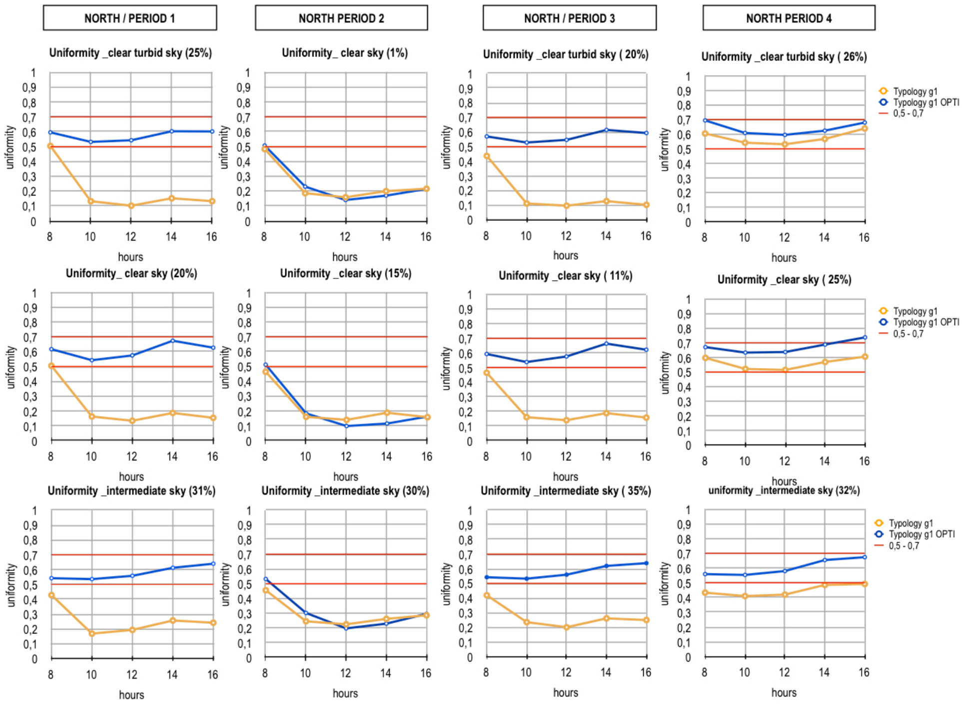


Vertical Illuminance temporal maps-North Optimized

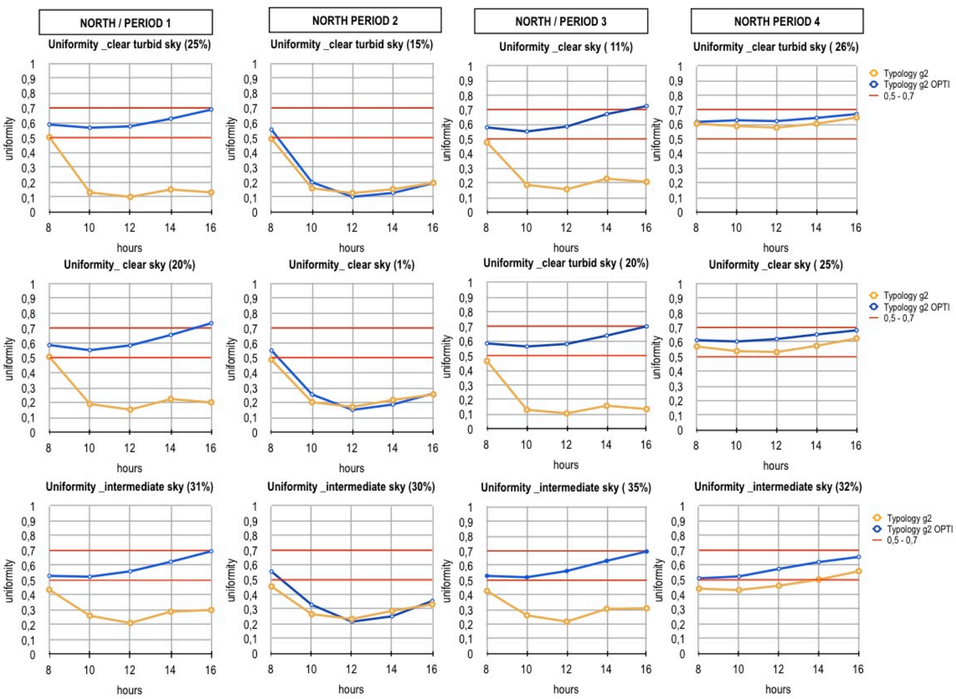


TYPOLOGY g1 Original		OPTI	TYPOLOGY g2 Original		OPTI	TYPOLOGY g3 Original		OPTI
Too Low	33%	37%	Too Low	31%	37%	Too Low	31%	38%
In range	51%	62%	In range	41%	62%	In range	39%	61%
Too high	16%	1%	Too high	28%	1%	Too high	30%	1%

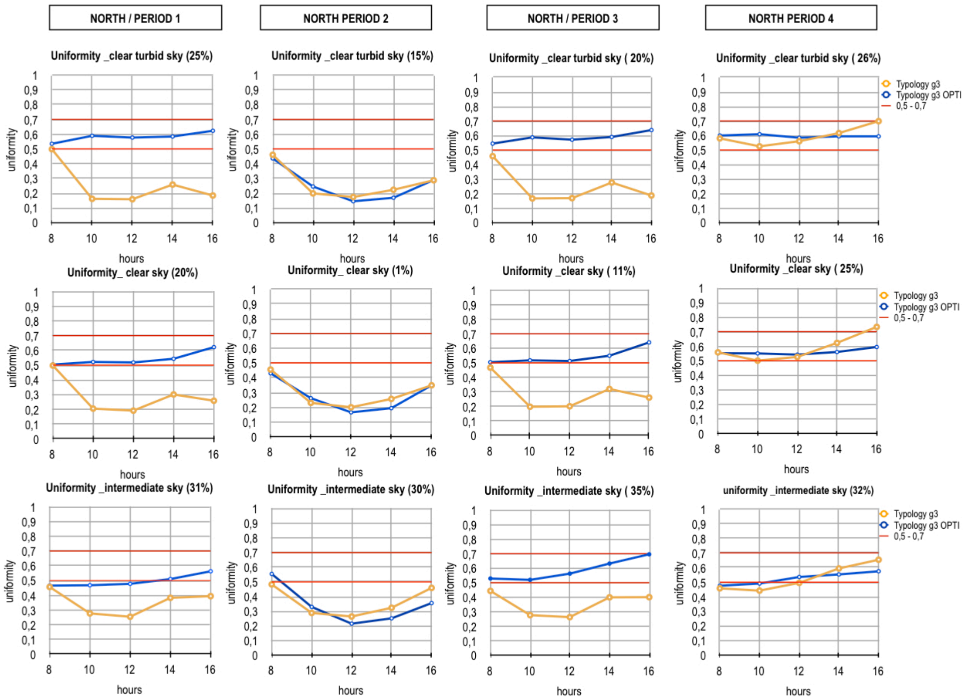
Uniformity Typology g1 North-facing classroom



Uniformity Typology g2 North-facing classroom

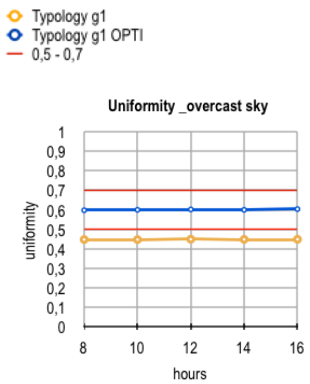


Uniformity Typology g3 North-facing classroom

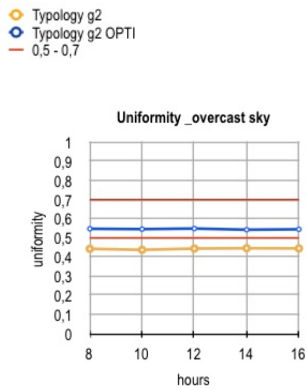


Uniformity Typology g1, Typology g2 and Typology g3 North-facing classroom with overcast sky:

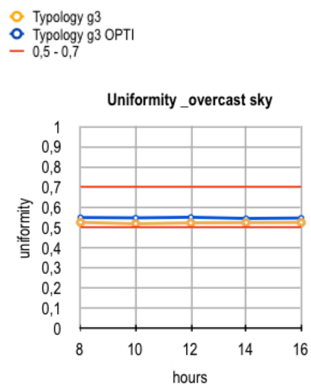
Typology g1



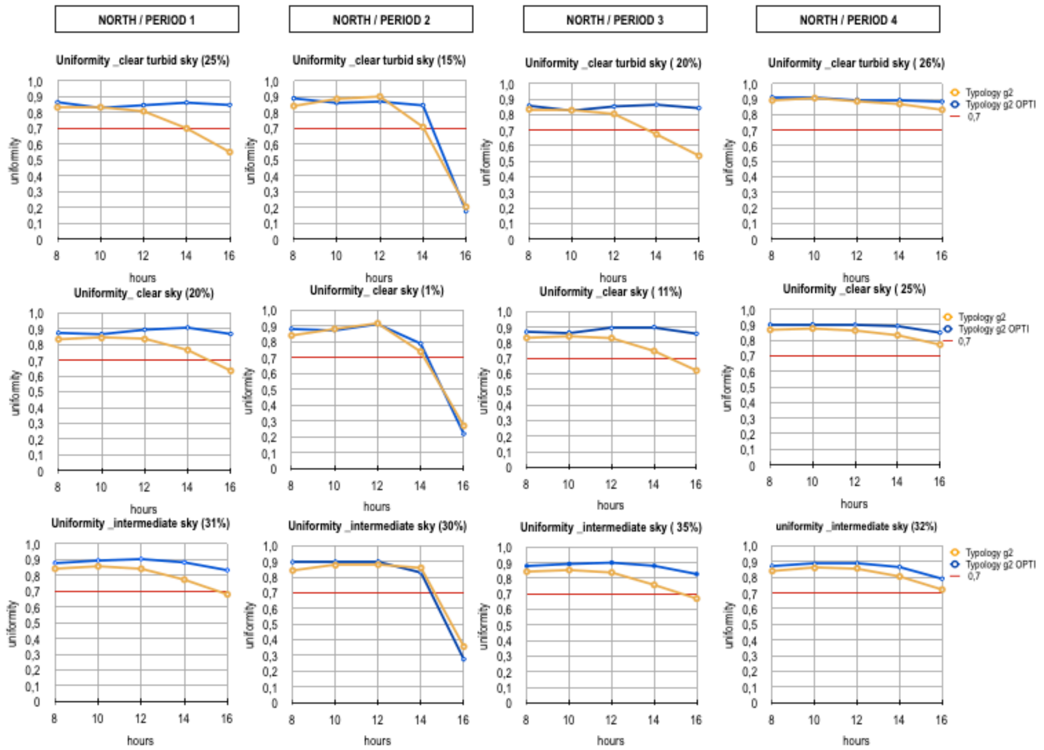
Typology g2



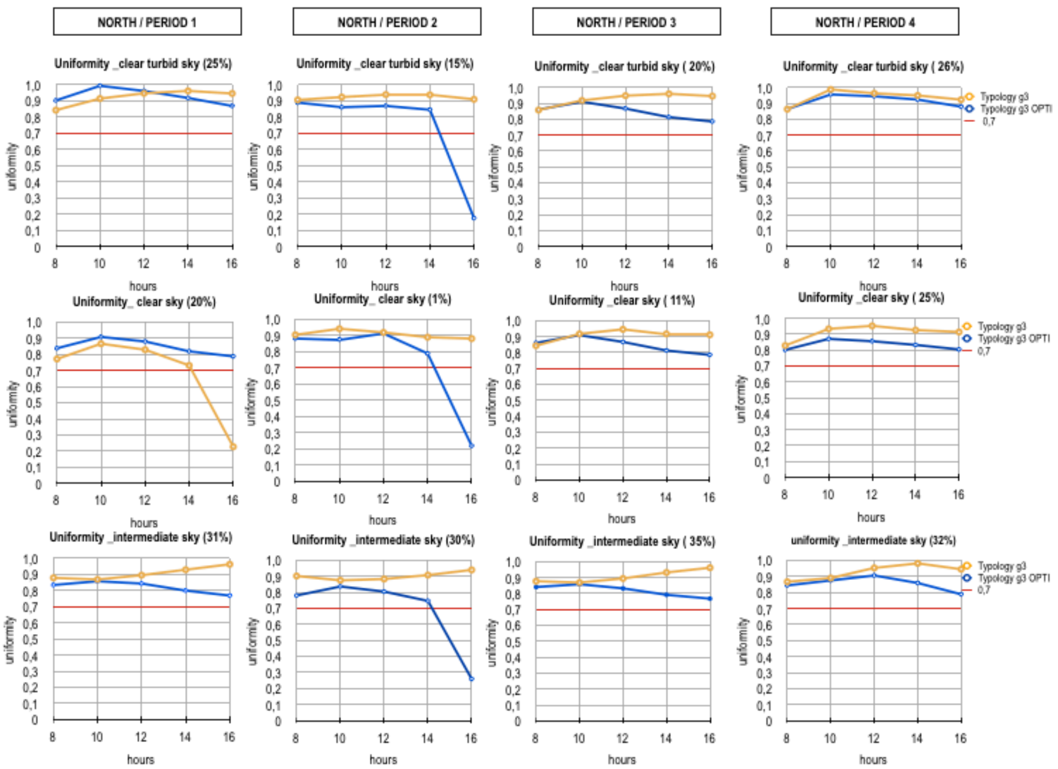
Typology g3



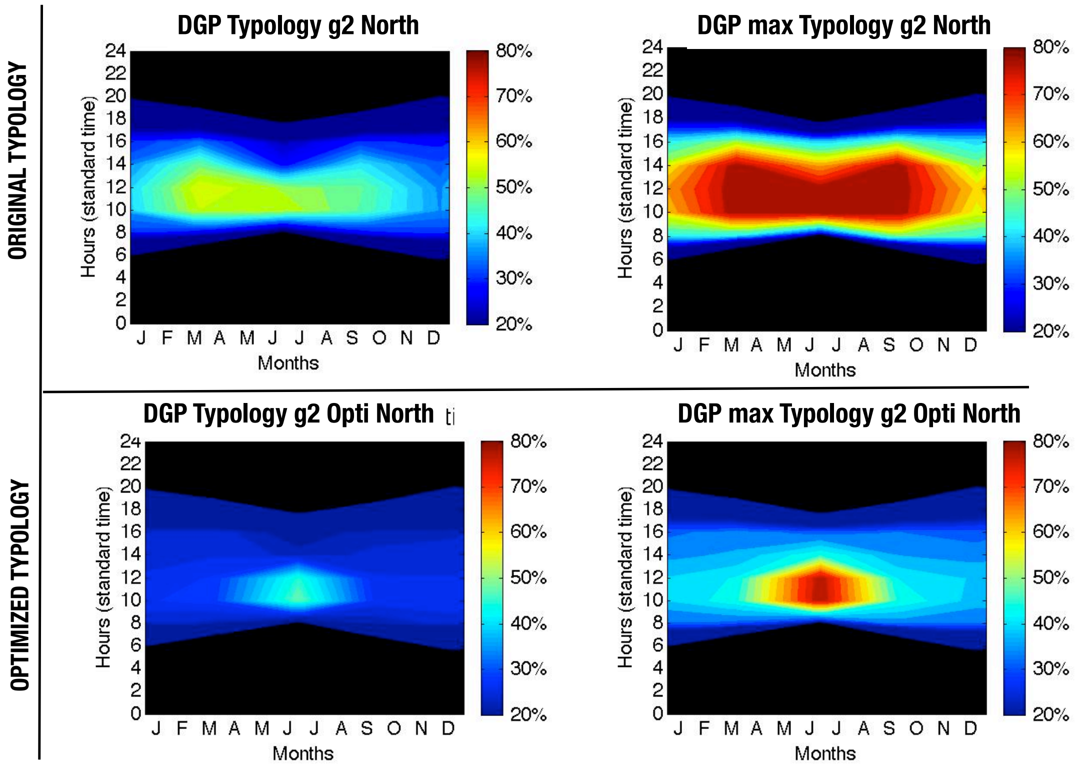
Vertical Uniformity Typology g2 North-facing classroom



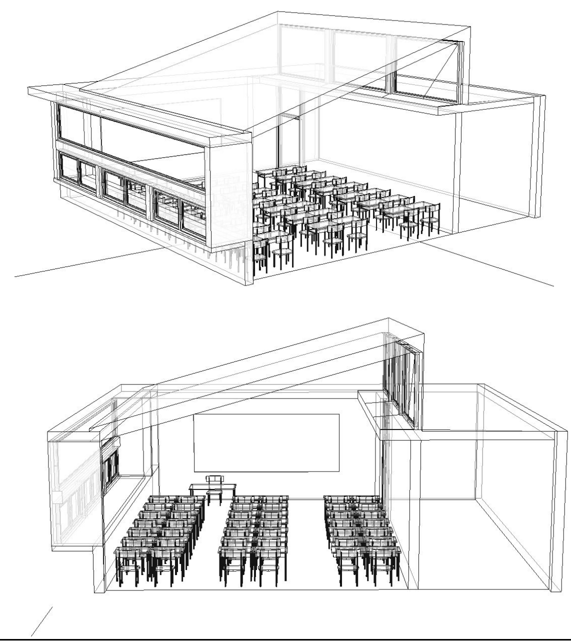
Vertical Uniformity Typology g3 North-facing classroom

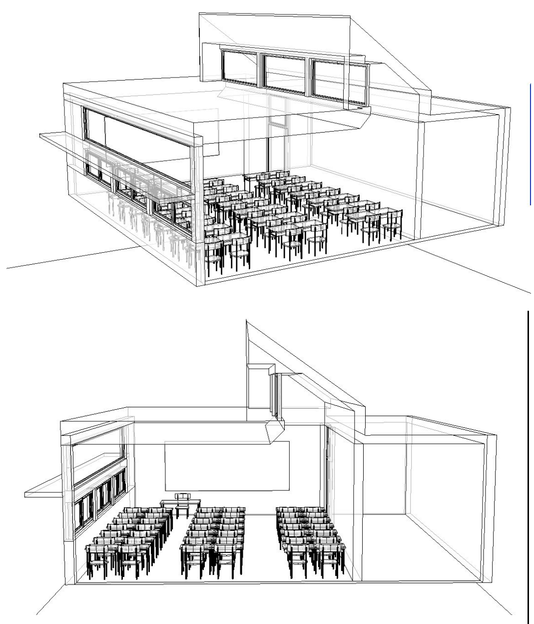


Comparison between original and optimized Typology g2's temporal DGP maps North-facing classroom

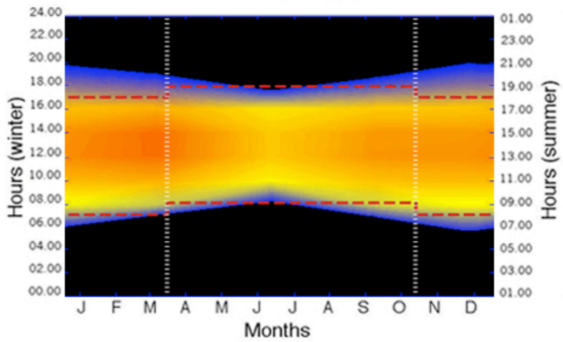


Simulations without optimized results: Typology g2 and Typology g3

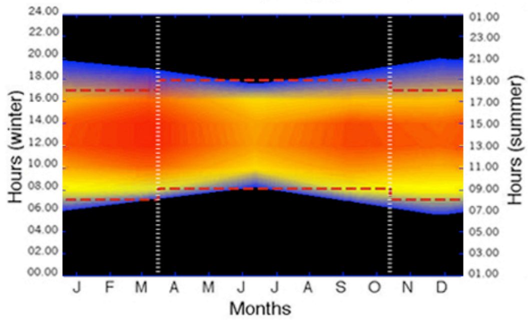




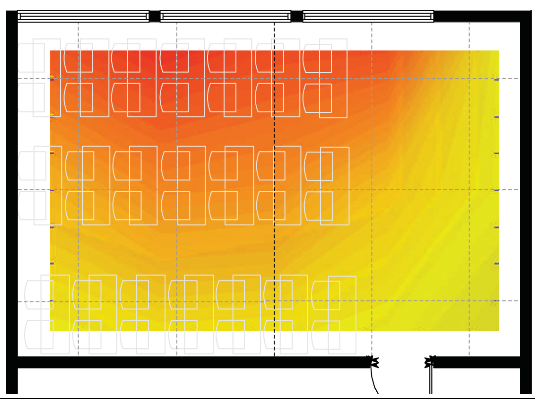
Horizontal Illuminance : Typology g2 north optimized



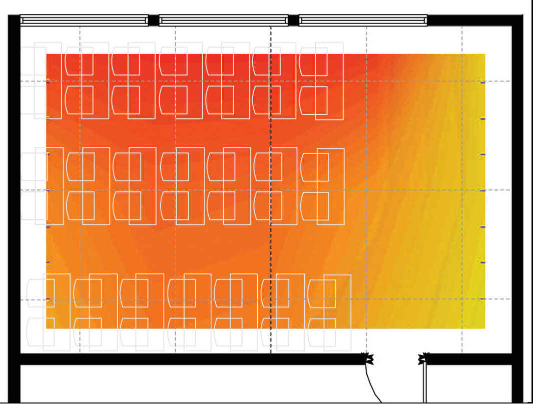
Horizontal Illuminance : Typology g3 north optimized



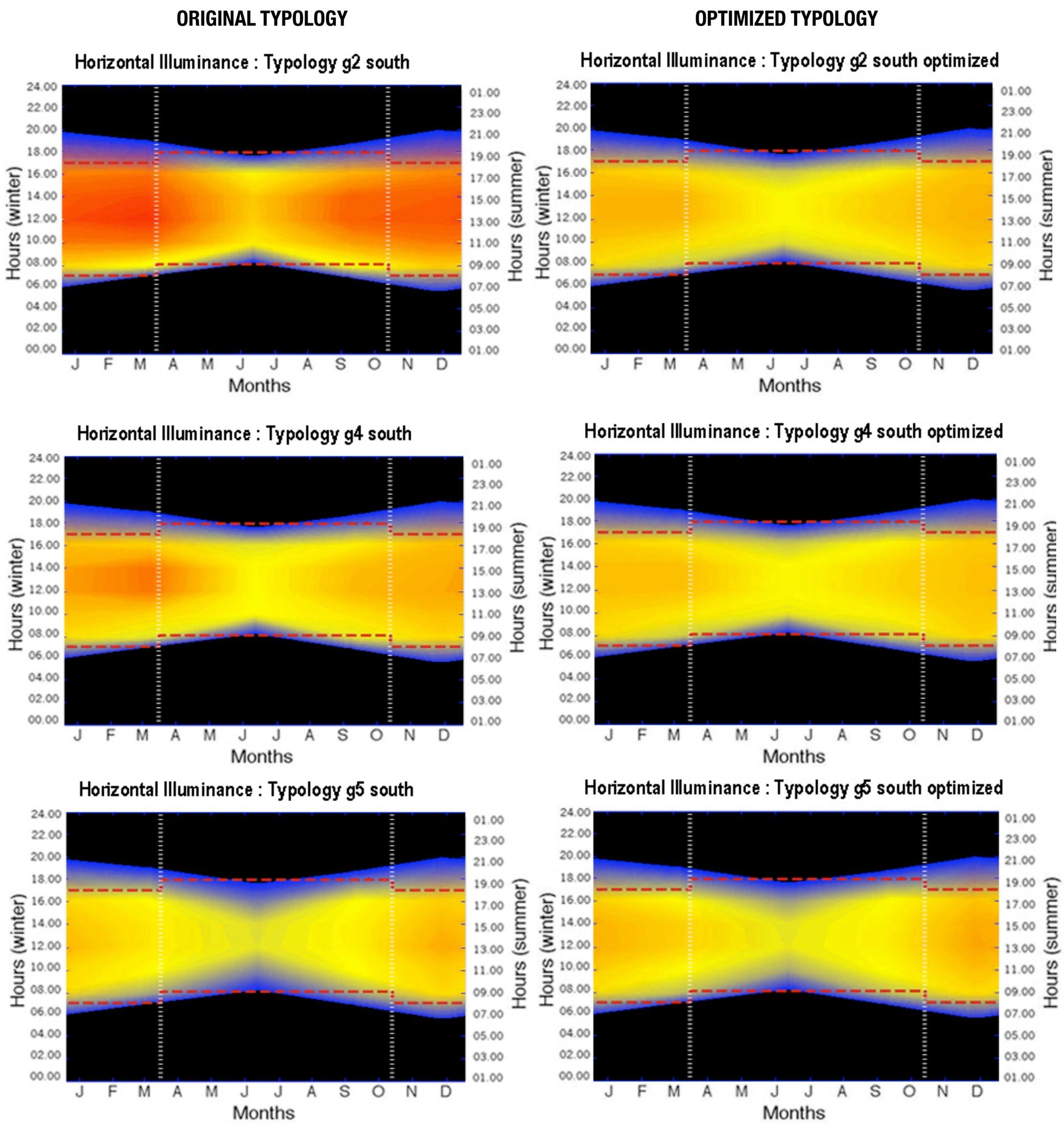
Spatial Illuminance distribution Typology g2 Opti

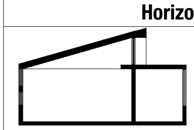
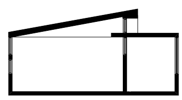
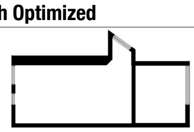


Spatial Illuminance distribution Typology g3 Opti

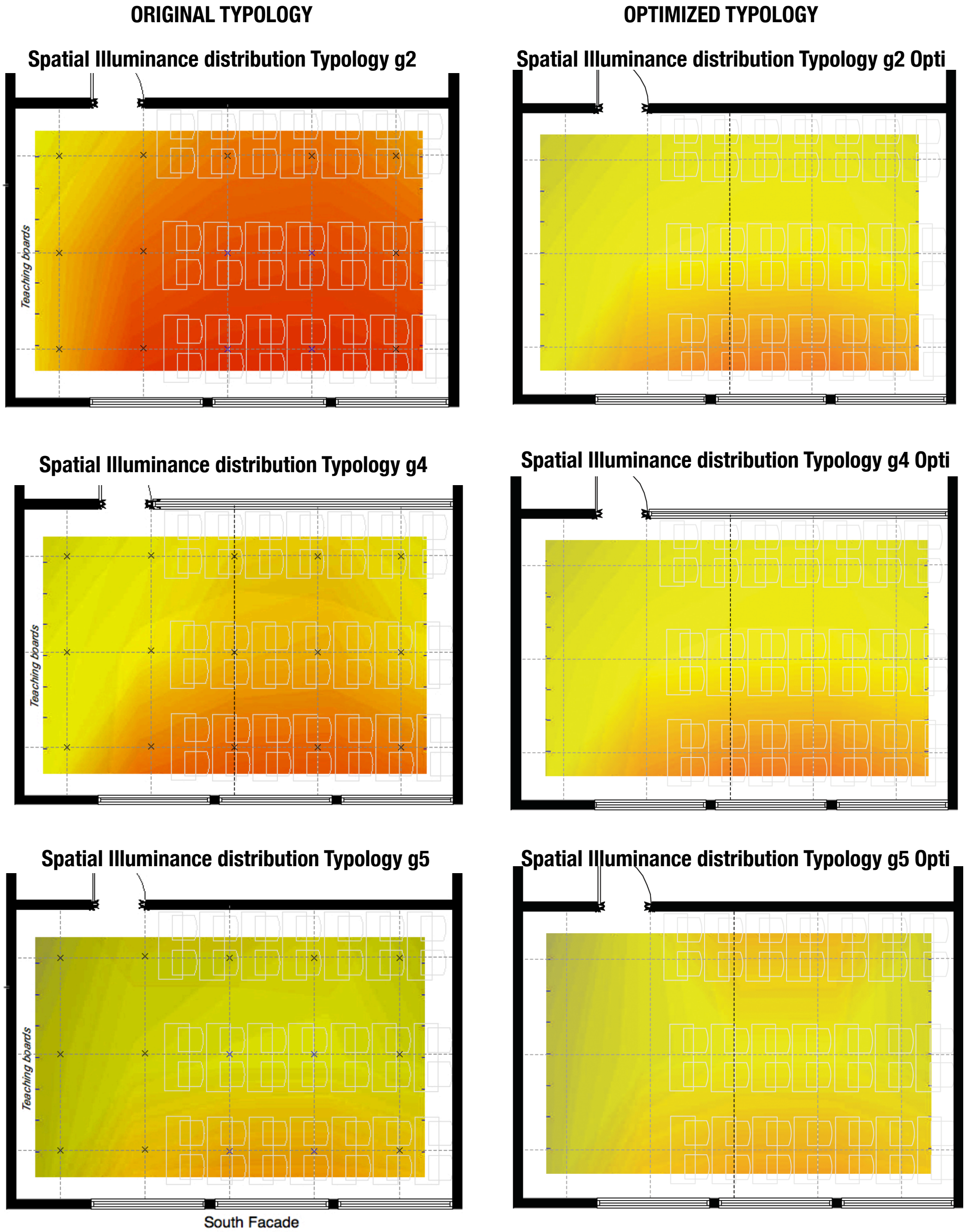


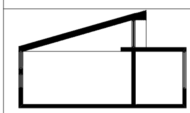
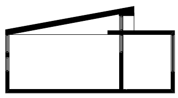
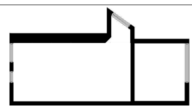
SOUTH FACING CLASSROOMS OPTIMIZED RESULTS



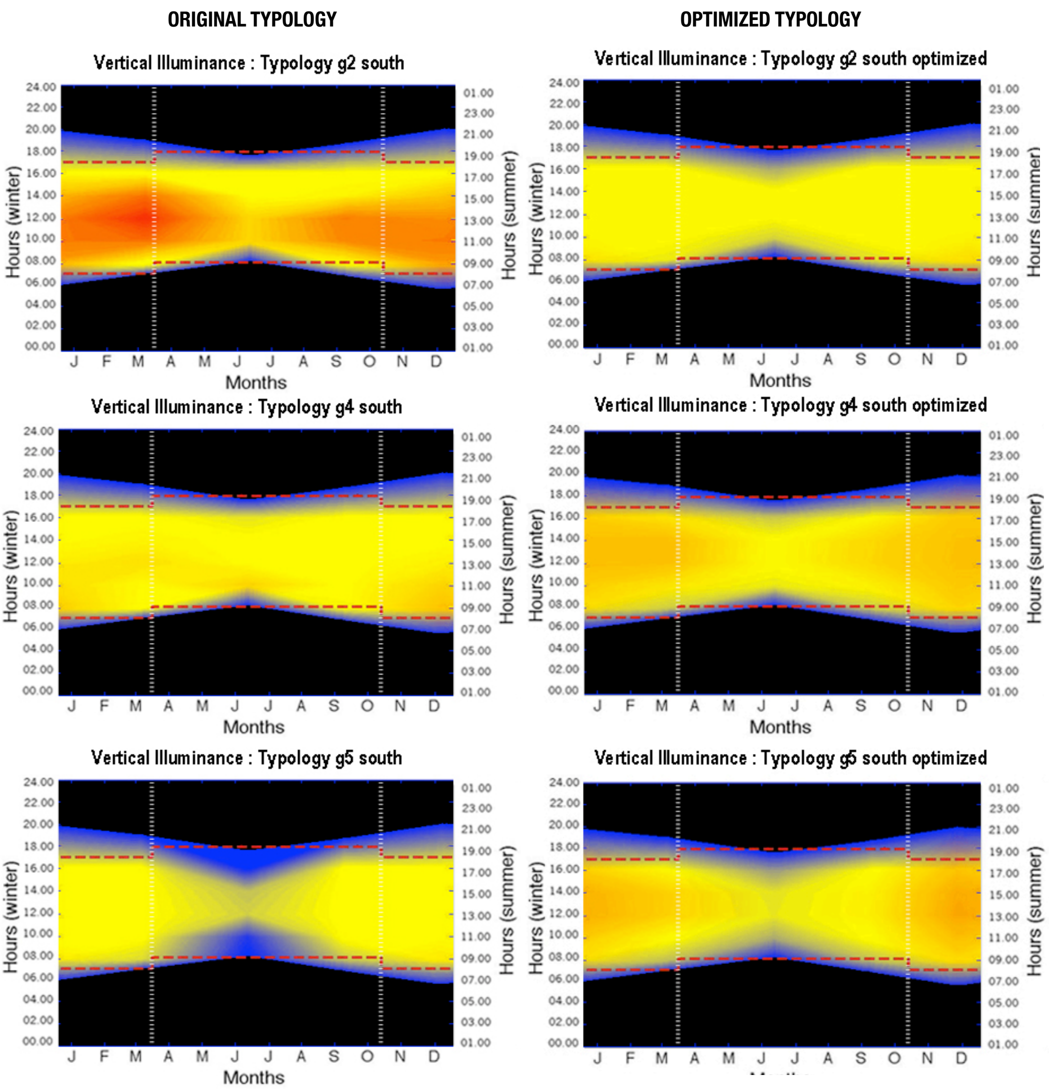
Horizontal Illuminance temporal maps - South Optimized								
								
TYPOLOGY g2 Original		OPTI	TYPOLOGY g4 Original		OPTI	TYPOLOGY g5 Original		OPTI
Too Low	31%	34%	Too Low	32%	34%	Too Low	38%	36%
In range	33%	52%	In range	50%	55%	In range	54%	55%
Too high	36%	14%	Too high	18%	11%	Too high	8%	9%

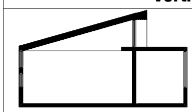
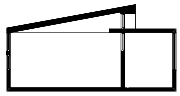
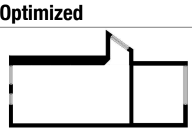
South facing classrooms optimized results



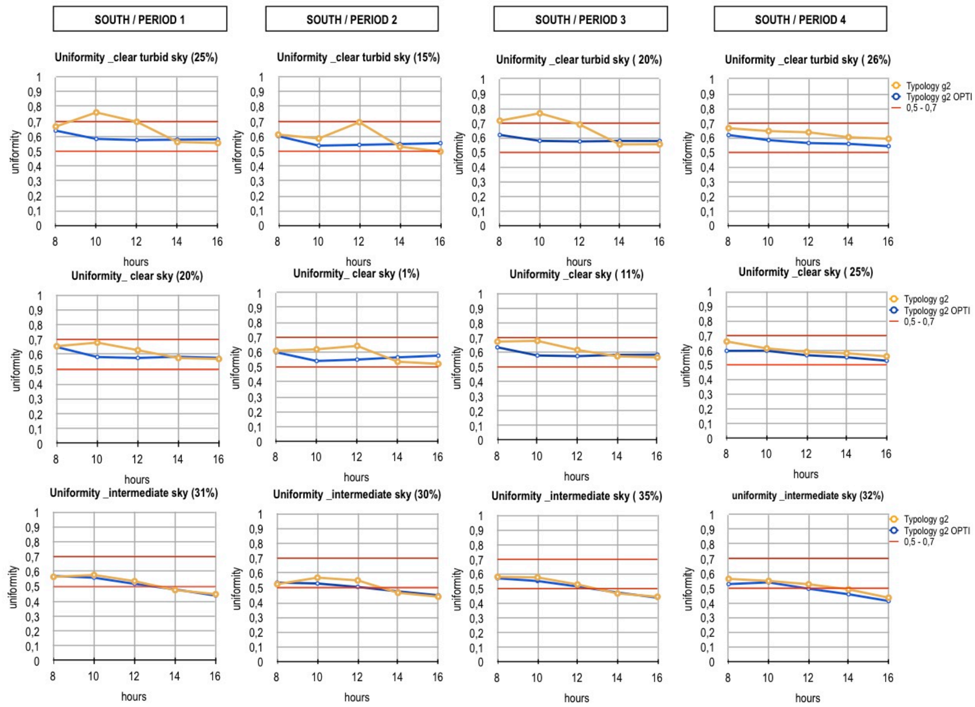
Spatial Illuminance maps - South Optimized					
					
TYPOLOGY g2 Original	OPTI	TYPOLOGY g4 Original	OPTI	TYPOLOGY g5 Original	OPTI
Too Low 5%	10%	Too Low 7%	10%	Too Low 17%	14%
In range 50%	74%	In range 71%	77%	In range 74%	75%
Too high 45%	16%	Too high 22%	13%	Too high 9%	11%

South facing classrooms optimized results

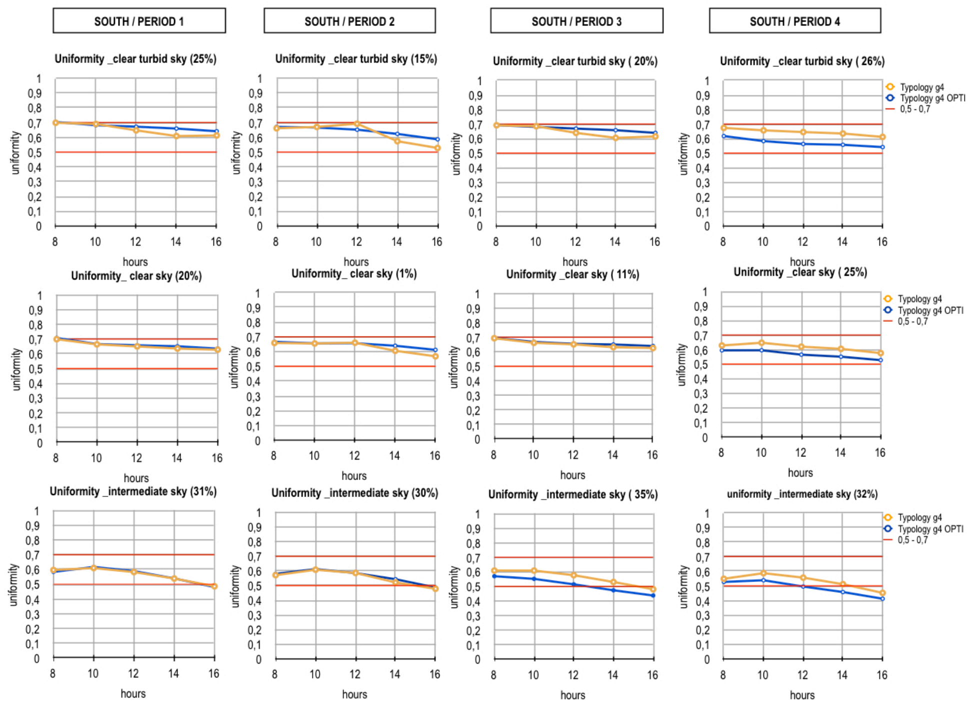


Vertical Illuminance temporal maps - South Optimized								
								
TYPOLOGY g2 Original		OPTI	TYPOLOGY g4 Original		OPTI	TYPOLOGY g5 Original		OPTI
Too Low	31%	33%	Too Low	32%	33%	Too Low	38%	38%
In range	45%	66%	In range	64%	65%	In range	61%	62%
Too high	24%	1%	Too high	4%	2%	Too high	1%	0%

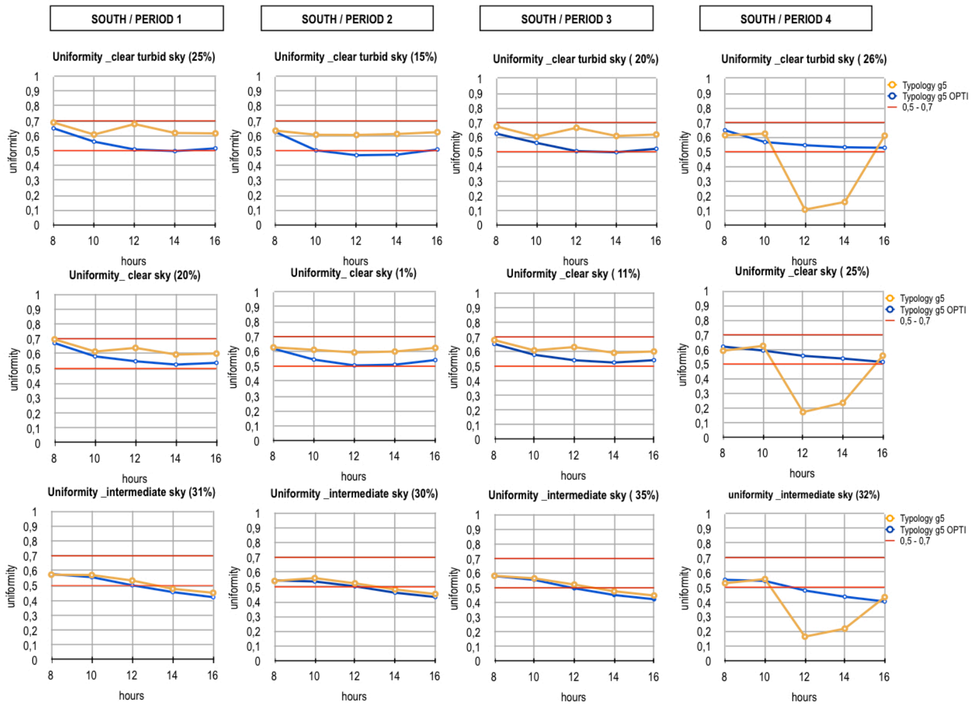
Uniformity Typology g2 South-facing classroom



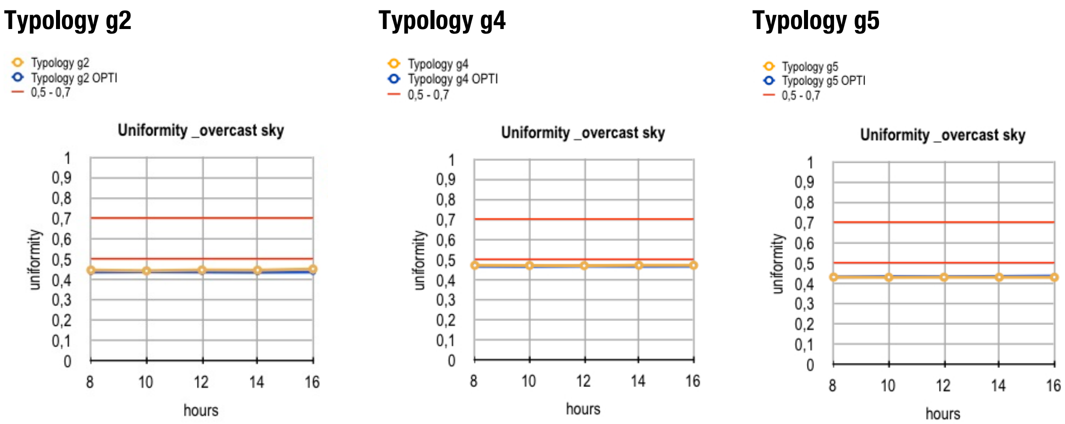
Uniformity Typology g4 South-facing classroom



Uniformity Typology g5 South-facing classroom

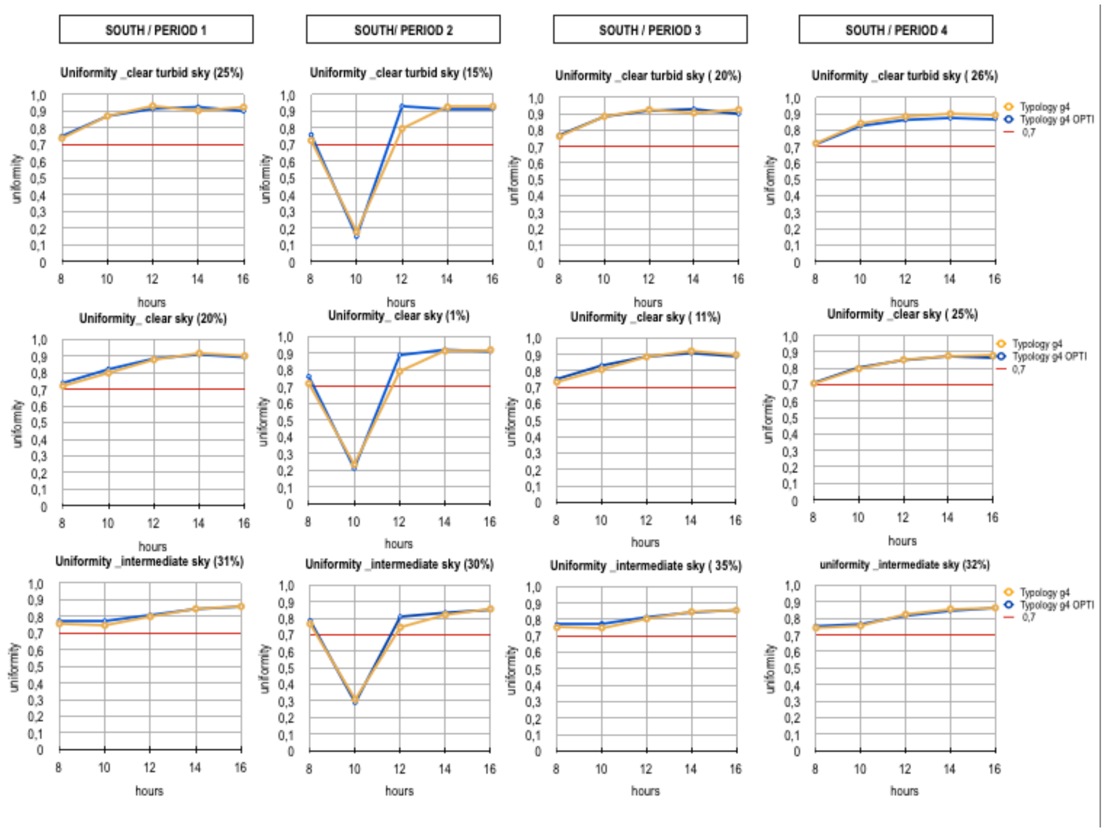


Uniformity Typology g2, Typology g4 and Typology g5 South-facing classroom with overcast sky:

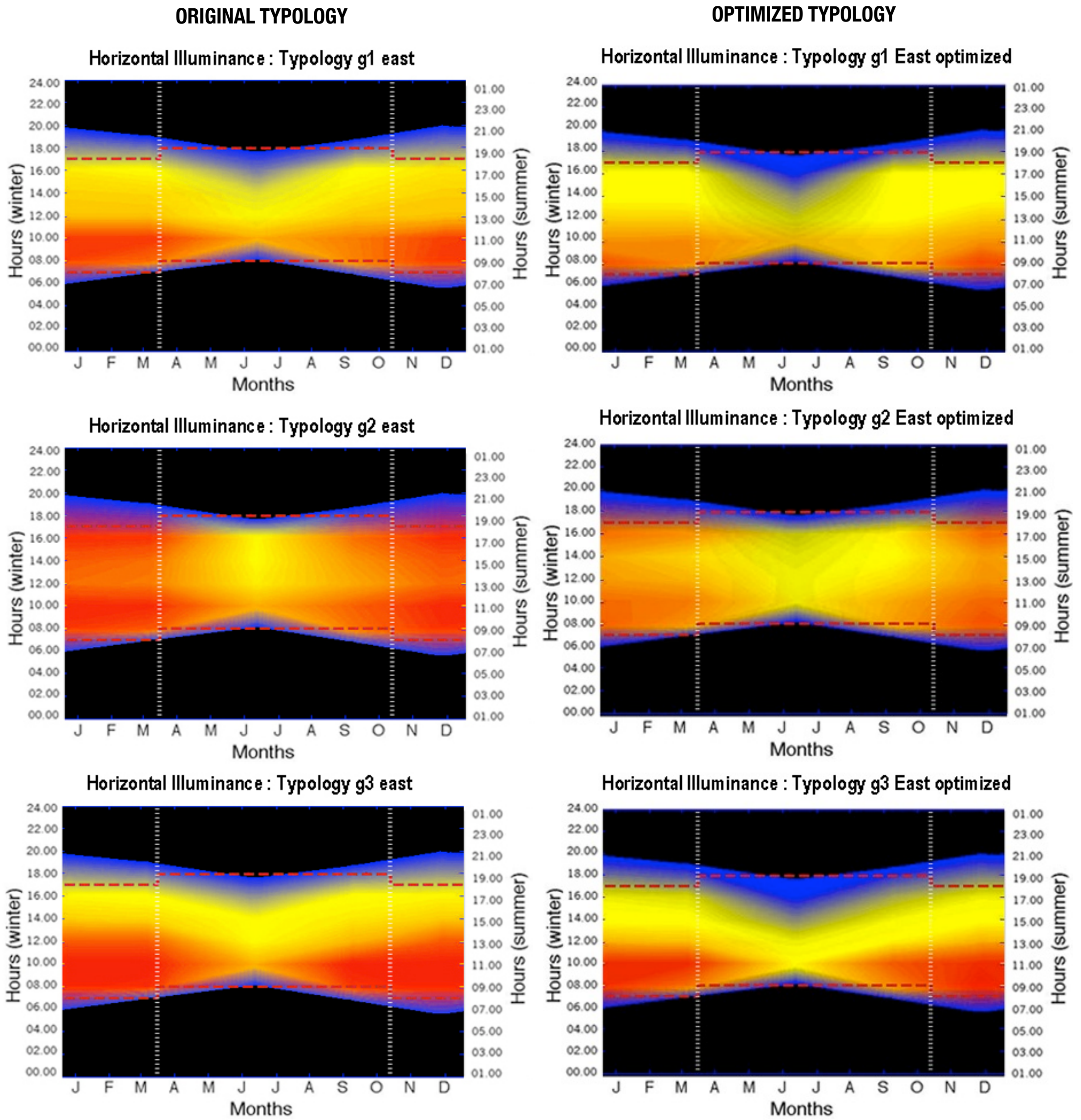


Period/Overcast	**(1) = 24 %**	**(2) = 54 %**	**(3) = 34 %**	**(4) = 18%**

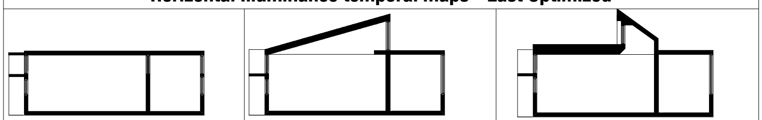
Vertical Uniformity Typology g4 South-facing classroom



EAST FACING CLASSROOMS OPTIMIZED RESULTS



Horizontal Illuminance temporal maps - East Optimized

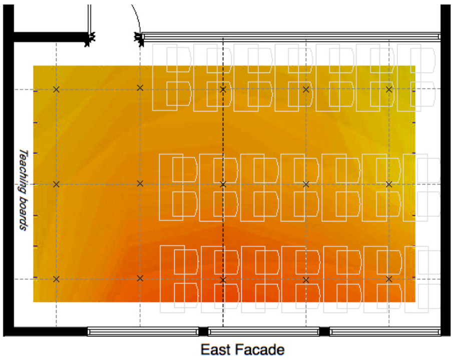


TYPOLOGY g1 Original		OPTI	TYPOLOGY g2 Original		OPTI	TYPOLOGY g3 Original		OPTI
Too Low	33%	35%	Too Low	31%	32%	Too Low	32%	37%
In range	41%	50%	In range	21%	42%	In range	33%	41%
Too high	26%	15%	Too high	48%	26%	Too high	35%	22%

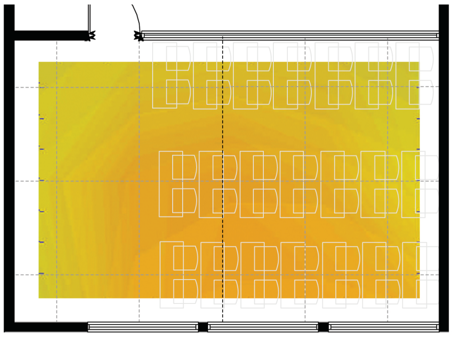
East facing classrooms optimized results

ORIGINAL TYPOLOGY	OPTIMIZED TYPOLOGY

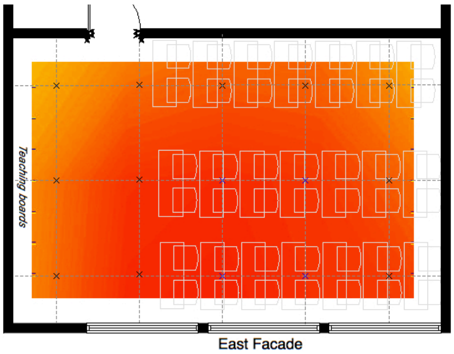
Spatial Illuminance distribution Typology g1



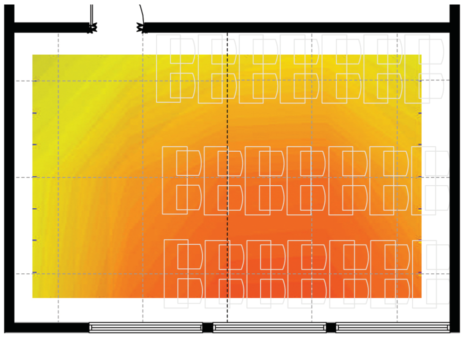
Spatial Illuminance distribution Typology g1 Opti



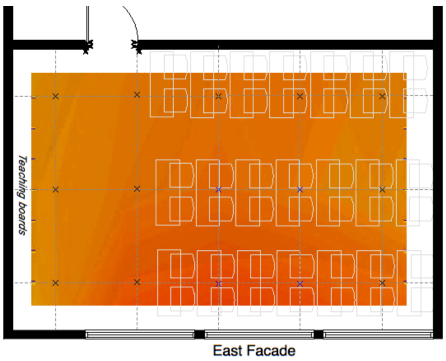
Spatial Illuminance distribution Typology g2



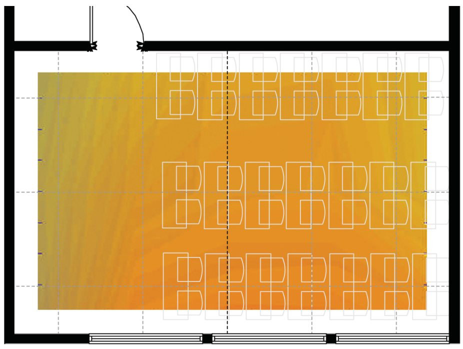
Spatial Illuminance distribution Typology g2 Opti

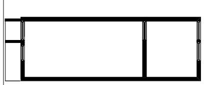
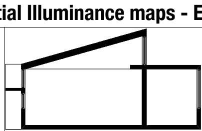
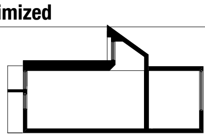


Spatial Illuminance distribution Typology g3

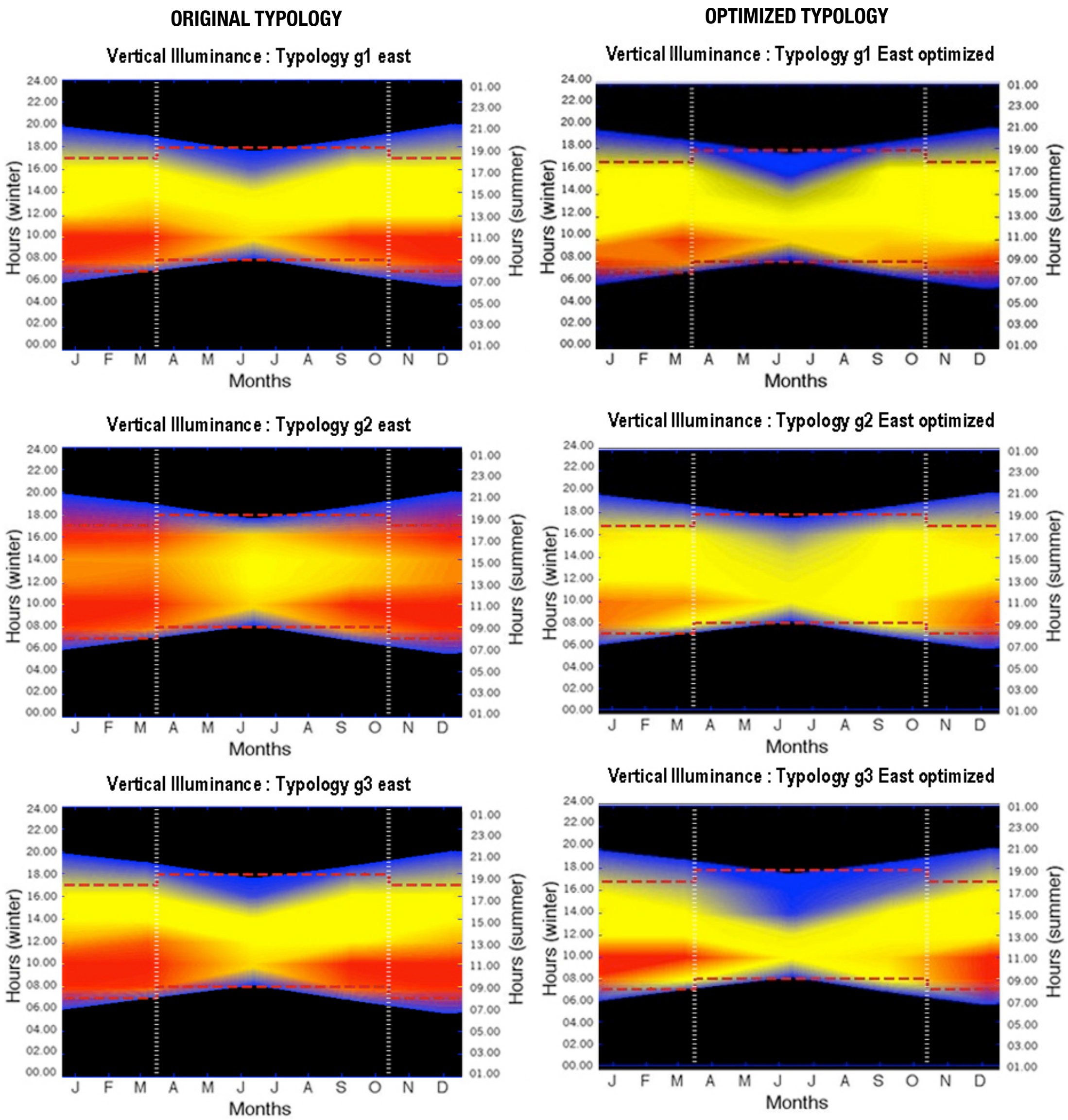


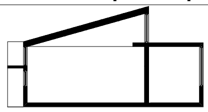
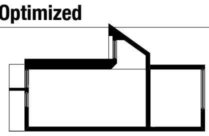
Spatial Illuminance distribution Typology g3 Opti



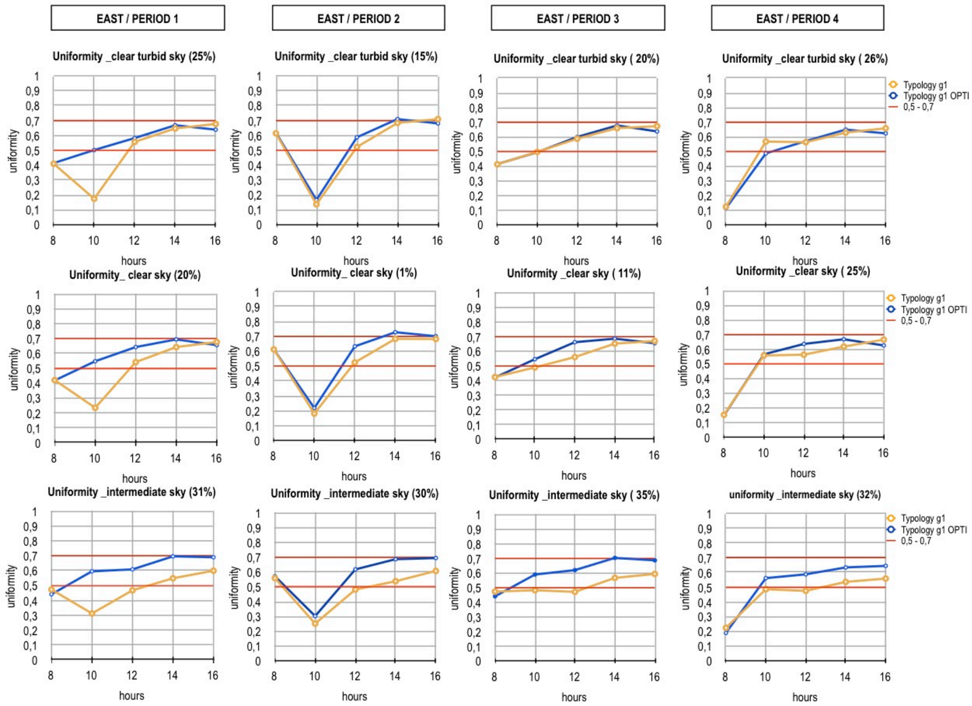
Spatial Illuminance maps - East Optimized								
								
TYPOLOGY g1 Original		OPTI	TYPOLOGY g2 Original		OPTI	TYPOLOGY g3 Original		OPTI
Too Low	9%	14%	Too Low	5%	8%	Too Low	8%	16%
In range	59%	69%	In range	36%	62%	In range	48%	57%
Too high	32%	17%	Too high	59%	30%	Too high	44%	27%

East facing classrooms optimized results

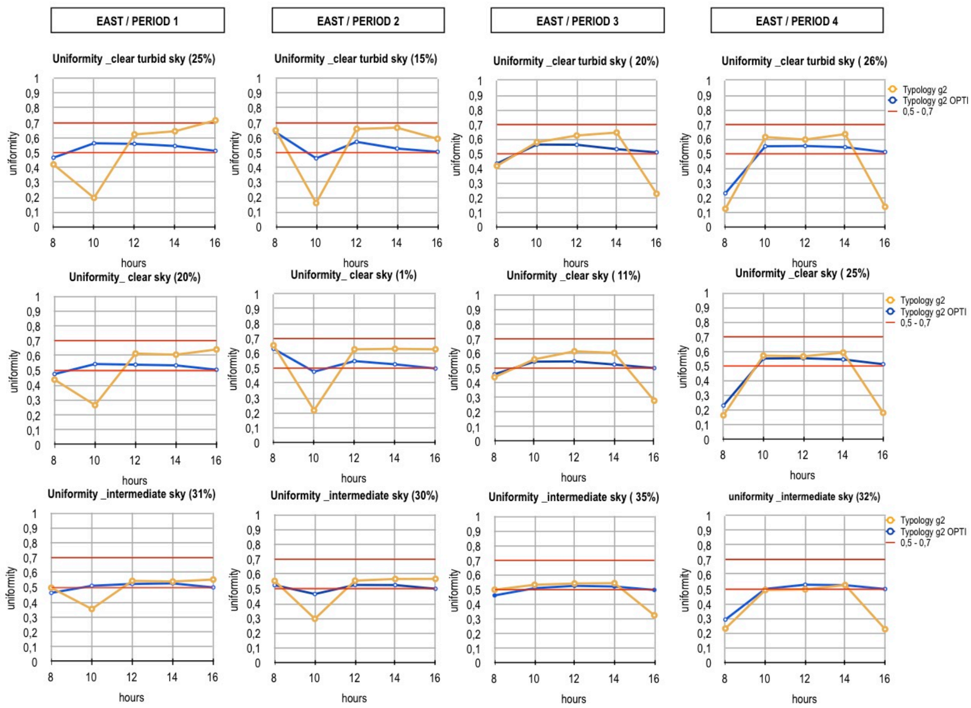


Vertical Illuminance temporal maps - East Optimized								
								
TYPOLOGY g1 Original		OPTI	TYPOLOGY g2 Original		OPTI	TYPOLOGY g3 Original		OPTI
Too Low	33%	34%	Too Low	31%	33%	Too Low	33%	39%
In range	44%	53%	In range	24%	56%	In range	38%	46%
Too high	23%	13%	Too high	45%	11%	Too high	29%	15%

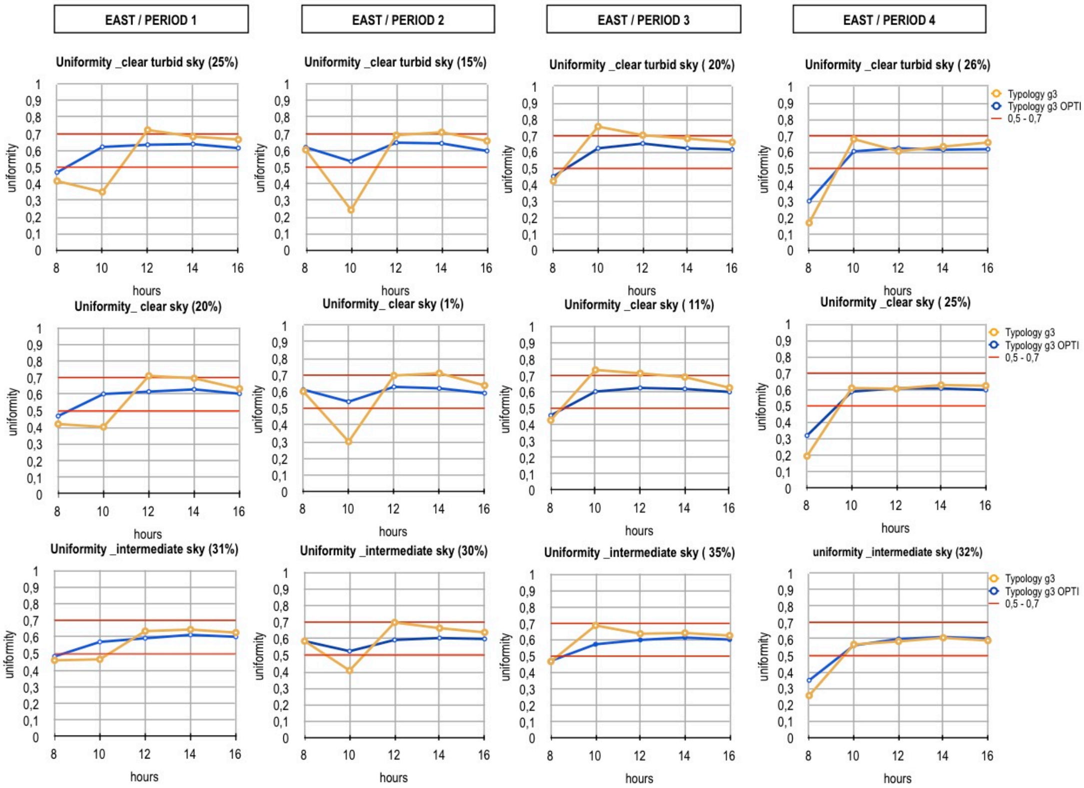
Uniformity Typology g1 East-facing classroom



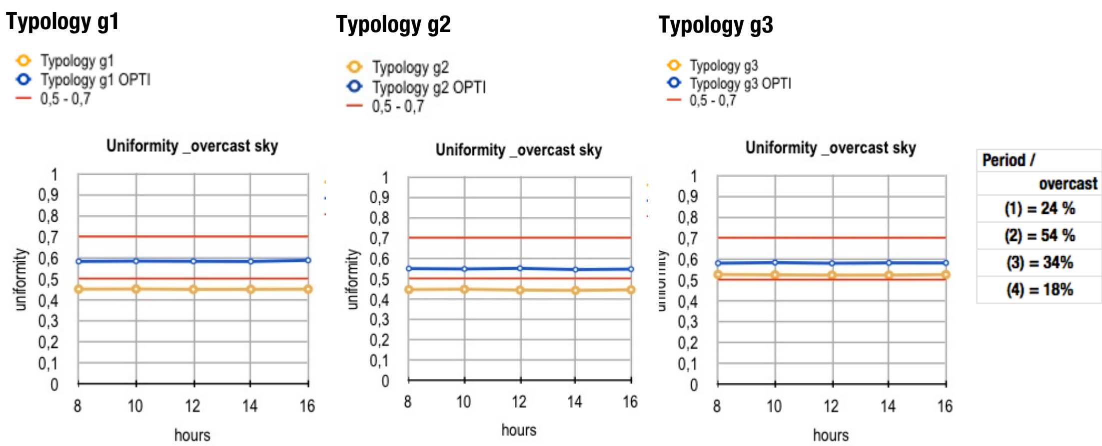
Uniformity Typology g2 East-facing classroom



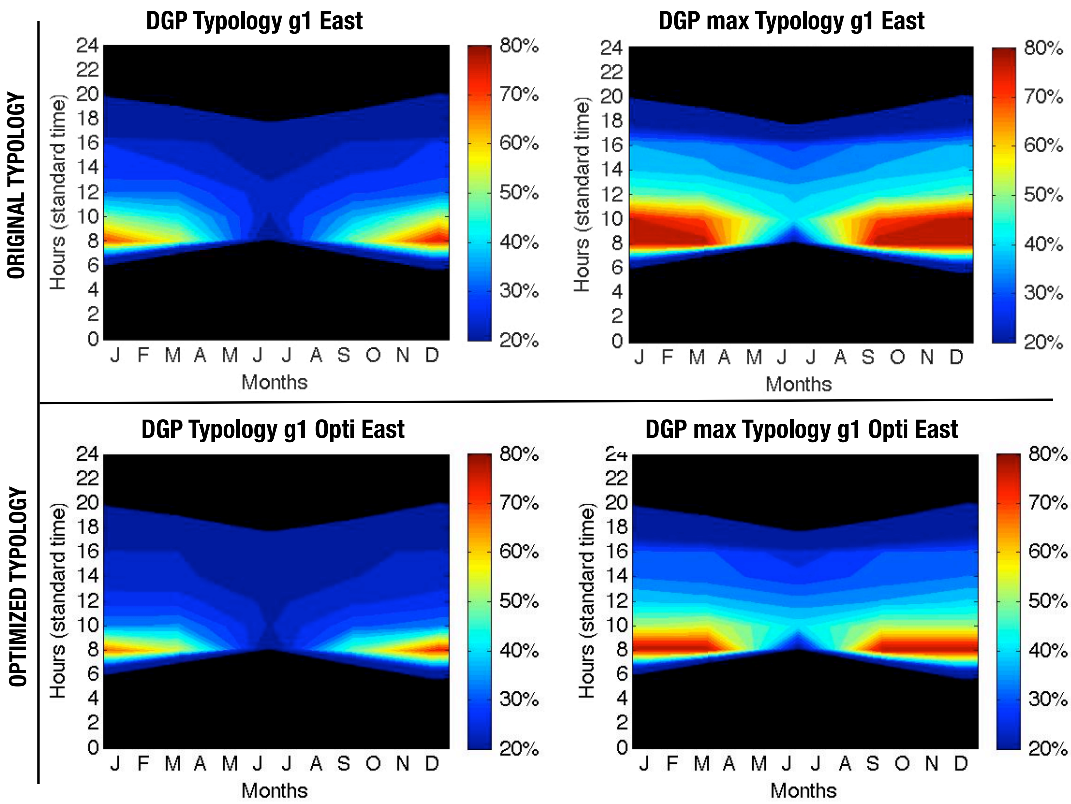
Uniformity Typology g3 East-facing classroom



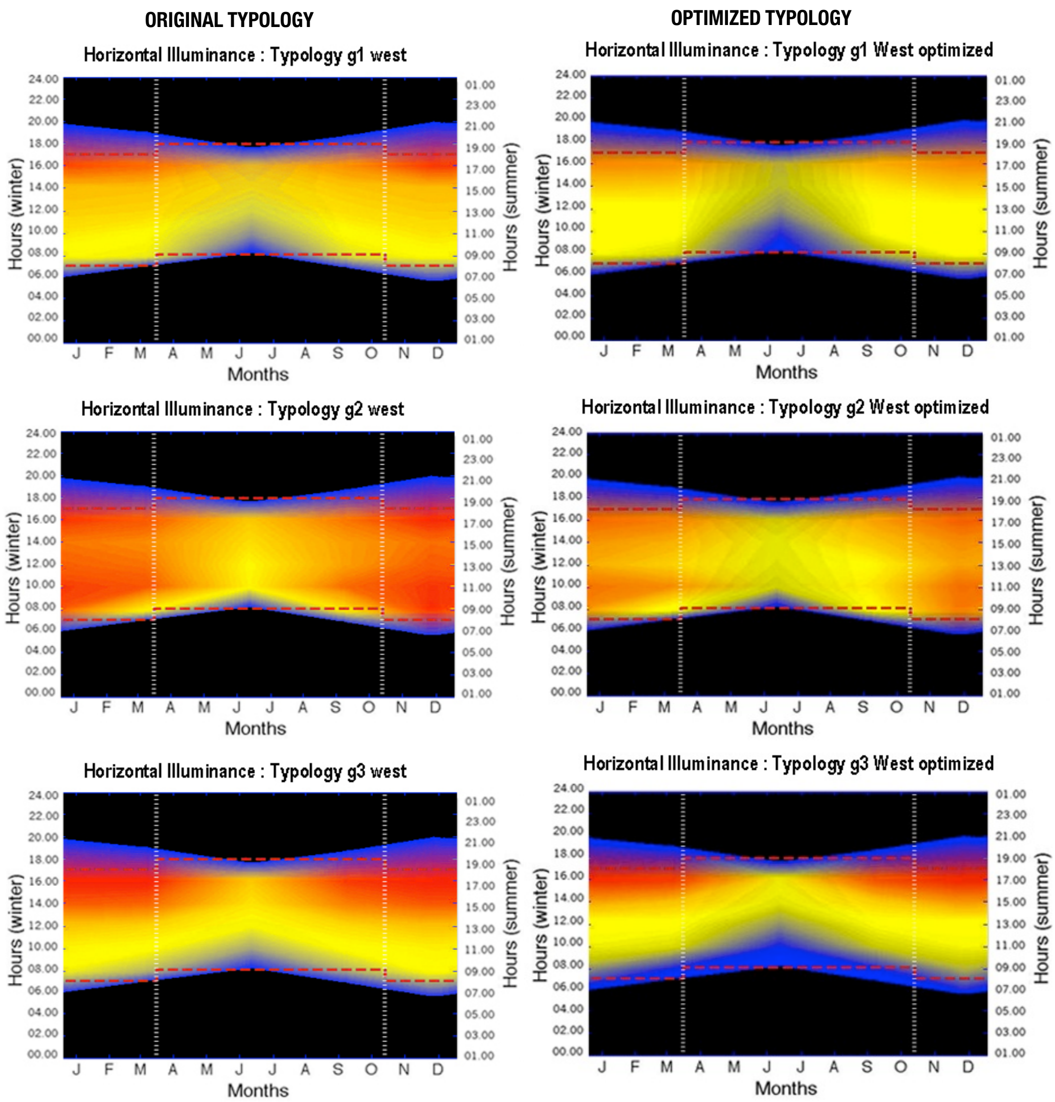
Uniformity Typology g1, Typology g2 and Typology g3 East-facing classroom with overcast sky:



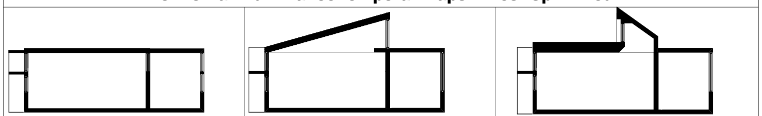
Comparison between original and optimized Typology g1's temporal DGP maps East-facing classroom


ORIGINAL TYPOLOGY
DGP Typology g1 East
DGP max Typology g1 East
OPTIMIZED TYPOLOGY
DGP Typology g1 Opti East
DGP max Typology g1 Opti East
Hours (standard time)
Months
J F M A M J J A S O N D
0 2 4 6 8 10 12 14 16 18 20 22 24
20% 30% 40% 50% 60% 70% 80%

WEST FACING CLASSROOMS OPTIMIZED RESULTS



Horizontal Illuminance temporal maps - West Optimized								
TYPOLOGY g1 Original		OPTI	TYPOLOGY g2 Original		OPTI	TYPOLOGY g3 Original		OPTI
Too Low	34%	37%	Too Low	31%	33%	Too Low	35%	44%
In range	49%	55%	In range	28%	45%	In range	40%	42%
Too high	17%	8%	Too high	41%	22%	Too high	25%	14%

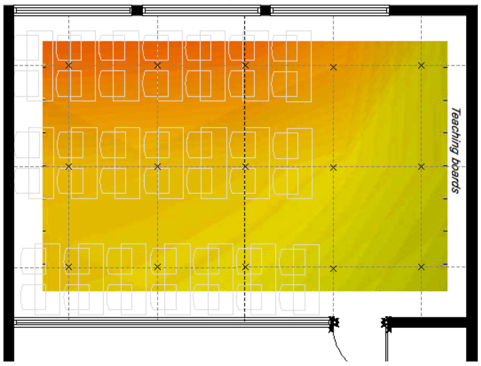


West facing classrooms optimized results

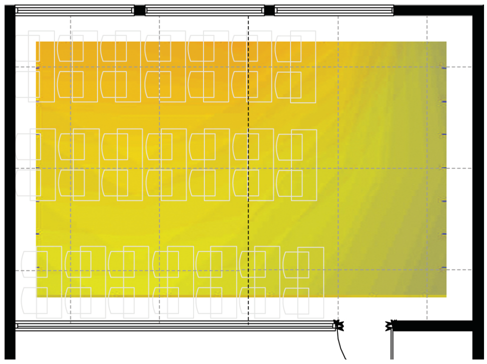
ORIGINAL TYPOLOGY

OPTIMIZED TYPOLOGY

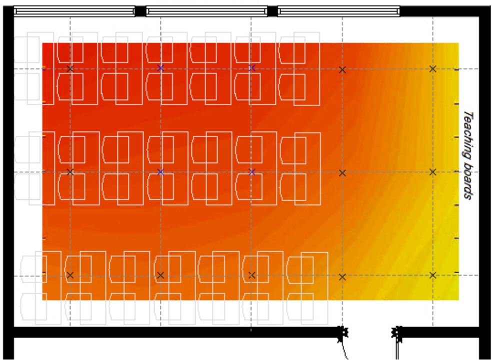
Spatial Illuminance distribution Typology g1



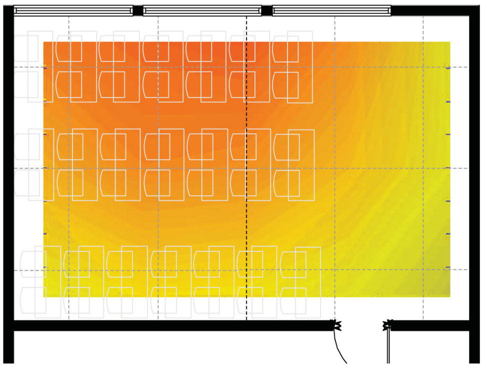
Spatial Illuminance distribution Typology g1 Opti



Spatial Illuminance distribution Typology g2

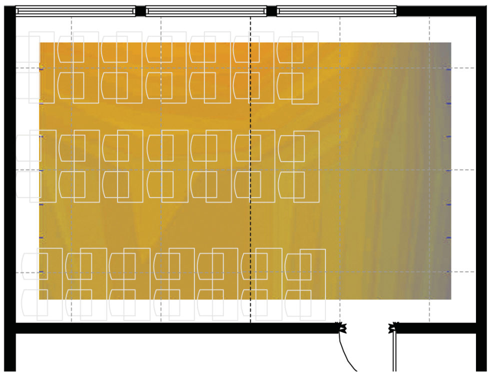


Spatial Illuminance distribution Typology g2 Opti

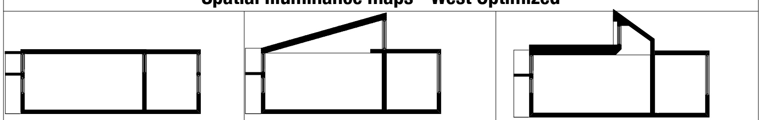


Spatial Illuminance distribution Typology g3

Spatial Illuminance distribution Typology g3 Opti

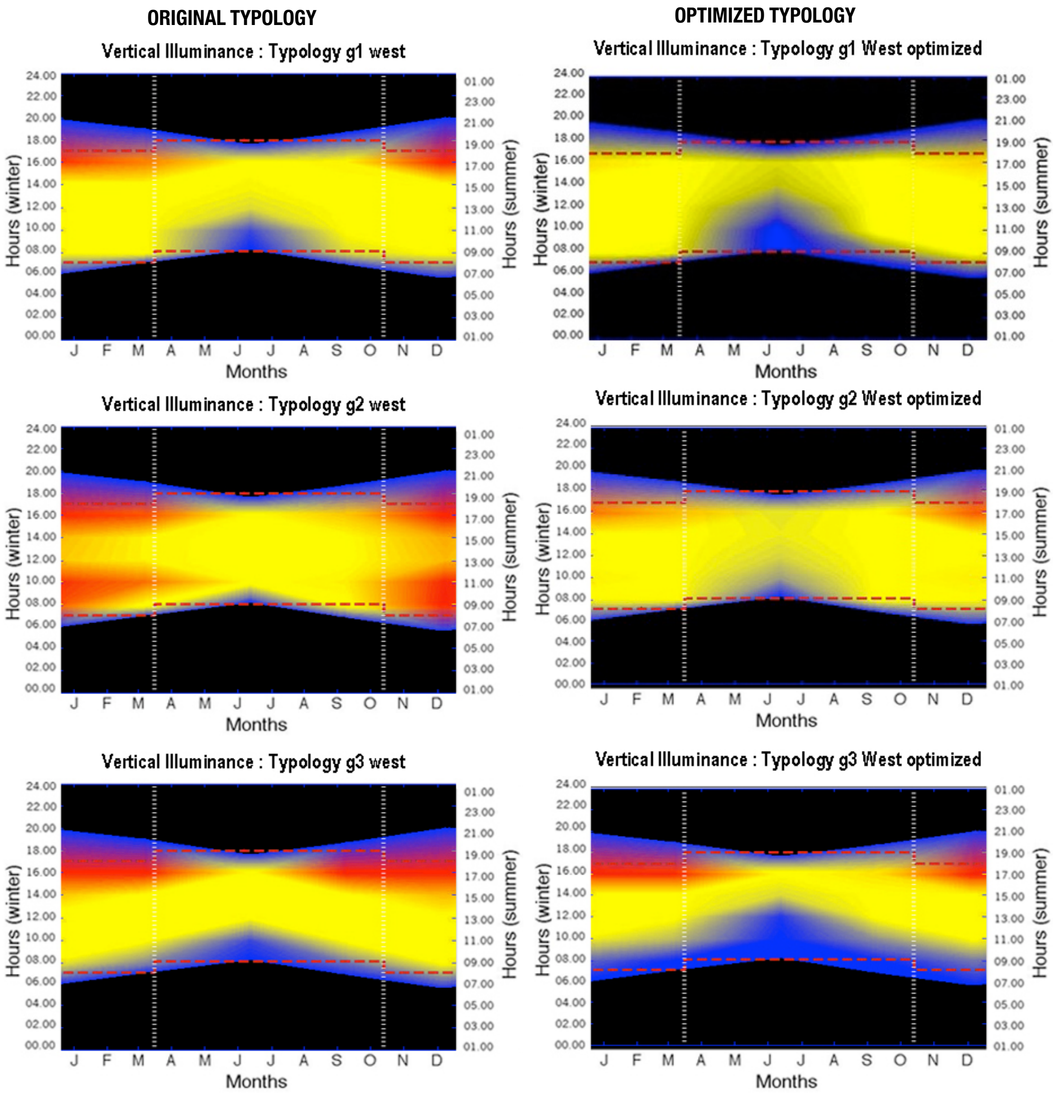


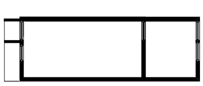
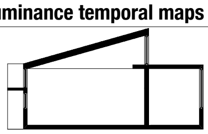
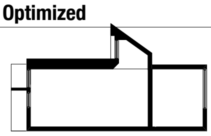
Spatial Illuminance maps - West Optimized



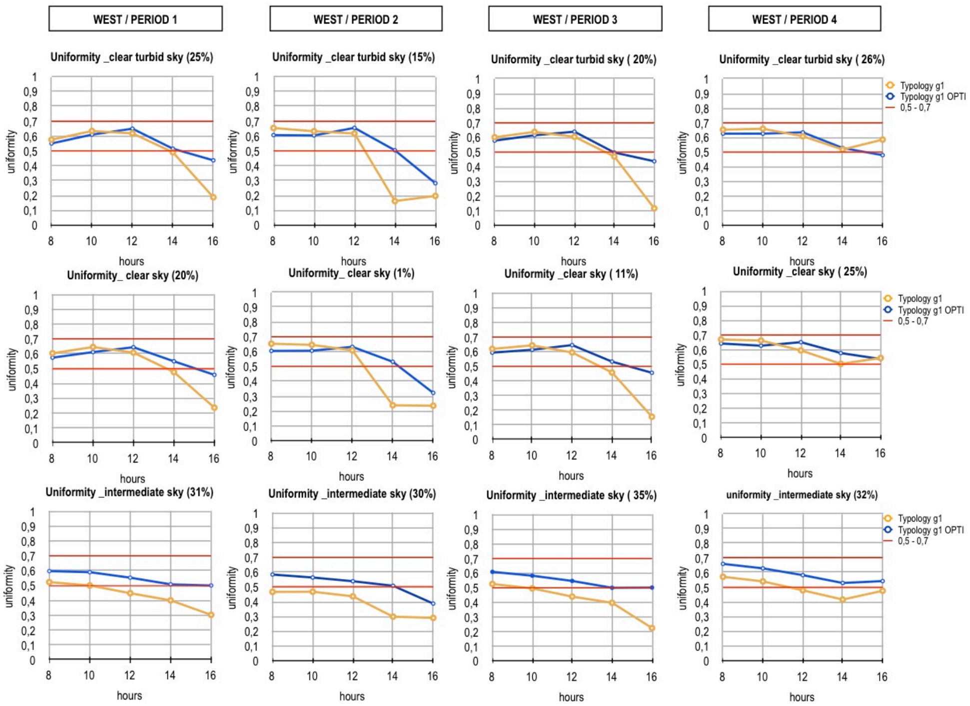
TYPOLOGY g1 Original		OPTI	TYPOLOGY g2 Original		OPTI	TYPOLOGY g3 Original		OPTI
Too Low	11%	17%	Too Low	5%	9%	Too Low	11%	26%
In range	68%	73%	In range	45%	66%	In range	57%	57%
Too high	21%	10%	Too high	50%	25%	Too high	32%	17%

West facing classrooms optimized results

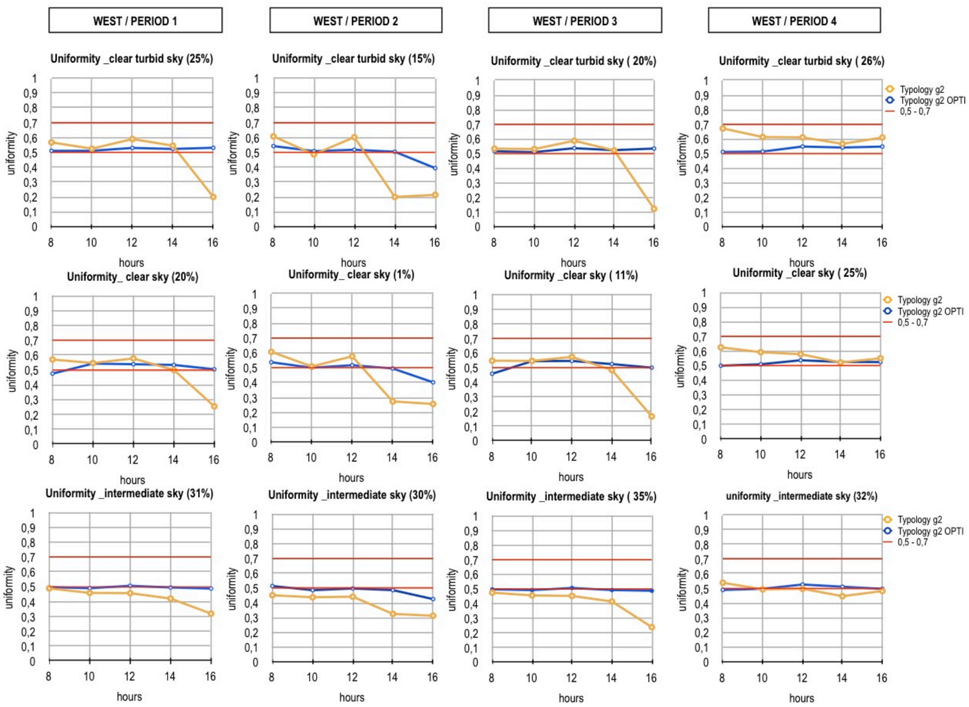


Vertical Illuminance temporal maps - West Optimized								
								
TYPOLOGY g1 Original		OPTI	TYPOLOGY g2 Original		OPTI	TYPOLOGY g3 Original		OPTI
Too Low	34%	38%	Too Low	31%	33%	Too Low	37%	49%
In range	58%	61%	In range	43%	61%	In range	49%	41%
Too high	8%	1%	Too high	26%	6%	Too high	14%	10%

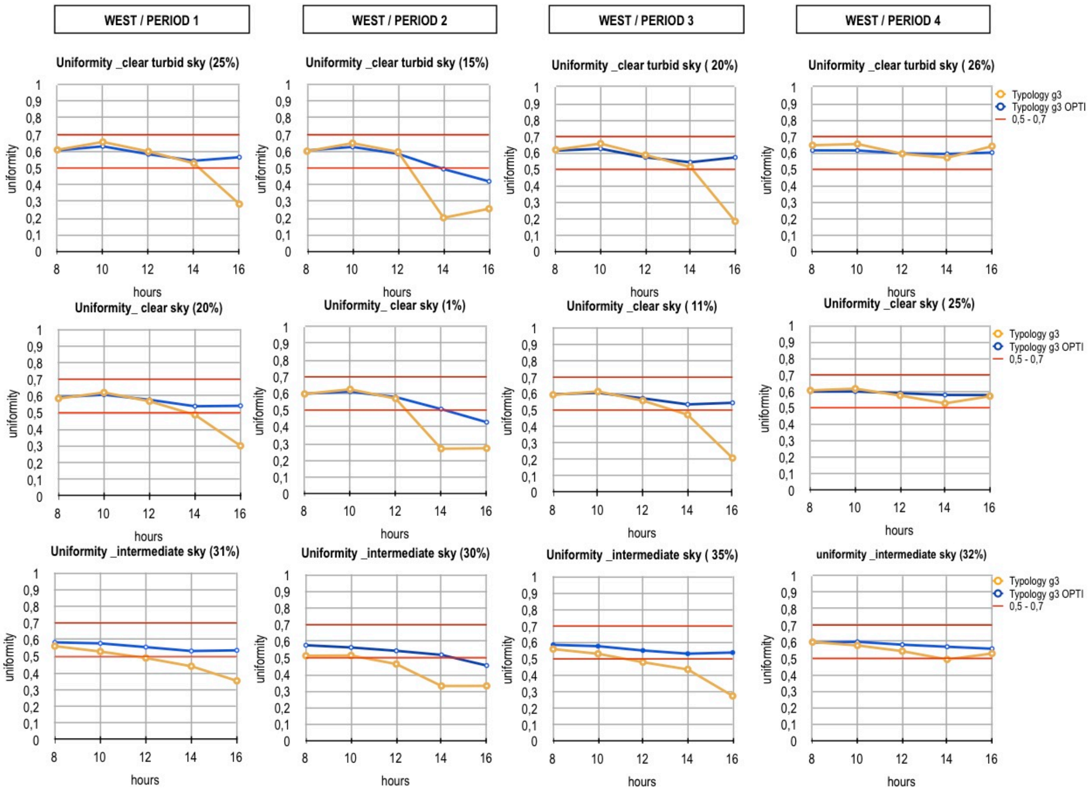
Uniformity Typology g1 West-facing classroom



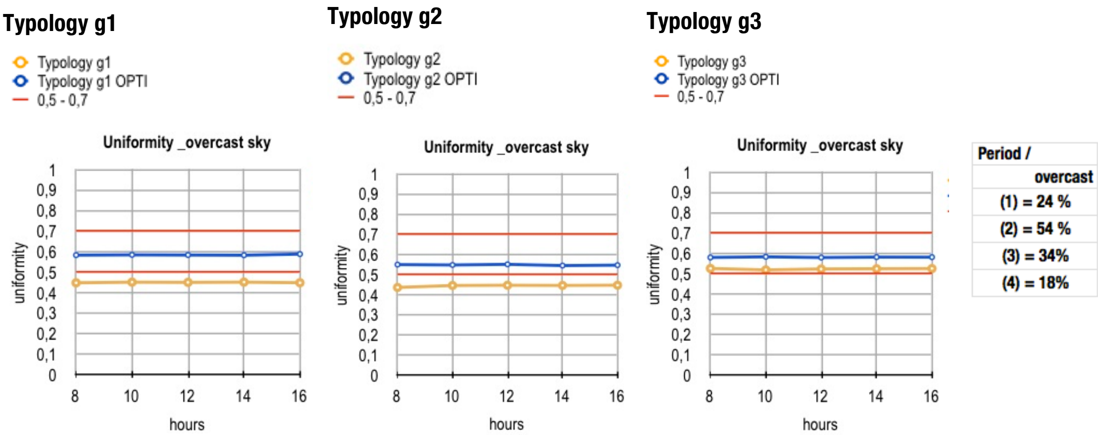
Uniformity Typology g2 West-facing classroom



Uniformity Typology g3 West-facing classroom



Uniformity Typology g1, Typology g2 and Typology g3 West-facing classroom with overcast sky:



Comparison between original and optimized Typology g1's temporal DGP maps west-facing classroom