Optimization of Natural Lighting Design for Visual Comfort in Modular Classrooms: Temuco Case

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Abstract. The emergency situations generated by the earthquakes in Chile have revealed the country’s lack of preparation to face these kinds of disasters. Many educational buildings were destroyed by these natural events. In response, a system of modular schools was implemented. Although these have been a temporary fast solution, they have not met the needs that a classroom demands.

This article focuses on studying daylighting strategies to achieve the visual comfort of students, as many investigations indicate that this is one of the key environmental factors in their wellbeing and performance. The article also focuses on achieving a correct distribution of horizontal illuminance by implementing design strategies, looking to achieve uniformity inside classrooms, avoiding annoying glare points. The implementation of these strategies fosters the use of daylight in order to reduce the energy consumption of artificial lights and generate optimal conditions for students to perform their school activities.

The studied classroom is a modular prototype located in Temuco, Chile, and the evaluated strategies were defined based on the “Guía de Eficiencia Energética para Establecimientos Educacionales (Energy Efficiency Guide for Educational Facilities or GEEEduc)”. These were evaluated independently in order to compare, starting from the results obtained from computer simulations, the compliance of the lighting comfort standards set out in said guide, focusing on the light uniformity and illuminance level indicators. The strategies with the best results were later evaluated in detail, ultimately reaching the case with the best performance.

The study proved there are several ways to respond to the presented need, allowing concluding from a set of evaluated strategies, which one of them better serves the required standards. Likewise, implementing strategies of the “GEEEduc” as well as its indicators, results in a practical application of this guideline, allowing the identification of potential errors and good options for future applications.

1. Introduction

Daylighting in educational spaces is a subject which has been addressed in research from different points of view. Access to daylight has documented benefits, like those presented by Heschong [1], who ran a study on over 2000 classrooms, concluding that students who had daylighting finished their tests quicker than those with less natural lighting. Specifically, they completed math tests 20% quicker and reading tests, 26% quicker. In addition, there are research projects that studied the link with the circadian cycle. Küller and Lindsten [2] concluded that working in classrooms without daylight alters...
the basic hormonal pattern, with this affecting the capacity of children to concentrate or cooperate, eventually having an impact on the annual body growth and on medical leaves. On the other hand, daylighting is associated with higher test scores, better work habits and a fall in fatigue, headaches and eyestrain. Students in classrooms with larger windows and skylights score up to 14% higher in end-of-year exams than students in schools with less daylight [3].

Schools also have the advantage that their opening hours coincide with the sunlight hours, therefore the use of daylight has a key role in terms of energy efficiency, reducing the consumption of energy associated to artificial lighting systems. Yu et al. [4] concluded in their study that the annual energy saving, taking advantage of the daylight, ranges between 40% and 46% for a new educational building in the United Kingdom.

Reaching quality daylighting within classrooms is conditioned by a suitable design, which must allow daylight to enter and must be capable of generating a uniformly lit space without producing glare on the workspaces. Likewise, the lighting distribution will also be conditioned by the finish of the surfaces – material, color and texture – inside the classroom, along with the geometric proportions [5].

In Chile, the Chilean Energy Efficiency Agency (AChEE) has developed the Energy Efficiency Guide for Educational Facilities (GEEEduc) that presents a set of recommendations for classroom design, considering the performance and comfort parameters these must reach, with daylighting being one of the parameters within this guide.

On the other hand, the natural disasters and other catastrophes which have affected Chile over the last few years, have led the Ministry of Education (MINEDUC) to identify infrastructure to respond to these emergencies, although it provides quick solutions, is often deficient for the children’s learning [6]. MINEDUC, within this scenario, proposed a contest in 2017 to design a “Modular System for New Educational Spaces”, aiming at having a prefabricated modular school design available for emergency situations when required.

In this context, the study of a modular classroom is proposed, which focuses on the analysis of daylighting strategies adopted following the GEEEduc, for the specific case of a primary school classroom in the city of Temuco, with the idea of identifying the pertinence of these strategies and the particular aspects of these which allow improving visual comfort conditions inside classrooms.

The city of Temuco was studied on being a city with a predominantly overcast sky condition, with the highest number of educational establishments [8]. It is located at a latitude of 38°46’ south and longitude 72°38’. It is inland, in the south of Chile, with a «Csfb» category following the Köppen climate classification.

2. Methodology

2.1. Base case

This study focused on analyzing a prefabricated modular classroom that is easy to move and build. The base case assessed is a standard classroom that is 12.0m (long) (comprising four 3.0m (wide) modules) x 6.0m (wide). Its roof is sloped, with a variable indoor height of 2.5m and 3.0m (Figure 1 and 2).

The percentage of openings foreseen for the base case (Figure 3) is due to different functional needs and the wellbeing of the occupants, which complement the light comfort.

Windows are placed at different heights on the north-facing facade, looking to guarantee a view outside from the different positions the students have inside the classrooms, letting them see into the distance. The openings to the south, where the halls between classrooms are found, are vertical allowing seeing everything happening inside the classroom from the hall. There is also a connection established from the classroom with what happens in the school. Finally, on the western side, an opening was placed at the height of a seated child’s field of vision, which provides a view to intermediate greenhouses between classrooms, a short distance view. Li et al. [9] demonstrated that views from the classroom towards green landscapes have significant and positive effects on the
recovery from stress and mental fatigue. The eastern side does not have openings to locate the board there.

Figure 1. Volumetric layout of the analyzed basic classroom

Figure 2. Base case architectonic floorplan

Figure 3. Base case classroom facades
Table 1. Base case – Light transmission and reflection indexes

| Construction Element | R  | TL  | Source        |
|----------------------|----|-----|---------------|
| Walls                |    |     |               |
| *Over 2m             | 0.5| -   | GEEEduc       |
| *Under 2m            | 0.5| -   | GEEEduc       |
| Floor                | 0.2| -   | GEEEduc       |
| Ceiling              | 0.7| -   | GEEEduc       |
| Furniture            | 0.25| - | GEEEduc       |
| Board (dark color)   | 0.2| -   | TDRe          |
| Transparent glass    | -  | 79% | Velux Daylight visualizer |
| Translucent glass    | -  | 50% | Velux Daylight visualizer |

Table 1 presents the reflection indexes of the surfaces and the light transmission of the windows considered for the base case.

The class period set out by MINEDUC’s school year for the Araucanía Region, defined between March 5th and December 5th for school with Full Time School Day (JEC in Spanish), was considered to evaluate the base case and its variants. Regarding hours of use, the Terms of Reference with energy efficiency and environmental comfort parameters (TDRe) determine a school day as being between 8am and 6pm.

Considering these periods of use of the classrooms, the strategies proposed for four moments of the year were assessed: the two equinoxes (March 21st and September 21st), the winter solstice (June 21st); while a date close to the summer solstice which was within the school year (November 21st) was chosen, for the three moments of the day: 9am, 1pm and 5pm.

According to Ilumina Chile [8], it was identified that the most common sky condition for the study area is cloudy, occurring 46% a year, so this sky condition is considered for the evaluation, see Figure 4.

Figure 4. Occurrence percentage by sky type. Own preparation based on information from Ilumina Chile
Understanding that this study’s goal is the comfort of the students using the classroom in question, a work plane is considered at 70cm in height, which is the optimal work plane considering the anthropometric dimensions for primary school children. An additional piece of information that was considered for the design was the average height of the field of vision for students of these ages, which was set at 90cm from the floor.

2.2. Variations over the base case
The strategies shown below (Figure 5) were implemented following the design recommendations described in the GEEEduc. Two criteria were considered for their choice, the pertinence for the weather conditions in Temuco and the ease with which this case study can be adapted to the prefabricated modules system.

| E1 - Opaque tray | E2 - Perforated tray |
|------------------|----------------------|
| March 2 / Sept 21 | March 2 / Sept 21 |
| June 21 | June 21 |
| November 21 | November 21 |

| E3 - Translucent tray | E4 - Skylight attached to south wall |
|-----------------------|-------------------------------------|
| March 2 / Sept 21 | March 2 / Sept 21 |
| June 21 | June 21 |
| November 21 | November 21 |

| E5 - Upper window – south facade | E6 - Central lighting with translucent window / 22% opening on cover |
|---------------------------------|---------------------------------------------------------------|
| March 21 / Sept 21 | March 21 / Sept 21 |
| June 21 | June 21 |
| November 21 | November 21 |

| E7 - Central lighting with translucent window / 11% opening on cover | E8 - Central lighting with transparent glass and diffuser screens / 11% opening on cover |
|---------------------------------------------------------------------|---------------------------------------------------------------|
| March 2 / Sept 21 | March 2 / Sept 21 |
| June 21 | June 21 |
| November 21 | November 21 |

*Window width = 0.5m

Figure 5. Evaluated strategies
2.3. Resulting Case
On the resulting case, with the best lighting and distribution levels, variants are studied increasing the reflection indexes of the indoor surfaces to improve their performance. This increase was made based on the GEE Educ recommendations. Table 2 outlines the light reflection and transmission characteristics used.

Table 2. Resulting case – Light transmission and reflection indexes

| Construction element | R   | TL   | Source     |
|----------------------|-----|------|------------|
| Walls                |     |      |            |
| *Over 2m             | 0.7 | -    | GEE Educ   |
| *Under 2m            | 0.5 | -    | GEE Educ   |
| Floor                | 0.5 | -    | GEE Educ   |
| Ceiling              | >0.7 (0.8) | - | GEE Educ   |
| Furniture            | 0.5 | -    | GEE Educ   |
| Opaque tray and diffuser screens | >0.8 (0.9) | - | GEE Educ   |
| Board (dark color)   | 0.2 | -    | TD Re      |
| Transparent glass    | -   | 79%  | Velux Daylight visualizer |
| Translucent glass    | 50% |      |            |

2.4. Sequential evaluation methodology
The cases presented were evaluated using a sequential evaluation methodology. Initially, the base case was analyzed using the Velux Daylighting Visualizer software, considering the classroom and weather conditions, looking to identify the light conditions in the primary school classroom. Later, following the GEE Educ guidelines, more appropriate strategies were established and the variations over the base case were assessed individually, using the same software and considering the average illuminance on the work plane indicator to determine more effective strategies.

Later, the strategies which best match the aforementioned factor were identified, and strategies that were compatible in a same model were combined looking to show the performance, while also considering the uniformity on the work plane coefficient for this stage. The combination of strategies ends up being the best way to optimize the use of daylighting, as shown by Al-Khatatbeh et al. [7].

Finally, the reflection indexes were modified, on the best model resulting from the combinations, to identify the optimal values for the end design – the resulting case -; the light distribution, uniformity index and the existence of contrasts in the field of vision were the factors to consider within this evaluation. Figure 6 explains the methodological outline.

2.5. Evaluation indicators
The strategies implemented were assessed through horizontal daylighting and uniformity levels. The following indicators and their optimal ranges were considered, as recommended by GEE Educ (Table 3)

Table 3. Indicators considered to assess the studied cases

| Indicator          | Unit | Optimal Range | Categories                  |
|--------------------|------|---------------|-----------------------------|
| Average lighting   | lux  | 300 - 200     | Worst case: 0 < 200         |
|                    |      |               | Deficient: 200 - 300        |
|                    |      |               | Overlighted: 2000 - 5000    |
|                    |      |               | Visual discomfort: > 5000   |
| Uniformity         | Coefficient | > 0.5 | Worst case: 0 < 0.2         |
|                    |      |               | Deficient: 0.2 – 0.3        |
|                    |      |               | Acceptable: 0.3 – 0.4       |
|                    |      |               | Good: 0.4 – 0.5             |
3. Results

3.1. First phase. Average lighting:
Starting from the analysis of the strategies adopted for the standard classroom, those which have the best lighting performance considering the average lighting on the work plane values were identified, using computer simulations. Table 4 describes the results obtained for the strategies evaluated individually.

As can be seen, the results obtained in the E6, E7 and E8 strategies stand out on being the only ones that on their own reach the minimum visual comfort levels for classrooms. E6 has the likelihood of over-lighting and is discarded for exceeding the lighting percentages recommended.

3.2. Second phase. Average lighting and uniformity:
In the case of the E7 and E8 strategies, these have similar results, with E8 being closest to the desired comfort conditions after an analysis of the field of vision luminance levels (Figure 7), presenting more standard luminance levels, while guaranteeing no bothersome glare in the students’ field of vision.

Regarding the other strategies, E3 and E4 approach the optimal lighting levels; however, they do not reach the minimum levels required most of the year, when considering the average illuminance.

Continuing with this, two cases were considered for the second phase of the analysis: the first combined the tray and skylight attached to the wall strategy (E3+E4), and the second solely considered the spotlights (E8). Figure 8 presents the two cases in detail.
Table 4. Summary of the illuminance levels obtained for the strategies

| Strategy                  | Period                        | 21 March / Sept | 21 June | 21 November |
|---------------------------|-------------------------------|-----------------|---------|-------------|
|                           | Hours 9hs 13hs 17hs 9hs 13hs 17hs 9hs 13hs 17hs | Em (lux) 92.5 124.2 39.6 41.6 69.3 3.7 106.7 133.4 55.9 | Emín 4.7 7.0 27.8 1.5 3.9 0.3 7.9 9.9 3.1 | Emáx 461.1 612.9 197.1 207.1 348.0 18.1 545.6 695.2 280.9 | DF 1.55% |
|                           |                              | Em (lux) 158.6 211.2 68.7 72.3 120.4 6.5 185.1 236.1 98.0 | Emín 11.7 154.9 4.1 6.4 10.9 0.7 20.1 25.0 10.2 | Emáx 531.1 706.5 227.6 242.5 407.2 21.7 620.2 786.6 325.0 | DF 2.59% |
| E1 – Opaque tray          |                              | Em (lux) 146.9 197.3 63.5 66.7 111.3 6.0 169.9 216.1 90.3 | Emín 15.1 17.3 5.9 4.7 8.4 0.4 7.5 5.8 2.7 | Emáx 534.7 710.4 228.3 247.3 410.7 22.5 621.4 792.4 327.0 | DF 2.39% |
| E2 – Perforated tray      |                              | Em (lux) 178.5 235.4 76.9 80.4 135.1 8.2 205.6 262.6 108.8 | Emín 8.9 12.8 4.0 4.9 7.0 1.8 9.0 13.2 4.6 | Emáx 584.1 768.3 249.6 258.6 451.3 24.4 682.6 897.9 358.2 | DF 2.91% |
| E3 – Translucent tray     |                              | Em (lux) 257.7 345.4 110.9 115.6 195.8 10.3 299.9 382.5 158.1 | Emín 5.7 14.7 5.4 5.0 10.1 0.5 12.0 19.8 6.3 | Emáx 756.5 1006.4 324.0 338.9 569.7 30.6 874.7 1118.7 461.2 | DF 4.20% |
| E4 – Skylight attached to |                              | Em (lux) 257.7 345.4 110.9 115.6 195.8 10.3 299.9 382.5 158.1 | Emín 5.7 14.7 5.4 5.0 10.1 0.5 12.0 19.8 6.3 | Emáx 756.5 1006.4 324.0 338.9 569.7 30.6 874.7 1118.7 461.2 | DF 4.20% |
| south wall                | Emín 5.7 14.7 5.4 5.0 10.1 0.5 12.0 19.8 6.3 | Emáx 756.5 1006.4 324.0 338.9 569.7 30.6 874.7 1118.7 461.2 | DF 4.20% |
| E5- Upper window – south  |                              | Em (lux) 178.5 235.4 76.9 80.4 135.1 8.2 205.6 262.6 108.8 | Emín 8.9 12.8 4.0 4.9 7.0 1.8 9.0 13.2 4.6 | Emáx 584.1 768.3 249.6 258.6 451.3 24.4 682.6 897.9 358.2 | DF 2.91% |
| facade                    |                              | Emín 5.7 14.7 5.4 5.0 10.1 0.5 12.0 19.8 6.3 | Emáx 756.5 1006.4 324.0 338.9 569.7 30.6 874.7 1118.7 461.2 | DF 4.20% |
| E6 – Central lighting     |                              | Em (lux) 257.7 345.4 110.9 115.6 195.8 10.3 299.9 382.5 158.1 | Emín 5.7 14.7 5.4 5.0 10.1 0.5 12.0 19.8 6.3 | Emáx 756.5 1006.4 324.0 338.9 569.7 30.6 874.7 1118.7 461.2 | DF 2.91% |
| with translucent window   |                              | Emín 5.7 14.7 5.4 5.0 10.1 0.5 12.0 19.8 6.3 | Emáx 756.5 1006.4 324.0 338.9 569.7 30.6 874.7 1118.7 461.2 | DF 2.91% |
| / 22% opening on cover    |                              | Em (lux) 178.5 235.4 76.9 80.4 135.1 8.2 205.6 262.6 108.8 | Emín 8.9 12.8 4.0 4.9 7.0 1.8 9.0 13.2 4.6 | Emáx 584.1 768.3 249.6 258.6 451.3 24.4 682.6 897.9 358.2 | DF 2.91% |
| E7 – Central lighting     |                              | Em (lux) 257.7 345.4 110.9 115.6 195.8 10.3 299.9 382.5 158.1 | Emín 5.7 14.7 5.4 5.0 10.1 0.5 12.0 19.8 6.3 | Emáx 756.5 1006.4 324.0 338.9 569.7 30.6 874.7 1118.7 461.2 | DF 2.91% |
| with translucent window   |                              | Emín 5.7 14.7 5.4 5.0 10.1 0.5 12.0 19.8 6.3 | Emáx 756.5 1006.4 324.0 338.9 569.7 30.6 874.7 1118.7 461.2 | DF 2.91% |
| / 11% opening on cover    |                              | Em (lux) 178.5 235.4 76.9 80.4 135.1 8.2 205.6 262.6 108.8 | Emín 8.9 12.8 4.0 4.9 7.0 1.8 9.0 13.2 4.6 | Emáx 584.1 768.3 249.6 258.6 451.3 24.4 682.6 897.9 358.2 | DF 2.91% |
| E8 – Central lighting     |                              | Em (lux) 257.7 345.4 110.9 115.6 195.8 10.3 299.9 382.5 158.1 | Emín 5.7 14.7 5.4 5.0 10.1 0.5 12.0 19.8 6.3 | Emáx 756.5 1006.4 324.0 338.9 569.7 30.6 874.7 1118.7 461.2 | DF 2.91% |
Figure 7. Comparison of field of vision of strategies E7 and E8

Figure 8. Cases evaluated in the second phase
The mean uniformity (Um) values were considered for this second stage of analysis as an additional analysis criterion. The results presented in Figure 9 and Table 5 were obtained through dynamic simulations. It is seen that the combination of strategies E3 and E4 have a better joint performance than being implemented independently. For E8 (Figure 10), although its average illuminance values were already known and continue being higher than the first case (E3+E4), the uniformity coefficient in the work area has a value that is closer to the optimum recommended by GEEEduc than the other case. As a result, a third stage of analysis was run, focusing solely on E8.

Figure 9. Case E3 and E4. Light distribution

Table 5. Results of the illuminance and uniformity levels for the case with E3 and E4 and the case with E8 strategies
3.3. Third stage. Improved reflection indexes:
In this stage, the reflection indexes of the indoor surfaces were increased using the maximum values suggested by GEE Educ (Table 2). The results obtained with this modification, case E8+ri, are shown in Table 6 and Figure 11.

Table 6. Case E8 + ri. Illuminance and uniformity levels

| Strategy | Reflection indexes | Period | 21 March / September | 21 June | 21 November |
|----------|--------------------|--------|----------------------|---------|------------|
|          |                    | Hours  | 9hs  | 13hs | 17hs | 9hs | 13hs | 17hs | 9hs | 13hs | 17hs |
| E-8 Spotlight with diffuser screens / 11% opening | As per Table 1 | Em (lux) | 343.99 | 458.18 | 193.14 | 163.34 | 258.94 | 14.23 | 442.94 | 516.55 | 256.63 |
|          |                    | Emin   | 37.18 | 54.70 | 10.48 | 24.44 | 21.41 | 2.69 | 90.96 | 112.62 | 56.50 |
|          |                    | Emix   | 577.86 | 777.60 | 327.38 | 271.95 | 442.50 | 24.73 | 699.06 | 896.61 | 447.74 |
|          |                    | Uniformity | 0.11 | 0.12 | 0.05 | 0.12 | 0.08 | 0.19 | 0.22 | 0.22 | 0.22 |
|          | As per Table 2     | DF     | 0.05 |      |      |      |      |      |      |      |      |
|          |                    | Em (lux) | 366.58 | 483.89 | 205.11 | 197.15 | 274.84 | 14.30 | 410.81 | 522.88 | 261.00 |
|          |                    | Emin   | 78.07 | 105.16 | 44.46 | 23.87 | 51.69 | 3.04 | 95.99 | 117.34 | 60.66 |
|          |                    | Emix   | 593.76 | 791.15 | 330.60 | 319.73 | 446.37 | 25.07 | 695.30 | 883.67 | 440.80 |
|          |                    | Uniformity | 0.21 | 0.22 | 0.22 | 0.15 | 0.19 | 0.21 | 0.23 | 0.23 | 0.23 |
|          |                    | DF     | 0.06 |      |      |      |      |      |      |      |      |
4. Discussion

The sequentially presented results allow identifying relevant aspects for each stage of analysis. In the first stage, only one type of strategy (central spotlighting) met the needs of the classroom in terms of daylighting levels. “For this stage, beyond reaching the level of daylight, the evaluation of the strategies was positive, allowing clear and direct comparisons to be made on the same space.”

For the second stage, where the results of the uniformity of the lighting on the work plane were linked, the levels obtained with strategy E8 stand out. The proposed combination of strategies E3 + E4 was due to the results obtained in the first stage and GEEduc’s recommendations, where because of the reach of the light in depth of the space of each one of these two strategies, it was suggested to combine them. However, the uniformity obtained fell outside the required levels.

In the third stage, the relevance of indoor surface reflection indexes have in the lighting behavior of a space was evaluated. Although it was not possible to conclude if these were enough on their own to reach optimal indexes, their contribution was positive in terms of light comfort and are simple measures to implement. This aspect is especially important for the case study, as on dealing with a prefabricated modular classroom, the ease of implementation is essential.

With regard to the role of the windows, this study focused on their job of lighting the indoor space; however, it is clear that these perform multiple roles in buildings in general and also in classrooms, on allowing visual contact with the outside and playing a key role in the indoor air quality, allowing ventilation. They likewise contribute to the thermal performance of inner space, on forming part of the envelope. In an integrated analysis, the multiple dimensions mentioned to guarantee the global environmental comfort within the classroom, must be considered.
5. Conclusions
The rapid response to buildings, in this case educational ones, has been implemented in Chile during post-disaster periods. Currently, the priority has been to cover the basic needs of the affected population, playing down the importance of comfort conditions. This study identified, through a sequential construction method, possible strategies that aside from responding to the conditions that an easy and quick to build modular construction classroom demands, also met the visual comfort needs for their occupants, an aspect whose relevance has been broadly mentioned in this study.

The combination of the translucent tray and skylight attached to the wall strategies is the one which is closest to optimal lighting levels, but it is insufficient regarding lighting uniformity. The combination of these two strategies, along with the optimization of their components, could offer a good daylighting alternative.

The central spotlighting provided the best lighting performance for the case study, regarding daylighting levels and uniformity on the work plane. Specifically, strategy E8, which implemented diffuser screens under the glazed surface, was the one that managed to avoid high contrasts in the field of vision and obtain a balanced lighting which met the needs of use for the space evaluated. The increase of the reflection indexes (E8+ri) allowed reaching daylighting levels that were, on average, 5% over those obtained in the second stage for this same strategy, and an increase in the daylighting uniformity on the work plane of up to double what was obtained in most evaluations.

Finally, it is worth highlighting that the strategy, E8+ri, could be applicable in other cities with different latitudes and sky conditions, reaching optimal indoor visual comfort conditions. The results showed that this strategy is an effective alternative to capture daylight, because thanks to the diffuser screens implemented, the lighting captured is uniformly distributed within the space, either diffusely or directly.

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