Diagnostics of existing lighting conditions in existing public schools in Central-Southern Chile: Measurements and predictions for retrofit

Andrea Martínez Arias[1], Isaac Soto San Martin[1], Pierina Bustos[1], y Ma. Isabel Rivera[1,2]

[1] Departamento de Arquitectura, Facultad de Arquitectura, Urbanismo y Geografía, Universidad de Concepción, Chile
[2] Centre for Sustainable Urban Development (CEDEUS), Chile

Abstract. Daylight is one of the indoor environmental qualities that most influence students' development in learning in a classroom. However, many existing schools do not optimize daylight. Indeed, standardized façade designs result in wasted energy in artificial lighting while daylight could be harvested. This study provides a diagnostic of illuminance levels and their distribution in a typological classroom based on field data for a school in the central-south region of Chile. The government built these schools during the second half of the 20th century, and they are still operational, maintaining the same original façade, with no differentiation regarding orientation. Through simulations, it analyzes potential retrofit strategies to identify the ones that could result in better light distribution and autonomy. Facing a lack of local standards for lighting levels in schools' classrooms, international standards are used as thresholds for actual lighting levels and a series of retrofit scenarios.

Keywords: Existing schools, Diagnostic, Retrofit, Daylighting.

1 Introduction

Schools are critical spaces for children for their learning and general wellbeing. However, whether for public or private ownership type or considering specific climatic conditions, indoor environmental conditions (i.e., acoustics, daylighting, and comfort) in Chilean schools have been shown to be poor, whether for public or private ownership type nor considering specific climatic conditions (Armijo, Whitman, & Casals, 2011; M.I. Rivera, 2019; M. I. Rivera & Kwok, 2019; Trebilcock, Soto-Muñoz, Yañez, & Figueroa-San Martin, 2016; Trebilcock, Soto, & Figueroa, 2014). Some of these environmental conditions get stressed out as classrooms are overcrowded, the current Chilean D.S. 548 established that the minimum area is 1m^2 per student, much lower than the average space in OCDE countries (M.I. Rivera, 2019).

The typology from the "Sociedad Constructura" from the 70s', was a school prefabricated steel and light school structure in Chile, which is still predominant and operational in many cities today. The latter was a response to the massive construction response after the Educational Reform in the 1960s, intending to build as many schools infrastructure to provide free access to education to primary students in Chile. (Exss Cid, 2018). The historical and typological significance of these systematic and industrialized schools have been covered in previous studies. (Exss Cid, 2018; Torres & Rojas, 2017), while others have highlighted the need for their improvement (Martinez, Rivera, & Arriagada, 2022).

Access to daylight in Chilean schools is a common resource many designers take advantage of; we observed that it is not studied and distributed in a manner that could improve visual comfort for students and teachers if the façade had some special treatment. Classrooms only rely on the use of indoor curtains for solar control. Teachers usually keep curtains closed because of drafts from the windows in winter or overheating in the summertime, and use projectors for class instruction to create high contrast and control glare or uneven distribution. Additionally, using artificial lighting is expected due to insufficient daylight. However, they do not provide sufficient lighting levels. Due to lighting fixtures being usually outdated, they need to be more efficient in light quality and energy efficiency.

Figure 1. Interior view of the study classroom typology during wintertime. This image was taken during the pandemic, thus the less students seating arrangement than normal school year. It is possible to observe paint over glass panes in lower areas of the window and curtains typical in classrooms for direct sun control. Source: Authors, 2023**.**

Along with integrating daylight performance in new high-performance schools, improving existing ones is also crucial, as many remain operational beyond their lifetime with minimum maintenance. It has been estimated that 80% of buildings in 2050 are already built (Lee, Matusiak, Geisler-Moroder, Selkowitz, & Heschong, 2022). Among these, retrofitted schools are called to restore health and environmental quality together, given the climate crisis. In the long-term, any added retrofit cost could pay for itself due to decreased energy costs for artificial lighting and future earnings for the fruits of students' and teachers' improved well-being.

1.1 The importance of daylight in classrooms

The evidence that exposure to daylight and views are essential to human life is widely documented for decades (Heschong, 2021; Ludlow, 1976), especially how it impacts human systems such as the visual (Boyce, Hunter, & Howlett, 2003) production of Vitamin D and circadian regulation (Crowley, Cain, Burns, Acebo, & Carskadon, 2015; Mirrahimi, Ibrahim, & Surat, 2013). Currently, daylighting is recognized as one of the most influential factors in creating a positive learning environment, creating optimal conditions for the development of tasks, facilitating learning, and improving performance (Aumann, Heschong, Wright, & Peet, 2004; Rahman & Tuhin, 2019; Susan & Prihatmanti, 2017; Tanner, 2009).

In particular school design, daylight was incorporated as a physical environmental condition fundamental to students' health from the beginning of the 20th century in some government design guidelines (Heschong, 2021 citing American guidebooks; Hobday, 2015 citing British guidelines). After the prolificacy of mechanical means that resulted in a period of windowless schools in some developed countries, a boom in the importance of passive strategies after the oil crisis of the 1970s derived in passive solar schools being built with daylight as a priority (Wu & Ng, 2003). Some research has focused on the importance of the design of windows as a concern for the eye development of children (Hobday, 2015). In addition to the benefits of incorporating natural light, is the connection to the outside, as a positive effect on the quality of life (Kent, 2022) the view to nature has also been linked with children’s wellbeing (Lindemann-Matthies, Benkowitz, & Hellinger, 2021) and learning outcomes (Heschong Mahone Group, 2003). All these studies provide the foundation that must inform architecture and industry (Lee et al., 2022), not only in new designs but mostly in existing buildings.

1.2 Metrics, building codes and standard values for daylighting

Even though the Chilean government has pushed for improvement in new and existing schools, there needs to be a policy for schools to comply with high performance, no energy code, or special certification at a national level that can mandate schools comply with current standards. A limited set of indoor parameters, including a minimum average of 180 lux for the entire classroom area, are defined in a rule for schools from the 1980s D.S. 548, which does not address the quality of its distribution and control for glare. (Ministerio de Educación, 1989) (Ministerio de Educación, 1989).

Table 1. International standards, design guidelines and recommended values

Parameter	Value	Reference
Illuminance (lux)	180 lux	DS 548 (1989)
	300 lux (min) - classroom 500 lux – whiteboard 750 lux – drawing general	ACEE (2016) based on TDR (2012, Table 16)
	300 lux (area - min) – classroom general, elementary school 500 lux (area – min) 750 lux (Task -average) – Science Lab	IES (2020)
Daylight Factor (DF)	2% minimum 2% - 5% acceptable 5% - 10% day lit autonomous >10% glare probability	TDR (2012) pg. 195
Spatial Daylight Autonomy (sDA)	75% floor area with 300 lux in 50% time occupied hours	LEED v 4.1 Daylight. exemplary performance
	>80% high potential 50%-79% medium potential <50% low potential	TDR (2012) pg. 197
	>90% $sDA_{300/90\%}$	CHPS 2014
ASE	(ASE1000,250) <10%	LEED v 4.1 Daylight. exemplary performance

Source: Authors, 2023. Based on Decreto Supremo 548 (1989) del Ministerio de Educación, Chile; Términos de Referencia (TDR) (Ministerio de Obras Publicas, 2012), Ministerio de Obras Públicas, Chile. Lighting Educational Facilities American National Standard (Illuminating Engineering Society, 2020)

Main metrics point to evaluating the availability of light in a space in ranges that allow task to be performed without discomfort. Among these, *Illuminance* (lux) is the amount of light that falls in a determined area, which along with its uniformity, will determine light availability according to space type. When compared to outside, *Daylight Factor* (DF) establishes the percentage of skylight outside a building that is available indoors at a given point. Light levels outdoors can rich more than 100.000 lux in direct sun and 15.000 lux in the shade on a clear day (Norton & Siegwart, 2013). Minimum DF requirements typically range between 2% and 5%. Finally, some annual metrics are currently used in building certification as indicators high-performance. *Spatial Daylight Autonomy* (sDA) is an indicator of daylight harvest potential and consequent energy savings on artificial light. At the same time, *Annual Sunlight Exposure (*ASE) indicates the percentage of the regularly occupied floor area that is overlit (receiving direct sunlight >1000 lux) for more than 250 occupied hours. International standards serve as references with recommended values for a series of metrics, as described below in Table 1.

2 Methodology

This study presents the results based on fieldwork data of a diagnosis for one school. However, it is part of a more extensive study that includes three schools in the central southern regions of Chile. The case study includes a classroom with a north orientation in its current conditions and studies a retrofit strategy for improving daylight availability and distribution in its north facade. A Li-cor illuminance meter was used for actual measurements, with a 10-second average in a horizontal grid defined by the students' desks' height at 0.75 meters (2.5 ft.) above the floor. Those measurements were analyzed on tables and processed on an online open-source tool for contour plots (Plotly, 2023).

Table 2. Retrofit strategies simulated for a north-oriented classroom

Iteration #	Description of retrofit strategy
1	White-paint in ceiling of the classroom
2	Light-shelf (exterior, 90cms)
3	Light-shelf (interior, 30cms)
4	Light-shelf (exterior + interior)
5	Light-shelf (exterior + interior) + roller curtain

Source: Authors, 2023.

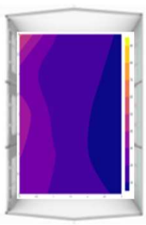
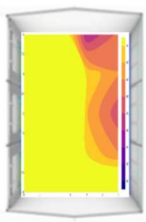
A Rhino model served to evaluate retrofit strategies through Climate Studio plugin (Solemma, 2023). The first step was the definition of a baseline for the representative classroom, which was built based on current materials in the classroom and sky conditions close to the registered from the onsite measurements (summer and winter). The "point on time" analysis was used, which allowed us to compare the values on the model with the field measured values. A grid was used to calculate the deltas on the lux values and their corresponding percentage. It is worth noticing that measurements were taken at different times of the year, which impacted the distribution and number of students' layout of desks and occupancy, defined by the government during the pandemic. Once the baseline was obtained, a second baseline without curtains was created to eliminate the shading effect and allow the following iterations (listed in Table 2) of passive strategies to a full extent of window areas. Subsequently, a series of iterations of strategies for daylight harvesting were simulated, as described in Table 2. The "Daylight Availability" analysis was run for the iterations to obtain indicators for annual base performance, represented in: Spatial Daylight Autonomy (sDA) and the Annual Sunlight Exposure (ASE).

3 Results

3.1 Diagnosis of daylighting performance in a typological classroom

Measurements in the school (open curtains, lighting fixtures turned off) reported that most of the classroom was not in a range of lighting for summer and winter. The current international recommendation of a minimum of 300 lux recommended by IES was not achieved in the classroom in summer. On the other hand, more than two-thirds of the space was overlit in winter.

Table 3. Illuminance levels for north-oriented classroom from one case study school.

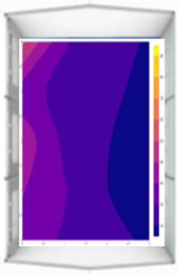
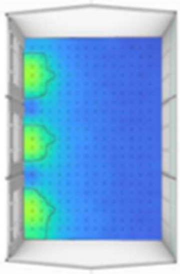
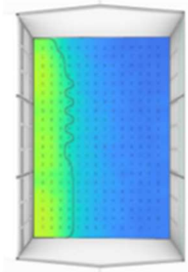
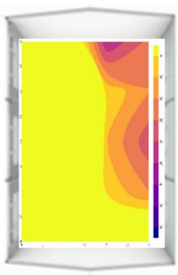
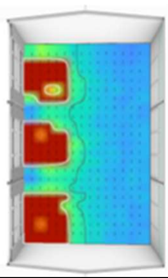
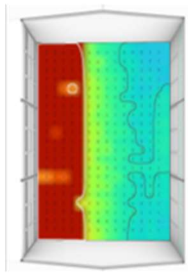
	Summer (only daylight, open curtains) 05/01/2022 10:30 am	**Winter (only daylight, open curtains)** 14/07/2021 12:20 pm
Contour plan	 Mean: 185 lux Median: 147 lux	 Mean: 2.510 lux Median: 850 lux
< 300 lux	**95 %**	0 %
>300-750lux<	5 %	21 %
>750 lux	0 %	**79 %**

Source: Authors, 2023

3.2 Definition of Baseline

The baseline model resulted in a better representation of summer than winter compared to reference field-measured values. For summer, a mean difference of -25.7% and a median difference of -12.3% existed. However, there was a mean difference of -311% for winter and a median difference of -289%.

Table 4. Illuminance levels for field measurements and resulting from the baseline(s) models for the north-oriented classroom from one case study school

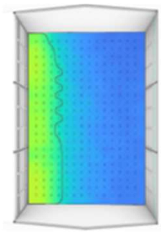
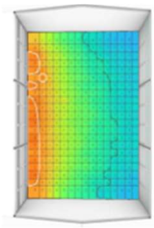
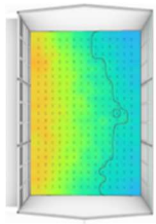
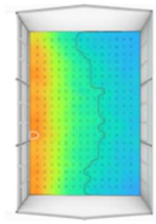
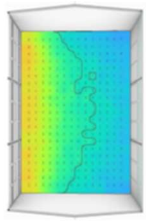
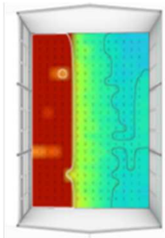
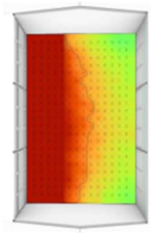
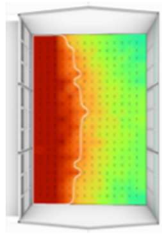
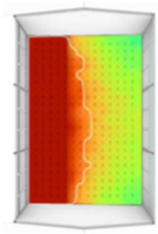
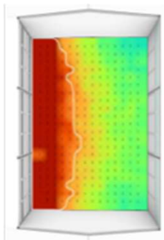
<table>
<tr><th></th><th>Field values
(only daylight, open curtains)</th><th>Baseline Model
(only daylight, open curtains)</th><th>Baseline Model
(only daylight, no curtains)</th></tr>
<tr><td>Summer
05/01/2022
10:30 am</td><td>
<table><tr><td>307</td><td>207</td><td>101</td><td>74</td></tr><tr><td>361</td><td>177</td><td>103</td><td>70</td></tr><tr><td>241</td><td>167</td><td>106</td><td>91</td></tr><tr><td>526</td><td>209</td><td>126</td><td>93</td></tr></table></td><td>
<table><tr><td>299</td><td>147</td><td>88</td><td>78</td></tr><tr><td>265</td><td>142</td><td>93</td><td>80</td></tr><tr><td>424</td><td>154</td><td>94</td><td>82</td></tr><tr><td>154</td><td>156</td><td>102</td><td>85</td></tr></table></td><td></td></tr>
<tr><td>Mean
Median</td><td>185 lux
147 lux</td><td>152 lux
116 lux</td><td>226 lux
174 lux</td></tr>
<tr><td>< 300 lux
>300-750lux<
>750 lux</td><td>95%
5%
0%</td><td>89%
11%
0%</td><td>74%
26%
0%</td></tr>
<tr><td>Winter
14/07/2021 12:24
– 12:40</td><td>
<table><tr><td>15000</td><td></td><td>902</td><td>847</td></tr><tr><td>4000</td><td></td><td>860</td><td>602</td></tr><tr><td>2900</td><td></td><td>844</td><td>796</td></tr><tr><td>2700</td><td>1632</td><td>850</td><td>696</td></tr></table></td><td>
<table><tr><td>5794</td><td></td><td>213</td><td>185</td></tr><tr><td>11329</td><td></td><td>226</td><td>183</td></tr><tr><td>11513</td><td></td><td>222</td><td>185</td></tr><tr><td>209</td><td>304</td><td>208</td><td>179</td></tr></table></td><td></td></tr>
<tr><td>Mean
Median</td><td>2.510 lux
850 lux</td><td>2.773 lux
269 lux</td><td>4.029 lux
424 lux</td></tr>
<tr><td>< 300 lux
>300-750lux<
>750 lux</td><td>0%
21%
79%</td><td>56%
21%
23%</td><td>24%
41%
35%</td></tr>
</table>

Source: Authors, 2023.

The winter difference of values could happen due to historical weather data or, most probably, because of the highly dynamic conditions of the sky (partially cloudy) at the time of measurement. The second baseline eliminated the effects of the curtains, considering that the interventions would not be compatible with them. This baseline elevated the values for winter with a median value closer to the field data.

3.3 Results of iterations of retrofits

Table 5. Diagrams with the different interventions for north-oriented classroom and annual indicators.

	0. Baseline (no curtains)	**1. White ceiling**	**2. White ceiling +Ext. 90cm light shelf**	**3. White ceiling + Int. 30cms light shelf**	**4. White ceiling + int + ext light shelves**
Summer					
Mean	226 lux	440 lux	420 lux	386 lux	364 lux
Median	174 lux	400 lux	395 lux	333 lux	320 lux
< 300 lux	74%	30%	30%	43%	46%
>300-750lux<	26%	63%	**70%**	56%	54%
>750 lux	0%	7%	0%	1%	0%
Winter					
	4.029 lux	4.376 lux	1.790 lux	4.342 lux	2.736 lux
	424 lux	793 lux	671 lux	749 lux	607 lux
< 300 lux	24%	0%	0%	0%	0%
>300-750lux<	41%	48%	61%	52%	**66%**
>750 lux	35%	52%	39%	48%	34%
DF Mean	1.6%	**1.9%**	1.3%	1.8%	1.2%
sDA (300lux 50% area)	63%	**100%**	**100%**	98.3%	96.3%
ASE	20%	29%	**14%**	29%	**14%**

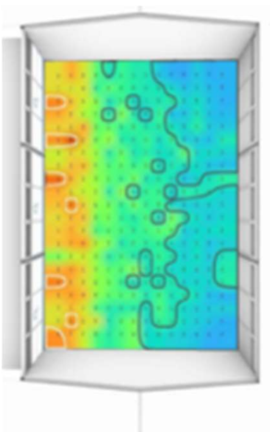
Source: Authors, 2023

The annual performance indicators, the Spatial Daylight Autonomy (sDA) as the percentage of the regularly occupied floor area that meet target illuminance level (300 lux) using daylight alone for at least 50% of occupied hours. The Annual Sunlight Exposure (ASE) represents the percentage of the regularly occupied floor area that is overlit with more than 1000 lux direct sun for more than 250 occupied hours).

The results illustrated in Table 5 showed that applying clear paint to the ceiling is a simple change that resulted in a daylight autonomy of 100%. Therefore, the increased reflectivity in that surface brought areas into the illuminance target range in both seasons, leaving only 30% of the classroom area under-lit in summer. However, ASE rose higher than the current situation due to excess direct light remaining in the border area. The exterior light shelf maintained a 100% SDA, which, complemented with an interior light shelf, allowed to bring 66% of the classroom within the target illuminance range, as it dimmed part of the over-lit values next to the window.

4 Discussion

The series of strategies were intended to test simple improvements that could be affordable for the limited budgets of public schools and feasible considering little disruption to school operations. Considering that the school year is in the south hemisphere, the operation in summer is limited to a couple of weeks (beginning of March); strategies to harvest daylight in winter would provide the opportunity for retrofits to result in energy efficiency.



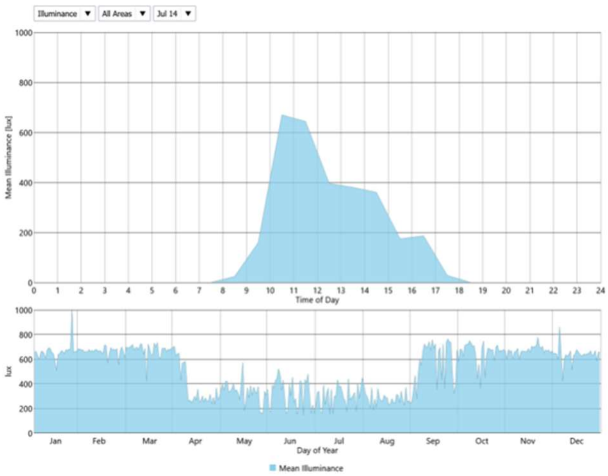


Figure 2. Illuminance distribution for the north-oriented classroom with a profile of mean Illuminance for a winter day (July 14) along with the annual profile. Source: Authors, 2023.

The combination of a clear-painted ceiling and light shelves seemed a solution that controlled excess light and bounced light levels in the interior area of the classroom. An additional intervention, incorporating a roller curtain in the lower window areas, was modeled to control the excess of light at the façade of the previous iterations and provide levels between the desired illuminance ranges, except in the early morning (Figure 2).

The modeling of certain features, such as the curtain or films in the glass, would need to be further explored. Likewise, it is worth mentioning that modeling existing spaces remains challenging due to estimating the existing material attributes, either to the natural aging or the representation of the multiple elements on the surfaces in actual classrooms.

5 Conclusion

This study embraced the evaluation of a set of simple strategies of design that could improve daylight availability in typological classrooms based on field data for a school in the central-south region of Chile. The performed simulations provided metrics to evaluate the potential of these retrofit strategies that could be affordable, considering the limited budgets for public school maintenance and upgrades. Simple actions such as painting the classroom ceiling and an exterior light shelf were shown to achieve 100% spatial daylight autonomy for a north-facing classroom. Likewise, bringing the studied classroom to recommended international standards could be possible. Further exploration would better calibrate models for closer prediction, considering the dynamics of weather and the complexity of the representation of surfaces in actual classrooms.

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References

Armijo, G., Whitman, C. J., & Casals, R. (2011). Post-occupancy evaluation of state schools in 5 climatic zones of Chile. *Gazi University Journal of Science, 24*(2), 265-374.

Aumann, D., Heschong, L., Wright, R. L., & Peet, R. (2004). *Windows and Classrooms : Student Performance and the Indoor Environment*.

Boyce, P., Hunter, C., & Howlett, O. (2003). The Benefits of Daylight through Windows.

Crowley, S. J., Cain, S. W., Burns, A. C., Acebo, C., & Carskadon, M. A. (2015). Increased Sensitivity of the Circadian System to Light in Early/Mid-Puberty.

The Journal of Clinical Endocrinology & Metabolism, 100(11), 4067-4073. doi: 10.1210/jc.2015-2775

Exss Cid, U. S. (2018). *De la racionalización constructiva a la arquitectura sistemática*.

Heschong, L. (2021). *Visual Delight in Architecture. Daylight, Vision, and View* (1st Edition ed.). London: Routledge.

Heschong Mahone Group. (2003). Windows and Classrooms: A Study of Student Performance and the Indoor Environment: California Energy Commission.

Hobday, R. (2015). Myopia and daylight in schools: a neglected aspect of public health? *Perspectives in Public Health, 136*(1), 50-55. doi: 10.1177/1757913915576679

Illuminating Engineering Society. (2020). Recommended Practice: Lighting Educational Facilities. . New York: IES.

Kent, M. (2022). Predicting Window View Preferences Using the Environmental Information Criteria. *LEUKOS, 19*, 1-20. doi: 10.1080/15502724.2022.2077753

Lee, E. S., Matusiak, B. S., Geisler-Moroder, D., Selkowitz, S. E., & Heschong, L. (2022). Advocating for view and daylight in buildings: Next steps. *Energy and Buildings, 265*, 112079. doi: https://doi.org/10.1016/j.enbuild.2022.112079

Lindemann-Matthies, P., Benkowitz, D., & Hellinger, F. (2021). Associations between the naturalness of window and interior classroom views, subjective well-being of primary school children and their performance in an attention and concentration test. *Landscape and Urban Planning, 214*, 104146. doi: https://doi.org/10.1016/j.landurbplan.2021.104146

Ludlow, A. M. (1976). The functions of windows in buildings. *Lighting Research & Technology, 8*(2), 57-68. doi: 10.1177/14771535760080020801

Martinez, A., Rivera, M. I., & Arriagada, P. (2022). *Informing Early-Stage Building Energy Retrofit for Prototypical Public Schools in Chile*. Paper presented at the RESILIENT CITY: Physical, Social, and Economic Perspectives. ARCC-EAAE 2022, Miami, US. Paper presentation retrieved from https://www.arcc-arch.org/2022-authors-of-papers-posters/

Ministerio de Educación. (1989). *Decreto 548*.

Ministerio de Obras Publicas. (2012). *Terminos De Referencia Estandarizados (TDRe)*.

Mirrahimi, S., Ibrahim, N. L. N., & Surat, M. (2013). *Effect of daylighting on student health and performance*.

Norton, T. T., & Siegwart, J. J. T. (2013). Light levels, refractive development, and myopia – A speculative review. *Experimental Eye Research, 114*, 48-48-57. doi: 10.1016/j.exer.2013.05.004

Plotly. (2023). Plotly Contour plots. *Plotly Graphing Libraries.* Retrieved august 4 2023, 2023, from https://plotly.com/python/contour-plots/

Rahman, F., & Tuhin, M. (2019). Daylight impact on learning environment in classrooms of secondary high school at Ishwardi, Pabna, Bangladesh. *International Research Journal of Engineering and Technology (IRJET), 6*(10), 1148-1153.

Rivera, M. I. (2019). *Indoor and Environmental Air Quality in Chilean Classrooms.* (22623056 Ph.D.), University of Oregon, Ann Arbor. Retrieved from https://search.proquest.com/dissertations-theses/indoor-xa0-environmental-quality-chilean/docview/2320962873/se-2?accountid=15690 ProQuest One Academic database.

Rivera, M. I., & Kwok, A. (2019). *Thermal comfort and air quality in Chilean schools, perceptions of students and teachers*. Paper presented at the Future of Praxis: Applied Research as a Bridge Between Theory and Practice. ARCC.

Susan, M., & Prihatmanti, R. (2017). Daylight characterisation of classrooms in heritage school buildings. *PLANNING MALAYSIA JOURNAL, 15*. doi: 10.21837/pmjournal.v15.i6.236

Tanner, C. (2009). Effects of school design on student outcomes. *Journal of Educational Administration, 47*. doi: 10.1108/09578230910955809

Torres, C., & Rojas, P. (2017). Tipificación: Experiencia de masificación e innovación en el diseño de edificios escolares públicos, construidos entre las décadas del 60 y 80 en Chile. *Arquitecturas del Sur, 35*(52), 15-29.

Trebilcock, M., Soto-Muñoz, J., Yañez, M., & Figueroa-San Martin, R. (2016). The right to comfort: A field study on adaptive thermal comfort in free-running primary schools in Chile. . *Building and Environment, 114*, 455-469. doi: http://doi.org/10.1016/j.buildenv.2016.12.036

Trebilcock, M., Soto, J., & Figueroa, R. (2014). *Thermal comfort in primary schools : a field study in Chile.* Paper presented at the Proceedings of 8th Windsor Conference: Counting the Cost of Comfort in a Changing World, Cumberland Lodge, Windsor, UK.

Wu, W., & Ng, E. (2003). A review of the development of daylighting in schools (Vol. 35, pp. 111-111-125).